Extending the Inductor Operating Frequency for Optimally-coupled Wireless Power Transfer Systems

Fabian L. Cabrera, Renato S. Feitoza and F. Rangel de Sousa
fabian.l.c@ieee.org, renato.feitoza@grad.ufsc.br, rangel@ieee.org

Laboratório de Radiofrequência
Universidade Federal de Santa Catarina

IMOC 2015
Inductive links

- Used to wireless powering IMD (implanted medical devices) and RFID tags.
Inductive links

- Used to wireless powering IMD (implanted medical devices) and RFID tags.
Inductive links

- Used to wireless powering IMD (implanted medical devices) and RFID tags.
- The secondary inductor must be miniaturized.
Inductive links

- Used to wireless powering IMD (implanted medical devices) and RFID tags.
- The secondary inductor must be miniaturized.
- The primary size constraints are more relaxed.
Efficiency must be maximized

\[ \frac{1}{\eta} = \frac{1}{k^2} \cdot \frac{1}{Q_1} \cdot \frac{1}{Q_2} \cdot \left( p + 2 + \frac{1}{p} \right) + p + 1 \]
Efficiency must be maximized

\[
\frac{1}{\eta} = \frac{1}{k^2} \cdot \frac{1}{Q_1} \cdot \frac{1}{Q_2} \cdot \left( p + 2 + \frac{1}{p} \right) + p + 1
\]

- Coupling factor squared
Efficiency must be maximized

\[ \frac{1}{\eta} = \frac{1}{k^2} \cdot \frac{1}{Q_1} \cdot \frac{1}{Q_2} \cdot \left( p + 2 + \frac{1}{p} \right) + p + 1 \]

- Coupling factor squared
- First Inductor quality factor

Power transfer efficiency
Efficiency must be maximized

\[ \frac{1}{\eta} = \frac{1}{k^2} \cdot \frac{1}{Q_1} \cdot \frac{1}{Q_2} \cdot (p + 2 + \frac{1}{p}) + p + 1 \]

- Coupling factor squared
- First Inductor quality factor
- Second Inductor quality factor
Power transfer efficiency

Efficiency must be maximized

\[
\frac{1}{\eta} = \frac{1}{k^2} \cdot \frac{1}{Q_1} \cdot \frac{1}{Q_2} \cdot \left( p + 2 + \frac{1}{p} \right) + p + 1
\]

- Coupling factor squared
- First Inductor quality factor
- Second Inductor quality factor
- Load matching dependence
Mutual coupling model

\[ k = \frac{M}{\sqrt{L_1 L_2}} \]

\[ M = \mu \sqrt{\frac{d_{avg1} d_{avg2}}{\pi}} \left[ \left( \frac{2}{\gamma} - \gamma \right) K(\gamma) - \frac{2}{\gamma} E(\gamma) \right] \]  

(1)

\[ \gamma = \sqrt{\frac{4 d_{avg1} d_{avg2}}{(d_{avg1} + d_{avg2})^2 + \pi d^2}}, \]  

(2)

Magnetic coupling factor when \( d_{avg2} = 4 \text{ mm}. \)
Quality factor model

\[ R(f) \]

\[ L \]

\[ C \]

Radiation:
\[ R \propto f^4 \]

Skin effect:
\[ R \propto f^{0.5} \]

Loss factor
\[ \Lambda = \frac{1}{Q} = \frac{R}{\pi f L} \]

Simulation Model:
\[ \Lambda \]

\[ d_{avg1} = 4 \text{ mm} \]
\[ d_{avg1} = 10 \text{ mm} \]
\[ d_{avg1} = 22 \text{ mm} \]
Quality factor model

\[ R(f) \]

\[ L \]

\[ C \]

\[ R \propto f^4 \]

\[ \text{Radiation} \]

\[ R \propto f^{0.5} \]

\[ \text{Skin effect} \]

\[ \Lambda = \frac{1}{Q} = \frac{R}{\pi f L} \]

\[ \text{d}_{\text{avg1}} = 4 \text{ mm} \]

\[ \text{d}_{\text{avg1}} = 10 \text{ mm} \]

\[ \text{d}_{\text{avg1}} = 22 \text{ mm} \]
Loss factor

\[ \Lambda = \frac{1}{Q} = \frac{R}{2\pi f L} \]
To maximize efficiency:

- $k$ must be maximized, this leads to a primary inductor bigger than the secondary.
To maximize efficiency:

- $k$ must be maximized, this leads to a primary inductor bigger than the secondary.
- Operating frequency is then limited by the biggest inductor.
## Trade-off

