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# DESIGN METHODOLOGY FOR APPLICATION-SPECIFIC ELECTROMAGNETIC ENERGY HARVESTERS

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## ABSTRACT

For energy harvesters to be used efficiently, they have to be adapted to the respective application. For kinetic excitations, electromagnetic harvesters are very promising as they allow a high degree of freedom in the design which in turn permits optimally adapted designs. A corresponding design methodology has been developed in a current research project. It is implemented as a design tool in MATLAB®, which performs an automated comparison between different basic structures. Prior to presenting first results of these structural comparisons, the general structure of the design process is explained. It is shown that the application-specific requirements are most important for the evaluation of the basic structures.

***Index Terms*** – Electromagnetic energy harvester, design methodology

## 1. INTRODUCTION

Energy-autonomous and high-performance sensor and actuator systems are required for a wide range of Industry 4.0 applications. Realizing the required intelligence of such energy-autonomous sensor systems, demands an increase of the provided energy, a reduction of the energy consumption per service, and the development of adapted energy management components. Therefore, current research activities pursue all three objectives [1]. A scheme of the overall construction of such systems is depicted in Fig. 1.

The focus of the current paper is the increase of the available energy. In this case, the required energy is obtained by conversion of kinetic energy from the application environment into electrical energy. The so-called kinetic energy harvesting allows a considerable extension of battery life or even a battery-free operation.

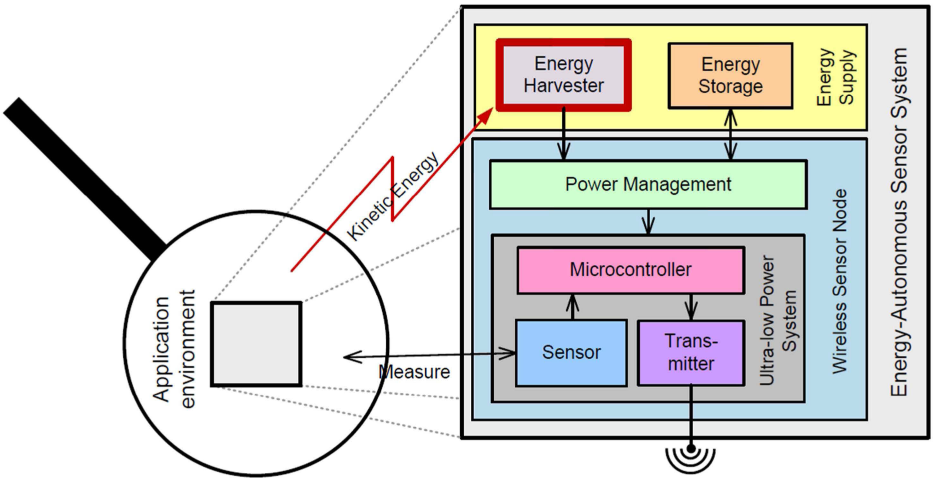


**Figure 1:** Scheme of an energy-autonomous sensor system

The most common principles for kinetic energy harvesters are based on piezoelectric, capacitive or electromagnetic conversion. In the industrial environment, electromagnetic harvesters convince by their high robustness and the possibility to convert a few hundred microwatts up to some milliwatts in a compact design space. In addition, a variety of different basic topologies are possible for electromagnetic harvesters. This allows optimally adapted designs.

In literature, the geometrical parameters for given principles are often dimensioned for specific application scenarios. However, a comparison between different principles is often avoided because this makes a fast design process difficult. For this purpose, a systematization and design methodology for cost-effective design of adapted energy harvesters for application-specific boundary conditions is developed. By developing a computer-aided design process, design space exploitation and harvester system optimization with the goal of increasing the harvester power density are made possible.

