15th International Workshop on Optimization and Inverse Problems in Electromagnetism
September 11 – 13, 2018, Hall in Tirol, Austria

Resonator Impedance Optimization for Quasi-static Magnetic Resonance Based Actuation

Matthias VANDEPUTTE[1]*, Luc DUPRE[1] and Guillaume CREVECOEUR[1*]

[1] Department of Electrical Energy, Metals, Mechanical Constructions & Systems, Ghent University, 9052 Ghent, Belgium

E-mail: matthias.vandeputte@ugent.be

**M. Vandeputte and G. Crevecoeur are affiliated with Flanders Make, the strategic research centre for the manufacturing industry in Flanders, Belgium.*

Abstract. Strongly coupled magnetic resonance 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.

Keywords: magnetic coupling, motoring, wireless power transfer, strongly coupled magnetic resonance.

INTRODUCTION

Wireless power transfer (WPT) has found increased research interest over the last decade. WPT is a further development of the more general inductive power transfer (IPT) [1]. WPT allows the transfer of energy from a transmitter coil to a receiver resonator coil over medium to large air gaps. A resonator is a series connected inductor-capacitor (RLC) circuit which has a certain resonance frequency. It has been proven that WPT is the most efficient when tuning the transmitter frequency to the resonance frequency of the magnetically coupled receiver coils (strongly coupled magnetic resonance – SCMR), as the impedance of the receiver is minimized at resonance, while the induced currents are maximized [2]. These currents can be directly used to apply resonator-resonator or transmitter-resonator forces/torques. Figure 1(left) shows an SCMR based motoring topology with a transmitter coil (*t*), a stator resonator (*s*) which is fixed in space and a rotor resonator (*r*) which rotates around an axle [3]. M_{ab} is the mutual inductance between coil *a* and coil *b* and is dependent on the rotor angle (θ).

RESONATOR IMPEDANCE OPTIMIZATION

For SCMR motoring, the phase difference between the currents in the RLC circuits of the system coils (transmitter, rotor and stator) affects the effectiveness of the torque generation. In this work, we explore detuning of the resonators by changing their capacitor value in order to improve the motoring capability of the SCMR motoring system. In a moving SCMR system, the induced voltage in coil *a* by the current in coil *b* can be expressed as:

$$\varepsilon_a = \frac{d}{dt}(M_{ab}i_b) = M_{ab}\frac{di_b}{dt} + \frac{dM_{ab}(\theta)}{d\theta}\frac{d\theta}{dt}i_b = M_{ab}\frac{di_b}{dt} + \frac{dM_{ab}(\theta)}{d\theta}\dot{\theta}i_b = M_{ab}\frac{di_b}{dt} + K_{ab}(\theta)\dot{\theta}i_b \quad (1)$$

The first part of Equation (1) is called the transformer electromotive force (EMF), while the second part is the motional EMF. The system currents in the SCMR system can now be derived from circuit laws:

$$\begin{bmatrix} R_t & j\omega M_{ts} & j\omega M_{tr}(\theta) + \dot{\theta}K_{tr}(\theta) \\ j\omega M_{ts} & R_s + jX_s & j\omega M_{sr}(\theta) + \dot{\theta}K_{sr}(\theta) \\ j\omega M_{tr}(\theta) + \dot{\theta}K_{tr}(\theta) & j\omega M_{sr}(\theta) + \dot{\theta}K_{sr}(\theta) & R_r + jX_r \end{bmatrix} I = Z_V I = \begin{bmatrix} V_t \\ 0 \\ 0 \end{bmatrix} \quad (2)$$

with $X_i = \omega L_i - \frac{1}{\omega C_i}$. The generated torque $T_m(\theta)$ can be obtained starting from the power flows in the system:

$$P_m = \dot{\theta} T_m(\theta) = \frac{1}{2} I^* \begin{bmatrix} 0 & 0 & \dot{\theta} K_{tr}(\theta) \\ 0 & 0 & \dot{\theta} K_{sr}(\theta) \\ \dot{\theta} K_{tr}(\theta) & \dot{\theta} K_{sr}(\theta) & 0 \end{bmatrix} I \rightarrow T_m(\theta) = \frac{1}{2} I^* \begin{bmatrix} 0 & 0 & K_{tr}(\theta) \\ 0 & 0 & K_{sr}(\theta) \\ K_{tr}(\theta) & K_{sr}(\theta) & 0 \end{bmatrix} I \quad (3)$$