<table>
<thead>
<tr>
<th>To maximize efficiency:</th>
</tr>
</thead>
<tbody>
<tr>
<td>▶ $k$ must be maximized, this leads to a primary inductor bigger than the secondary.</td>
</tr>
<tr>
<td>▶ Operating frequency is then limited by the biggest inductor.</td>
</tr>
<tr>
<td>▶ Therefore, the smaller inductor does not operate in its optimal frequency.</td>
</tr>
</tbody>
</table>
To maximize efficiency:

- $k$ must be maximized, this leads to a primary inductor bigger than the secondary.
- Operating frequency is then limited by the biggest inductor.
- Therefore, the smaller inductor does not operate in its optimal frequency.
- We can extend the operating frequency of the link using a segmented inductor.
Segmented inductor

\[ L = \frac{1}{C_S} \]

\[ C = C_{\text{Gap}} + C_D - \frac{1}{N} C_{\text{Gap}} \]

(a) Equivalent reactance when \( C_D = 0 \).
(b) Segmented inductor losses.
Segmented inductor

\[ C_s = \frac{C_G + C_D}{N - 1} \]

- \( C_G \) Gap capacitance
- \( C_D \) Discrete capacitor
- \( N \) Number of segments
Segmented inductor

\[ C_S = \frac{C_G + C_D}{N - 1} \]

- \( C_G \): Gap capacitance
- \( C_D \): Discrete capacitor
- \( N \): Number of segments

(a) Equivalent reactance when \( C_D = 0 \).
(b) Segmented inductor losses.

Graphs showing the equivalent reactance and resistance for different values of \( N \) and \( C_D \).
Segmented inductor quality factor

![Graphs showing segmented inductor quality factor](image)

- **$Q_1$** vs. $f$ [GHz] for different numbers of segments ($N$) and capacitance values ($C_D$): 1, 2, 4, 8.

- **$Q_1 Q_2$** vs. $f$ [GHz] for $N$ and $C_D$ values: 1, 2 (0-16 pF), 4 (1-16 pF), 8 (2-32 pF).
Effect of the capacitor losses

(a) Equivalent series resistance for discrete capacitors. (b) Quality factors product accounting the capacitors ESR.

Performance is no longer improved for higher values of $N$ because of the capacitor losses.
### Implementation

<table>
<thead>
<tr>
<th>$d_{avg2}$ [mm]</th>
<th>$d_{avg1}$ [mm]</th>
<th>$N$</th>
<th>$C_D$ [pF]</th>
<th>$d$ [mm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>4</td>
<td>22</td>
<td>4</td>
<td>3</td>
<td>15</td>
</tr>
</tbody>
</table>
Experimental results

![Graph showing experimental results.](image)

<table>
<thead>
<tr>
<th>$N$</th>
<th>$C_D$ [pF]</th>
<th>$\eta_{max}$ [%]</th>
<th>$f_{\eta_{max}}$ [MHz]</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>–</td>
<td>30</td>
<td>415</td>
<td>Meas. [3]</td>
</tr>
<tr>
<td>4</td>
<td>3</td>
<td>38</td>
<td>735</td>
<td>Sim.</td>
</tr>
<tr>
<td>4</td>
<td>1.5</td>
<td>37</td>
<td>990</td>
<td>Sim.</td>
</tr>
<tr>
<td>4</td>
<td>1.5</td>
<td>30</td>
<td>980</td>
<td>Meas.</td>
</tr>
</tbody>
</table>

Conclusions:

- The operating frequency of an optimally-coupled inductive link was extended from 415MHz to 980 MHz.
Conclusions:

- The operating frequency of an optimally-coupled inductive link was extended from 415MHz to 980 MHz.
- The extension of the operating frequency was achieved by dividing the primary inductor into four segments.
Conclusions:

- The operating frequency of an optimally-coupled inductive link was extended from 415 MHz to 980 MHz.
- The extension of the operating frequency was achieved by dividing the primary inductor into four segments.
- The technique presented offers potential improvements on the link efficiency, however that improvements are limited by the capacitor losses.
Conclusions:

▶ The operating frequency of an optimally-coupled inductive link was extended from 415MHz to 980 MHz.

▶ The extension of the operating frequency was achieved by dividing the primary inductor into four segments.

▶ The technique presented offers potential improvements on the link efficiency, however those improvements are limited by the capacitor losses.

▶ The extension of the primary inductor frequency offers flexibility to the inductive link design.