## 2. BASIC PRINCIPLE OF ELECTROMAGNETIC ENERGY HARVESTER

The first resonant electromagnetic harvesters were studied more than 20 years ago [2, 3]. Their basic components are at least one coil and one magnet. A time-varying magnetic field in the coil is caused by a relative movement of the two parts. Therefore, a voltage is induced. Depending on the flux linkage Ψ respectively the multiplication of the number of windings $N$ and the magnetic flux Φ, the induced voltage $\mathrm{U}_i$ is obtained from

$$\mathrm{U}_i = -\frac{d\Psi}{dt} = -N\frac{d\Phi}{dt} \tag{1}$$

As numerous survey papers show, the topological basic structures are very diverse [4, 5]. They are distinguished in particular by the number of coils and magnets, their relative arrangement, the direction of movement and the presence of a magnetic back iron. Common to all the principles, however, is the underlying network model, which consists of a mechanical and an electrical part (shown in Fig. 2).

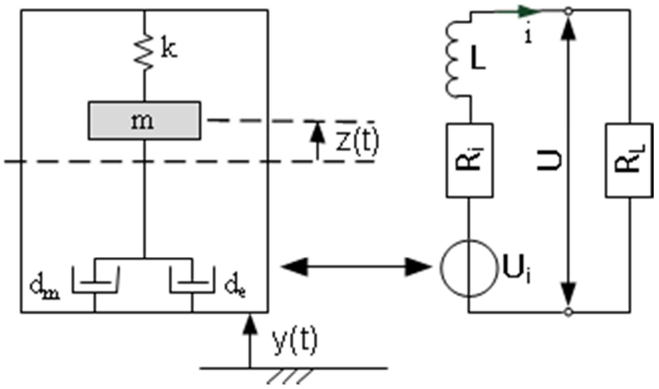


**Figure 2:** Network model of an electromagnetic energy harvester

The mechanical part can be described by a spring-mass-damper system. There are also systems without a spring element, but this is not considered further in this paper. An external excitation $y(t)$ causes a mass $m$ to move as a result of inertial forces. The mechanical damping $d_m$ describes all losses in the system which are not converted into electrical energy, for example material friction or air friction. The electrical damping $d_e$ describes the energy, which is withdrawn from the mechanical system and converted into electrical energy by the electromagnetic conversion mechanism. While the mechanical damping $d_m$ can usually only be estimated, the electrical damping coefficient $d_e$ is determined by the electro-magnetic design of the harvester. With respect to a simplified model, a linear damping behavior with a constant damping coefficient is applied. In general, however, the electrical attenuation depends on the deflection. The error by the calculation with a constant coefficient is tolerable for moderate deflections. Considering a linear spring stiffness $k$ the differential equation is

$$m\ddot{z} = -kz - (d_m + d_e)\dot{z} - m\ddot{y} \tag{2}$$

The realization of a linear spring is particularly suitable for sinusoidal excitations when a resonant coupling can be achieved. It has also been shown in the investigation of multifrequent excitations that a higher output power can be achieved with a linear spring system with a suitable choice of spring stiffness than with non-linear springs [6]. Therefore, a linear spring is used for the current work.

The converted energy could be considered as a voltage source with an internal resistance $R_i$ and an inductance $L$. Thus, the voltage available to electrical consumers is also dependent on the load itself. Since the required frontend circuit for rectification and voltage conversion is not available in the current project yet, an optimally adapted ohmic resistance $R_L$ is used as a load in the calculations at the moment. This will be adapted in the later project process by modeling the real circuit characteristics. When designing the frontend circuit, the inductive behavior of the source must be considered. However, for the following calculation of the maximum output power at a purely resistive load, the inductance is neglected.

