

Influence as a challenger to Induction for near-field wireless power transfer

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Abstract. We introduce what we call “Influence” WPT technology, which can be perceived as the dual of magnetic induction WPT. In Influence systems, two or more electric circuits are coupled by electric fields whereas Induction systems involve magnetic field coupling. We propose an unconventional approach to describe and study Influence, using coupling matrices, in analogy with the treatment of Inductive coupling, albeit with a larger number of parameters. In spite of their different natures, both technologies enable non-radiative near-field energy transfer at mid-range, and display interesting and sometimes counter-intuitive behaviors.

1. Introduction

Energy transfer through short distances using moving magnets or electrically charged bodies [1] had been accomplished centuries before Hertz’s discovery of electromagnetic waves. Here, we provide a soft introduction to the idea of energy transfer through electric fields using the experimental arrangements of figures 1(a) and (b). Figure 1(a) shows two electrically charged distant pendulums, initially in equilibrium. If one pendulum is set into oscillatory motion, energy is coupled to the second one due to their distant coulombic force interaction, hence producing oscillations in the latter. If one of the pendulums is replaced by an elongated conductor as shown in figure 1(b), application of forced oscillations to the pendulum can induce charge oscillations along the conductor. Such electrical charge displacements caused by an external charge was historically referred to as “electrical influence” in Europe [2]. Contemporarily, the term “electric induction” is more common, but may lead to confusion.

![Figure 1.](image)

Figure 1. (a) Induced oscillations in coupled pendulums (b) Induced charge motion in a conductor.
2. A modern form of Influence

The basic concepts presented above are at the heart of modern Influence WPT devices where energy is transported between oscillating electric dipoles, just like magnetic induction WPT involves coupled oscillating magnetic dipoles (figure 2). It is well-known that the coupling between dipoles is better if they are aligned [3]. A specificity of the electrically coupled systems is that it is much easier to realize asymmetric dipoles constituted by electrode pairs (figure 3). This may bring about an increase in the coupling coefficient $k$, efficiency, range as well as other interesting and unrivalled characteristics [3].

![Figure 2. Magnetic (left) and electric (right) oscillating coupled dipoles in longitudinal configuration.](image)

![Figure 3. Longitudinal asymmetric configuration.](image)

![Figure 4. Equivalent Circuit representation.](image)

Electric coupling can be represented through classical electrical circuits as in figure 4. However, in this ten-capacitor representation, some circuit nodes are virtual and some branches are crossed by virtual currents. In this work, we use an alternative representation shown in figure 5. In the circuit of figure 5, only circuit branches carrying measurable material currents are shown. We call them “open-ended representations”. They enable much clearer and more realistic portrayal of devices. In contrast to Induction where only three coefficients are concerned, the full description of all the voltages involved in capacitive coupling is contained in a 4x4 matrix with at most ten independent coefficients. This gives more degrees of freedom and increased technical possibilities. For instance, using asymmetry, it is possible to concentrate the electric field in a region between small facing electrodes.

$$
\begin{bmatrix}
\Omega_1 \\
\Omega_2 \\
\Omega_3 \\
\Omega_4 \\
\end{bmatrix} =
\begin{bmatrix}
C_1 & -C & 0 & 0 \\
-C & C_2 & 0 & 0 \\
0 & 0 & C_3 & 0 \\
0 & 0 & 0 & C_4 \\
\end{bmatrix}
\begin{bmatrix}
V_1 \\
V_2 \\
V_3 \\
V_4 \\
\end{bmatrix}
$$

![Figure 5. A possible configuration of closely spaced electrodes and its open-ended representation.](image)
As a result, reactive energy and high voltages are concentrated between these two “active” electrodes. Furthermore the casing of the original devices can be used as the large “passive” electrodes, allowing seamless integration of the technology in existing products. The specific geometries possible for electric coupling between electrodes also lead to a higher degree of flexibility in lateral positioning compared to magnetic coupling between coils (figure 6). In particular, there is no lateral misalignment that can nullify the coupling, in contrast to coupled coils. It should be pointed out that only the active electrodes of the Influence coupled devices are shown with the passive ones assumed to be far away.

