Finite elements method modeling of contactless energy transfer systems.

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Contactless energy transfer (CET) systems are used in many industrial sectors. These include conveyors, trolleys, storage and retrieval units, baggage handling, battery charging stations, mobile phones and medical implants. They provide cost reduction in energy transfer, compact design, maintenance free equipment, versatility and higher reliability.
The energy transfer model is quite similar to a classical transformer, except for the weak coupling between the primary and secondary windings and partial or non existing ferromagnetic closing path. Inductive coupling is commonly used in the range of a few mW to a few hundreds of kW.
Figure 1 shows a schematic view of a transmitting and receiving antenna for an electric car battery charging device. The transmitting coil is stationary and fed by a high frequency switching power source. The receiving antenna is inductively coupled to the transmitting antenna and supplies an electric power storage (battery or supercapacitors). The operational frequency is above the audible range but remains below 100 kHz to limit the switching losses in the power source. Resonant circuits are used in the primary and secondary sides to boost the transmitted power and minimize the voltage and current in the device. Total efficiency is usually above 90%.

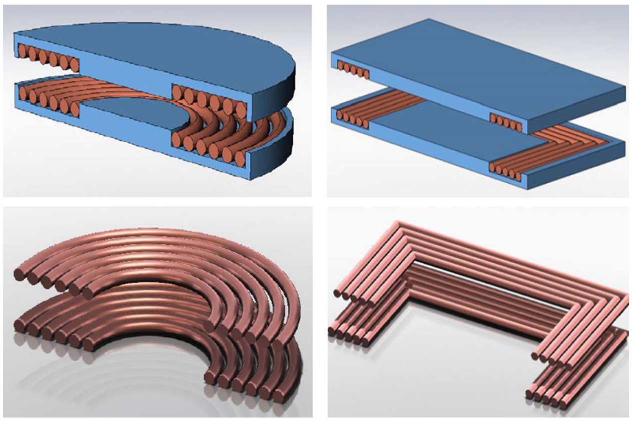

Figure 1: Iron core and coreless CET coils (Pavol Bauer, TU Delft).

The upper CET configurations in figure 1 use a soft ferrite yoke while the lower ones build up an ironless transformer. The left hand side models can be investigated via a 2D axisymmetric model while the right hand side models require a 3D analysis. A hybrid model can also consist of an air coil and back yokes made of ferrite disks (fig. 2). In this model, the ferrite yokes consist of a full disk (shown in light blue and dark blue over 180°) or consist of sectors. The emitting and receiving coils are shown in yellow and red colors.

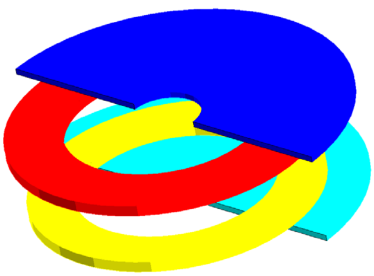

Figure 2: Schematic view of a coreless CET coils with ferrite back yokes.

System simulation and 2D analysis

For battery charging devices, the distance between the coils may be quite large (typically 100 mm) and misalignments between transmitting and receiving antenna must be taken care of. Due to the large airgap between the primary and secondary windings, the mutual inductance is low compared to the leakage inductances. Therefore the magnetizing current is high and generates excessive Joules losses.

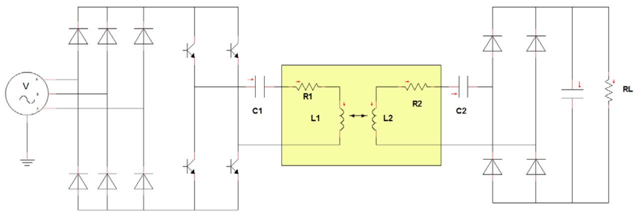

Figure 3: Equivalent circuit for a CET with power source and load in Portunus.