Resonance occurs for a minimized resonator impedance $R_a + jX_a$ by tuning X_a to zero. Figure 1(middle) shows the torque profile for stator and rotor resonators tuned to resonance (blue). The peak torque occurs when no magnetic stator-rotor coupling is present. Two coupled resonators display resonant behaviour at a lower frequency [4]. Driving the transmitter at the resonators' original resonance frequency then results in a phase shift and amplitude decrease of the resonator currents. Contrary to regular WPT to multiple receivers, the transmitter-rotor and stator-rotor phase difference also affects the torque profile of the SCMR motoring system. This angle dependent phase difference can be adjusted by detuning the stator and rotor capacitors (C_s and C_r), thus resulting in non-zero values for X_s and/or X_r. Figure 1(right) shows the average torque for varying values of X_s and X_r. The red dot shows the optimum found ($\mathbf{X}^{opt} = [X_s^{opt}, X_r^{opt}] = [-1.677, -0.796]$) by a gradient based optimization procedure starting from the resonant condition ($\mathbf{X}^0 = [X_s, X_r] = [0, 0]$). When the torque profile has negative values (compromising the starting capabilities of the SCMR motoring system), the objective function returns a zero average torque. Figure 1(middle) shows the optimized torque profile (red) with a 14% gain compared to the torque profile at the resonant condition (blue). The peak torque now occurs for a slightly coupled stator and rotor coil. The presented optimization methodology can be used to further optimize the resonator impedances when dealing with more complex topologies with multiple system coils.

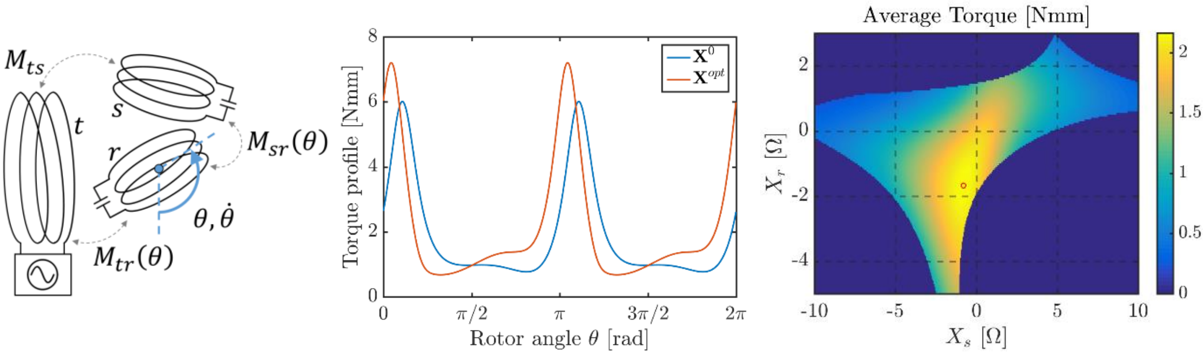

Figure 1: [left] The SCMR motoring topology with a transmitter coil (t), a stator resonator (s) which is fixed in space and a rotor resonator (r) which rotates around an axle. [middle, right] The average torque of the SCMR motoring system can be improved by 14% compared to resonant conditions.

CONCLUSIONS

It has been shown that 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.

REFERENCES

[1] G. Covic, G. and J. Boys (2013). Inductive power transfer. Proceedings of the IEEE, vol. 101(6), 2013, pp. 1276-1289.

[2] S. Hui, W. Zhong, and C. Lee. A critical review of recent progress in mid-range wireless power transfer. IEEE Transactions on Power Electronics, vol. 29(9), 2014, pp. 4500-4511.

[3] M. Vandeputte, L. Dupré and G. Crevecoeur, Quasi-static torque profile expressions for magnetic resonance based remote actuation. IEEE transactions on energy conversion, 2018, under review.

[4] D. Ahn and S. Hong. Effect of coupling between multiple transmitters or multiple receivers on wireless power transfer. IEEE Transactions on Industrial Electronics, vol. 60(7), 2013, pp. 2602-2613.