The coupling between the mechanical and the electrical part of the harvester network model is given by the electrical damping and the induced voltage. Both quantities depend on the coupling factor K, which describes the magnetic flux gradient. Eq. (1) can also be rewritten as

$$\mathrm{U}_i = -N\frac{d\Phi}{dz}\frac{dz}{dt} = -K\dot{z} \tag{3}$$

The current $i$ flowing as a result of the induced voltage causes the Lorentz force $F_L$, which brakes the mechanical system. The electrical damping coefficient is obtained by

$$\mathrm{d}_e = \frac{F_L}{\dot{z}} = -\frac{K\,i}{\dot{z}} = -\frac{K\,\mathrm{U}_i}{\dot{z}(R_i + R_L)} = \frac{K^2}{R_i + R_L} \tag{4}$$

The electrical output power $P$ at the ohmic resistance is given by

$$P = \frac{U^2}{R_L} = \frac{R_L}{(R_i + R_L)^2}U_i^2 = \frac{R_L}{(R_i + R_L)^2}K^2\dot{z}^2 \tag{5}$$

For a resonant system the average output power $P_m$ is given by

$$P_m = \frac{1}{2}\hat{P} = \frac{1}{2}\frac{\hat{a}^2m^2K^2R_L}{\left((R_i + R_L)d_m + K^2\right)^2} \tag{6}$$

where $\hat{a}$ indicates the acceleration amplitude and $\hat{P}$ the amplitude of the output power.

The design of the coil-magnet system significantly affects the moving mass, the coupling factor and the internal resistance of the coil. In addition to the required output power for the operation of a specific application, the available design space must also be considered. Often compact designs are sought which have a high power density. In addition to the arrangement of the coil-magnet system, the deflection of the moving mass in the design space must also be taken into account, which is also influenced by the moving mass and the damping in the system. As it can be shown in these fairly simplified formal relationships, the design of adapted electromagnetic harvesters is very complex. In order to facilitate the construction, a computer-assisted design process is presented in the following chapter.

## 3. DEVELOPMENT OF AN AUTOMATED DESIGN PROCESS

The developed design strategy is illustrated in Fig. 3. Firstly, the requirements for the energy harvester must be precisely specified. Based on the specification, possible solution variants are calculated in the design tool and presented to the user, who can then examine the designs under various technical and economic criteria. The tool was implemented in MATLAB®, including a graphical user interface for input and output.