A popular solution is to use a resonant circuit based on additional capacitors connected in series or parallel with the primary and secondary windings. The equivalent circuit for a compensated CET device supplied by a three phase rectifier and feeding a battery via an H-bridge is shown in figure 3. The equivalent circuit of the coupled antennas is inside the yellow box.
A simple CET model consists of primary and secondary linear inductances (L1 and L2), a mutual inductance and windings resistances. Due to the high supply frequency (25 to 60 kHz), the coils will consist of Litz wires which, despite the low fill factor, dramatically reduce the eddy current and proximity effect losses in the windings. The external capacitors C1 and C2 are used to build up a resonant circuit. The primary and secondary resonance frequencies are usually equal and can be approximately defined by:

$$\omega_0 = \frac{1}{\sqrt{C1 * L1}} = \frac{1}{\sqrt{C2 * L2}}$$

L1 is the primary inductance and L2 the secondary inductance. C1 and C2 are capacitors connected in series with the primary and secondary phases.

The model shown in figure 3 may be efficiently used in a system simulation software such as Portunus to optimize the device performances (choice of operational frequency, switching losses, number of turns, influence of load variation). The CET lumped circuit model does not include additional losses within the CET system (ferrite hysteresis losses, losses in the housing or in shielding plates). In case such phenomena need to be integrated in the model, it is possible to conduct a co-simulation between Portunus and FLUX® using a macromodel of the CET. The lumped circuit model shown in figure 3 would be replaced by a component describing the FEM model of the transformer. This model is solved in Flux and coupled to a circuit defined in Portunus. This method is more accurate as it takes into account an eventual iron saturation and other complex physical phenomena. It is however more time consuming, especially if the FEM model is three dimensional.

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A dynamical simulation using the lumped circuit model of the antennas requires a good knowledge of the windings inductances. These can be derived from an AC harmonic analysis with Flux 2D or Flux 3D. To determine the primary inductance L1, the primary winding is supplied with an AC current. The primary inductance L1 and the coupling inductance M are easily derived from the coupled fluxes. The same procedure is applied to the secondary winding to derive the secondary inductance L2. This model is valid for CET devices without ferrite or with linear ferrite permeability and without conducting regions (shielding plates for instance). Due to the large airgaps, the assumption on the linear behavior of the system is often valid.

Figure 4 shows an academic case of a CET device exhibiting transmitting and receiving coils, ferrite back yokes and an aluminium shielding above the moving coil. The CET device was modeled with Flux 2D using a current source on the primary side, series compensation capacitors and a resistive load. The primary and secondary capacitors were determined using the classical formula mentioned above in order to satisfy a resonance frequency of 40 kHz. It is worth mentioning that the formula does not take into account ferrite losses or losses in housing or shielding plates. The flux lines are displayed in figure 4 for a resistive load at resonance frequency. We notice that the upper shielding prevents the flux lines from extending out of the CET environment.

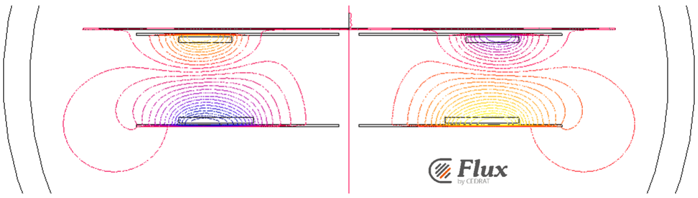

Figure 4: Flux lines in a CET device (AC Harmonic analysis with Flux 2D.

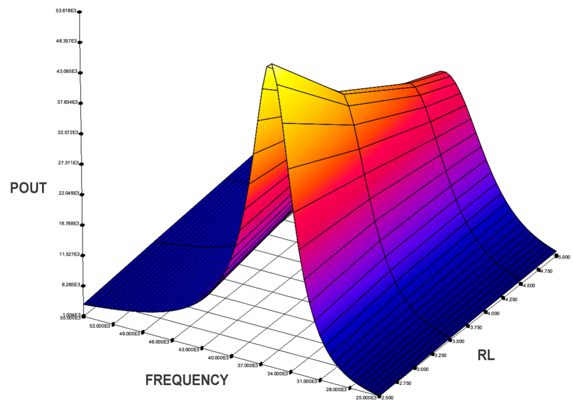

Figure 5: Transmitted power vs. operational frequency F and load resistance RL.

Figure 5 shows a 3D view of the power in a resistive load vs. operational frequency and load resistance. The computation is made on a 2D model. The resonance frequency is relatively constant when the load changes. Airgap variations can however create a drift on the resonance frequency and a fixed or variable frequency control must be decided depending on the working environment.

