Systematic comparison of basic structures for electromagnetic energy harvesters using an automated design methodology

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Abstract. This paper focuses on the systematic comparison of different basic structures for electromagnetic energy harvester to increase the power density of the converters. The goal is to select the optimal basic structure depending on the specific requirements. To achieve this, an automated design methodology was developed and implemented in MATLAB®. The systematic comparison and automation allows a cost-effective design of adapted energy harvesters for application-specific requirements. In studies, the influence of different boundary conditions on the evaluation of basic structures was investigated. It can be shown that none of the structures always delivers the highest output power.

1. Introduction
The application of electromagnetic kinetic energy harvesters to supply energy-autonomous wireless sensor and actuator systems allows a considerable extension of battery life or even battery-free operation. Especially in industrial environments and logistics, where mechanical movements are omnipresent, electromagnetic energy harvesters enable a mechano-electrical energy conversion in a range of a few hundred microwatts up to some milliwatts. Typical application areas are predictive maintenance or process optimization.

Figure 1. Components of an energy-autonomous Industry 4.0 compliant wireless sensor system.

Figure 1 illustrates the main components of the envisioned energy-autonomous wireless sensor system for industry applications. The energy provided by the harvester is processed by a front-end circuit. The alternating voltage is rectified, if necessary the voltage is boosted and currently
unused energy is stored in a suitable energy storage. An advanced energy management system monitors the available energy over time and adjusts the operation of the system accordingly.

In the literature there are overviews of different prototypes of electromagnetic harvesters [1]. For the realization of new products, however, there is no systematic approach to facilitate selection of an optimal basic structure according to the specific application requirements. With the help of the automated design methodology presented in this paper, application-specific designs can be generated quickly and easily and systematic comparisons between the structures can be made to select the best suited harvester structure.

2. Automated design methodology for electromagnetic energy harvesters

Electromagnetic energy harvesters, along with piezoelectric and capacitive harvesters, are typical vibration energy harvesters. They consist of at least one magnet and one coil. A time-varying magnetic field in the coil is caused by the relative movement of the two parts. Due to the freedom in the number and arrangement of the elements, different basic structures are possible (figure 2). For example, the magnet can move through the coil, parallel or vertical. In addition, there are arrangements with or without back iron.

![Figure 2. Examples of topological basic structures of electromagnetic harvesters.](image)

The multitude of possibilities allows optimally adapted designs, but also makes a fast design difficult. For this purpose, an automated design methodology [2] is developed for a cost-effective design of adapted energy harvesters for application-specific boundary conditions. By implementing a computer-aided design process, systematic comparisons are carried out in order to be able to assess the structures in relation to the boundary conditions. The scheme of the automated design process is shown in figure 3. First, the requirements for the harvester have to be specified precisely. In particular, the excitation characteristics, the available design space, the electrical output variables and manufacturing-related boundary conditions must be considered. Based on the specification, a preselection of potential structures is automatically carried out from the large number of topological basic structures. Suitable design variants are determined for these structures based on parameterized models and an internal selection of proposed solutions is carried out. The designer then has the opportunity to evaluate these proposals under further technical or economic criteria.

This methodology for automated design selection was implemented in MATLAB®. The input and output of the data is realized via a graphical user interface. The core of the design tool are the parameterized models for the various basic structures. By describing these structures in individual functions, the scope can be extended at any time. Currently, six different structures without back-iron have been implemented, as shown in figure 4. The structures with numbers 1x are modular arrangement variants of the variants x. Instead of only one coil, these arrangements have been extended to use two coils.
For the calculation of the optimized designs, the geometric relationships of the magnet and coil arrangements are first described so that they fit into the installation space, including consideration of the deflection. The mechanical-electrical coupling is done by an analytic description of the magnetic field. For the calculation of the induced voltage it is not the absolute flux that is decisive but the flux change. Therefore, instead of the axial flux through the coil, only the radial field component $B_r$ has to be calculated. The use of radial flux has the advantage that only the radial flux density on lateral surfaces has to be calculated and not the axial components in the entire volume. For a winding layer with radius $R$ and height $h$, the flux change is calculated from

$$\frac{d\Phi_{z,m}(z)}{dz} = -2\pi R \cdot B_{r,m}(z) \quad \text{where} \quad B_{r,m}(z) = \frac{1}{h} \int_{z-h/2}^{z+h/2} B_r(\bar{z}) \, d\bar{z}$$  \hspace{1cm} (1)
Different criteria can be selected for the optimization. Structures with maximum power do not necessarily provide sufficient voltage to be able to efficiently process it in the front-end circuit. For the comparison, the maximum output power was first calculated. The optimum design is then sought, which deviates from the maximum power by a maximum of one percent and provides the maximum voltage.

3. Systematic comparison
A comparative study of electromagnetic coupling architectures for resonant vibration energy harvesting devices with fixed design space of 1 cm$^3$ and one single excitation with 10 m/s$^2$ and 100 Hz has already been presented in [3]. In the current study, the influence of different boundary conditions on the evaluation of basic structures is shown. Figure 5 shows a comparison of the implemented six basic structures for a design space of 7.7 cm$^3$, which corresponds to an AA battery, and for a design space of 4 cm$^3$. The calculations are based on the boundary conditions as listed in table 1. The excitations were selected in the low-frequency range which is typical for many industrial applications.

Figure 5 shows that none of the structures always provides the highest output power. The modular structures (with designations 1x) usually deliver more output power than the simple structures. However, these are often associated with higher production costs even if it is not considered in the present comparison. It can also be seen that despite the same ranges of
maximum output power, the deflections are very different due to the different excitations. This has a significant influence on the evaluation of the basic structures.

Structures in which the magnet moves axially to the coil without passing through it (structures 2 and 12) are particularly suitable for small deflections due to higher excitation frequencies or small amplitudes. With large deflections the distance between coil and magnet is too large, so that the magnetic field and thus also the change with relative movement are very small. In the case of the example with $4\text{cm}^3$, the dependence on the aspect ratio of the installation space is also clearly shown. For rather flat systems the structure 11 shows clear advantages. For high systems, structures 3 and 13 provide the most output power.

| Description                     | Value | Unit |
|---------------------------------|-------|------|
| Wire diameter                   | 100   | μm   |
| Copper fill factor              | 0.55  |      |
| Specific electrical resistance  | 17.05 | mΩ·mm$^2$/m |
| Gap between coil / magnet       | 0.5   | mm   |
| Remanence flux density          | 1.3   | T    |
| Density of magnet               | 7.6   | g/cm$^3$ |
| Mechanical damping              | 0.1   | kg/s |
| Density of steel                | 7.85  | g/cm$^3$ |

4. Conclusions and outlook
We have showed that for the optimal design of electromagnetic harvesters not only the geometric dimensions of existing designs should be adapted, but also the choice of the underlying structure should be suitably selected. In order to perform this selection efficiently, an automated design methodology was developed and implemented in MATLAB®. In the future, these studies will be extended to non-sinusoidal excitations and basic structures with back-iron.

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[Image]