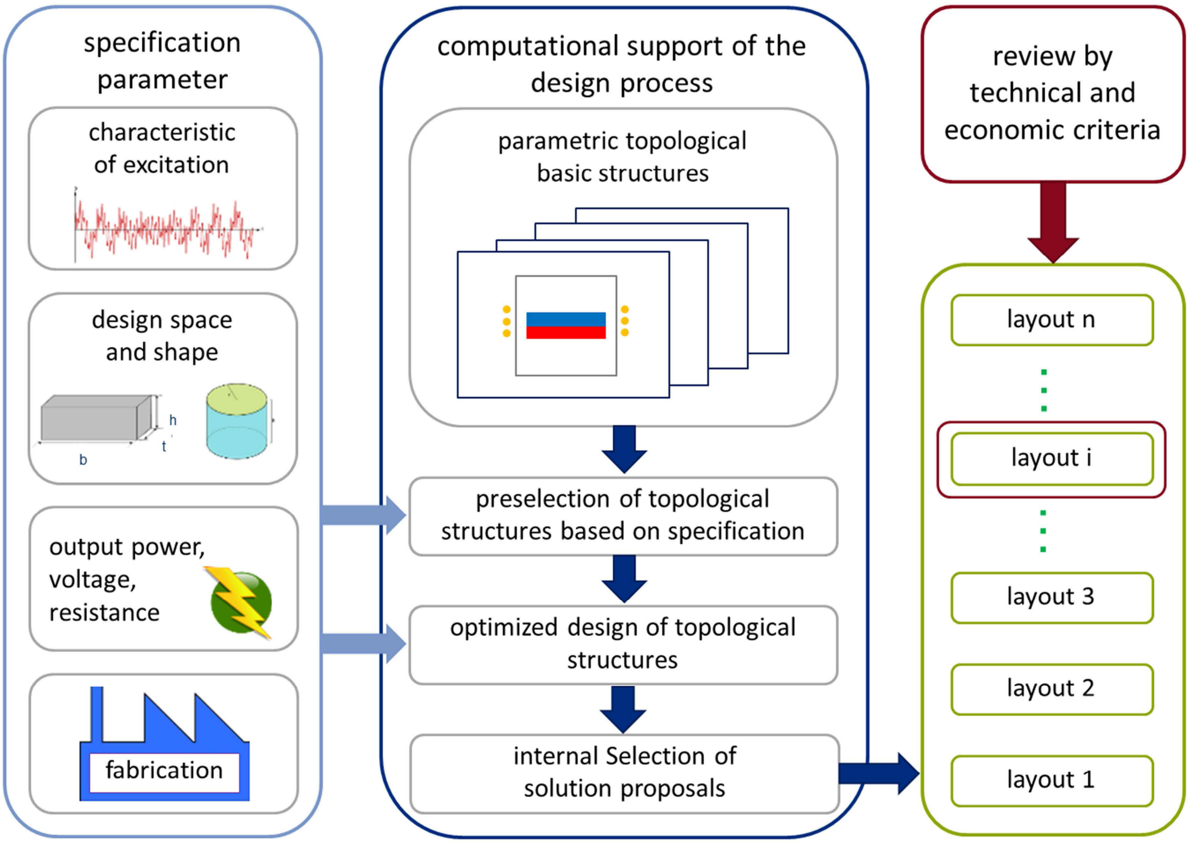


**Figure 3:** Structure of the computer aided harvester design process

The specification currently includes about 30 parameters. In particular, the excitation characteristics, the design space, the electrical output variables and manufacturing-related boundary conditions must be considered.

A challenge is the description of the excitation characteristic. In the simplest case, it is sinusoidal with a fixed known frequency. In some applications, however, the frequency is variable or there is a multifrequency excitation with a fixed excitation spectrum or even a stochastic excitation. In our implementation a certain number of excitation types are defined. Depending on the type, different data is stored and different calculations and analyses are carried out.

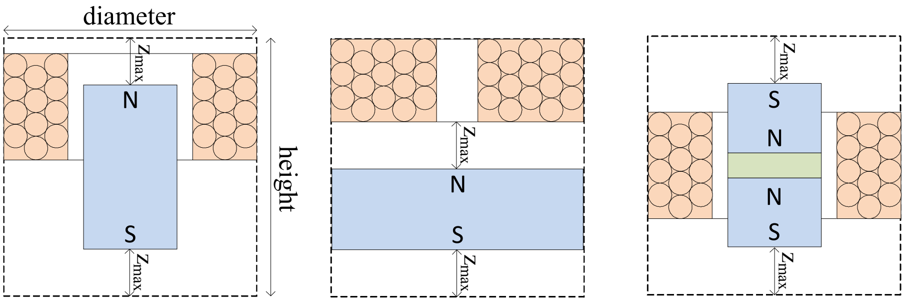
In addition to the total volume, the characterization of the design space also includes possible limitations in the form or aspect ratio. Moreover to the output power, the electrical output variables also account for requirements regarding the minimum voltage and the internal resistance of the following interface electronics. Finally, restrictions on minimum dimensions and tolerances can be specified in the area of production-related boundary conditions.

Based on the specification, a selection of design solutions is proposed by the computer-aided design process. This process is based on a variety of parameterized models that describe the behavior of the structures. The amount of structures under consideration can always be extended. In addition, the modular arrangement of basic structures within the design space is also made possible. Here, modularization means basic structures and their components, as required, to be used simply or repeatedly. Since the number of solutions with the number of modules involved can grow strongly, a limitation of the solution space by means of preselection of potential structures is necessary. For the implementation of such a preselection, numerous investigations are made whose first results are presented in chapter 4.

For each of the selected structures, the geometrical dimensions of the components are varied and thus different design variants are generated. From these variants, internal selections are carried out with regard to certain output variables such as, for example, output voltage or power. The designer then has the opportunity to evaluate these proposals under various technical or economic criteria.
Due to the high complexity of the possible constructions, currently only the transducer system is optimized as part of the overall design space. The various possibilities for constructing a spring with required characteristics as well as the housing design are to be considered in further work.