The output power takes into account the ferrite losses via a complex permeability and its dependence over the supply frequency. Also eddy currents are assumed to flow in an aluminium shielding plate (upper region). The transmitted power calculation is based on a constant copper and ferrite temperature. The maximum transmitted power will be however limited by the losses in the coils and in the ferrite, as well as the current density in the coils. The temperature distribution in the device can also be determined with the thermal analysis application of Flux.

The parametric solver of Flux can furthermore be used to assess various configurations. Also the influence of the number of primary and secondary turns, resonance capacitances or saturation can be investigated. The designer can make use of the parametric solver of Flux to determine the influence of key parameters. Among them are the resonance frequency for a rated load, variations of the transmitted power vs. airgap, device efficiency, influence of number of turns, power factor, etc.

3D finite element method analysis

A 3D FEM analysis is compulsory for some design cases: investigation of antennas misalignment, use of rectangular coils or ferrite yokes consisting of sectors. A small penetration depth in conducting regions can make the simulation very tedious and requires a long computation time. Flux 3D provides some interest features to conduct studies on CET devices. Non meshed coils are superposed to the finite element domain and need not be meshed. They can help model very complicated coil shapes, provided that eddy current and proximity effects are neglected. Non linear surfacic impedances are furthermore available for AC analysis. They efficiently model conducting regions where the penetration depth is small vs. region depth. On the other hand, lossy ferrites are modeled using complex permeabilities depending on the operational frequency.

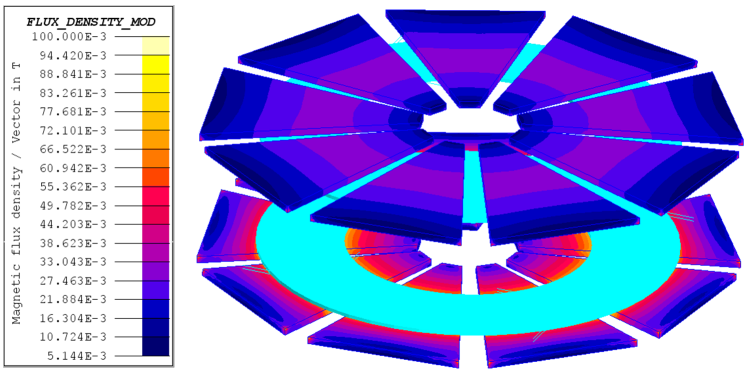

Figure 6: Flux lines distribution in a CET device (AC Harmonic analysis with Flux 3D).

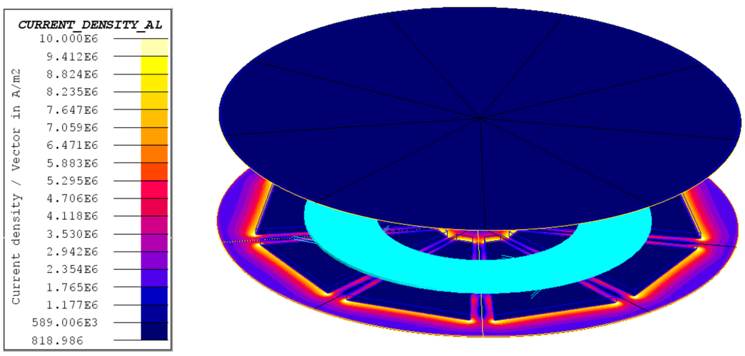

Fig 7: Current density distribution in the CET shielding plates (AC Harmonic analysis with Flux 3D).