![Magnetic coupling case](image)

**Table 1.**

| Flux Type          | Magnetic coupling case | Electric coupling case |
|-------------------|------------------------|------------------------|
| Maximum coupling  | Positive flux          | Maximum coupling       |
| Coupling is smaller| Negative flux          | Very small change      |
| Coupling is zero  | Leakage flux           | small decrease         |

Figure 6. Efficiency fall with lateral misalignment - inductive and capacitive coupling [5].

3. Power limitations

If we base our reasoning on the everyday experience that magnetic forces between magnets can be much larger than electrostatic forces, we might hastily conclude that Influence is fundamentally limited to much lower power transfer applications than Induction. Both technologies involve large amounts of reactive energy stored in the vicinity or inside the devices. Only a very small part of this energy is typically transferred at mid-range; however the transfer occurs many times per second according to the generator frequency, and can equate to quite high levels of transmitted power.

Using the classical expression for the energy density within a region of electric field, we may define a power density according to the formula: $P_d = \omega E^2 / 2$. At 1 MHz, in dry air, we obtain a maximum reactive power level of 250 kVA/dm$^3$. This leaves room for large power applications even if a minute part of this reactive power is transferred as real power. Practical limitations (just like for induction systems), are associated to dissipation and efficiency rather than to electrical breakdown. For applications requiring high power or long range, EMI regulations can also introduce limitations.

4. Use of resonances

For both technologies, resonances can be used to improve efficiency [4, 5]. The main idea (exploited by Tesla himself) being to recycle the untransferred energy instead of losing it at each alternation by integrating the coupling elements within a high Q-factor RLC circuit driven at its resonance frequency. This recycling can be done on both generator and load sides (it is more efficient to recycle the nearby energy on both sides). The effect of resonance is summarized in table 1. Another important factor is that capacitors generally have higher component Q-factors than inductors, resulting in a higher efficiency or range potential for Influence systems over Induction systems.
5. Impedance considerations

Exact solutions of Maxwell’s equations for fields produced by elementary electric or magnetic dipoles (current loop) are available. The term “elementary” means that dipole size is small compared both to the wavelength $\lambda$ (non relativistic movements) and to the measurement distance $d$. Generally the electric and magnetic field vectors have both a phase angle and a geometric orientation in space; their ratio cannot be characterized by a single number. However along an axis perpendicular to the dipole, electric and magnetic fields are at right angles allowing the definition of a complex impedance $Z = \frac{E}{H}$ which conveys information on both the amplitude ratio and the phase difference between the fields. The magnitudes of $Z$ for electric and magnetic dipoles are given in figure 7.

![Figure 7. Impedance in the near and far fields of elementary electric and magnetic dipoles.](image)

We note that the electric dipole’s near field displays high impedance, while that of the magnetic dipole displays low impedance. As expected, they converge to the value of the wave impedance of TEM waves in the far-field. Finally, the decisive factor for Influence technologies is their high impedance character. As for high-voltage distribution lines, they need, for the same power handling, far less conductive materials than their low-voltage competitors. Moreover, the use of copper electrodes is not mandatory for Influence: they can be made of transparent conductive plastic sheets.

6. Conclusions

Power can be transferred efficiently between two distant oscillating electrical dipoles coupled through their electric fields. Electric coupling between circuits is more difficult to grasp and represent than its magnetic counterpart because virtual currents exist outside the devices. In schematics, we propose to restrict the use of the classical capacitor symbol to cases of total influence and to adopt “open-ended” circuits for more general cases. Compared to Induction systems, Influence is more tolerant to positioning and provides other flexibilities. This high impedance technology is currently being used in consumer electronics [5]. Prospection for automotive applications has started [6]. Natural extensions to large low-cost arrays of switched electrodes to cover long distances or wide surfaces are expected.

7. References

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