## 4. COMPARISON OF DIFFERENT BASIC STRUCTURES

In order to facilitate a preselection of appropriate basic structures, the structures have to be examined extensively. A comparative study of electromagnetic coupling architectures for resonant vibration energy harvesting devices has already been presented in [7] for a fixed design space and one single excitation. For the current study, initially the structures shown in [7] were implemented in a similar form. In addition, the models were exptended so that the necessary deflections of the moving mass are taken into account when defining the design space. Furthermore, the influence of the boundary conditions on the evaluation of the structures was investigated.



Architecture 1 (A1) Architecture 2 (A2) Architecture 3 (A3)

**Figure 4:** Schemes of the considered architectures

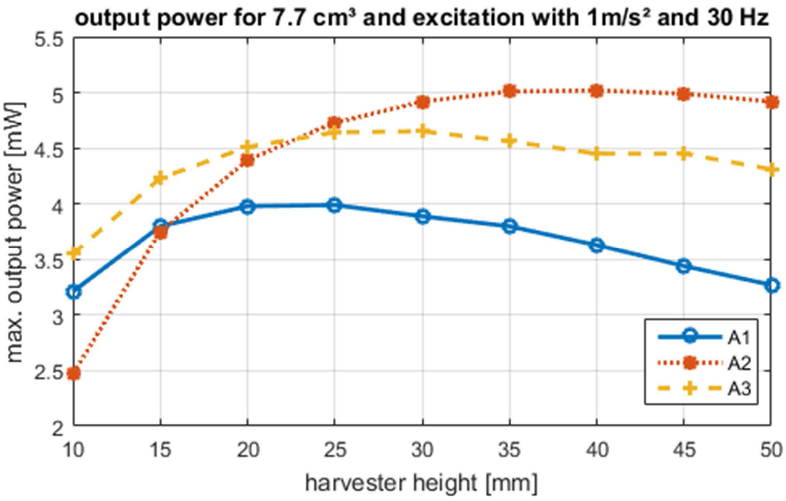


**Figure 5:** Dependency of the maximum output power on the harvester height

| Description | Value | Unit |
|---|---|---|
| Copper fill factor | 0.55 | 1 |
| Wire diameter | 50 | µm |
| Gap between coil / magnet | 0.5 | mm |
| Height of spacer for A3 | 2.0 | mm |
| Mechanical damping | 0.1 | kg/s |
| Grade of magnet | N42 | |

**Table 1:** Boundary conditions

An exemplary result for the examinations performed is shown in Fig. 5 for the architectures in Fig. 4. The influence of the harvester height on the evaluation of the basic structures was in-

vestigated for these simple cylindrical structures without a back iron. For the volume, $7.7\ \mathrm{cm}^3$ was selected in analogy to a conventional AA battery. The boundary conditions considered are listed in Table 1.
The results show that none of these structures always provides the highest output power. Architecture 2 is particularly suitable for large harvester heights, whereas architecture 3 is most suitable for rather flat systems, as long as the height of the spacer has no significant influence. Further studies have also shown that architecture 1 is suitable for flat systems with considerably smaller volumes.

## 5. CONCLUSION AND OUTLOOK

This paper presents a design methodology that makes the design process of electromagnetic harvesters more effective. The input interface for the specification parameters and a selection of parametrized topological basic structures have already been implemented in MATLAB®. The sizing of the component dimensions has been restricted to purely sinusoidal excitations so far. Moreover, no preselection of suitable structures is currently possible, as further studies have yet to be carried out. First analyses showed that the suitability of the structures clearly depends on the aspect ratio of the design space.
In the future, these studies will be extended to other boundary conditions and more basic structures. Furthermore, consideration of non-sinusoidal excitations will also be facilitated.

## ACKNOWLEDGEMENT

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