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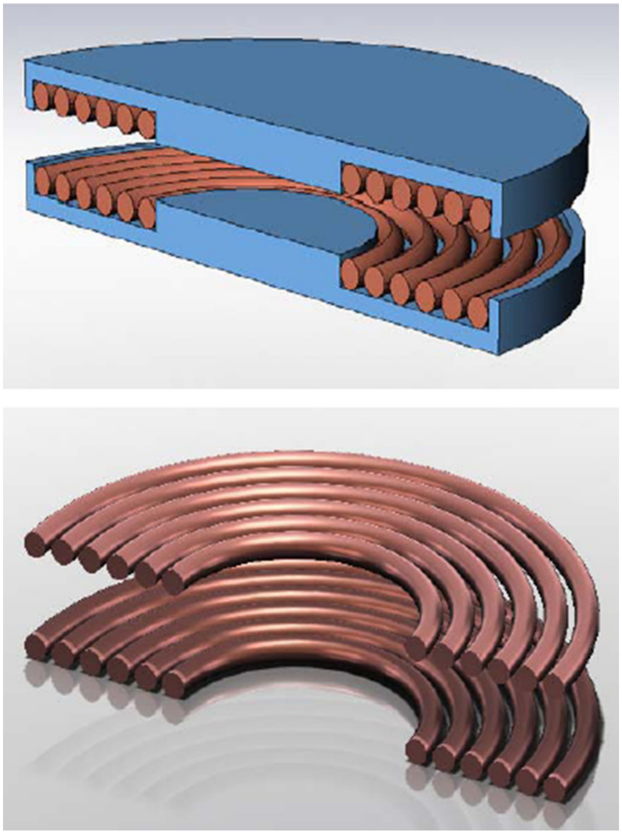
Figure 6 shows a case where sectored ferrite yokes are used. In this case only the primary winding is supplied with a current source at 40 kHz. We furthermore added thin aluminium shielding plates below the emitting antenna and above the receiving antenna. The ferrite yokes are modeled as magnetic conducting regions. Due to the high frequencies and small penetration depth in the aluminium, a volumic meshing of the shielding plates would require a high number of meshes. These regions are rather modeled in Flux 3D via surfacic impedances (boundary condition on the region surface). This allows a coarse discretisation of the shielding plates as the magnetic field is only computed on the surface.
The device ferrite yokes are each made of nine ferrite sectors. The symmetry of the domain allows to restrict the study to a 40° sector The device model is furthermore included in an 'infinite region' while the magnetic field is assumed to expand out of the airgap. This feature allows to assess the influence of the charging device on electronic components or optimize the shielding to limit the field radiated within the car body.
Figure 6 shows the flux density magnitude in the ferrite blocs. It is to be mentioned that the saturation flux density in MnZn ferrites hardly exceeds 0.5 T and the Curie temperature is around 220°C. Therefore it is strongly advised to check the losses in this region and assess their influence on the ferrite temperature. Figure 7 shows the loss density in the aluminium shielding plates in this configuration. The use of ferrite sectors instead of a ferrite disk can be justified in terms of price but the design must be carefully assessed in order to avoid hot points in the shielding plates.

Even if symmetry conditions are used, a 3D transient analysis of a CET device is quite time consuming. Therefore it should be used for AC analysis or at the final validation stage in case a transient analysis is required. Numerous tests might be necessary to assess the influence of misalignment and variable airgap over the transmitted power, the amount of losses in the car body, near field radiation, etc. The AC analysis of a single configuration requires a few minutes calculation time. The optimization of a 3D CET device might however require hundreds of parametric computations. This is where the use of the optimization tool GOT-It® can dramatically reduce the computation time. The user can set a certain number of constraints (coil volume, maximum current density, maximum airgap, coil shape,…) and objective functions (transmitted power, robustness vs. misalignment, power factor) and search for optimum configurations.

Conclusion

Depending on the configuration of the CET device, a 2D or a 3D FEM analysis might be required to assess the performances of the device. This can be conducted using various strategies.
Based on a simple model of the device (self and mutual inductances between emitting and receiving antenna, coil resistances), a fast prediction of the system behavior and switching losses can be done with the system simulation software Portunus. The lumped circuit model of the CET must beforehand be determined in Flux. It is easily and accurately derived from an AC harmonic analysis. For a more sophisticated approach, it is interesting to rely on a co-simulation model where the CET device is modeled in Flux and the circuit defined in Portunus. This strategy allows to predict an eventual saturation and hysteresis losses in the ferrites as well as eddy current losses in the housing and shielding plates. This procedure provides accurate results for the system dynamical behavior but at a higher computation time cost.

In order to assess the efficiency of the system, it is also possible to rely on a full FEM analysis with Flux. The parametric solver allows furthermore to investigate various configurations, determine the resonance frequency variation vs. different parameters (coil shape, airgap, misalignment, load resistance) and make necessary modifications to reach the system requirements.
A novel approach might also include the optimization tool GOT-It. Searching among several hundreds of configurations to find the most adapted one can be tedious, when not impossible if one relies on a parametric analysis. GOT-It allows to make an intelligent choice of a preferred solution using surface responses and various types of deterministic and stochastic optimization algorithms. The new GOT-It V2.0 version is also able to control a distributed flux resolution in parallel on several PCs, thus dramatically decreasing the optimization costs.



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