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Towards System-level Simulation of an Electromagnetic Energy Harvester Model

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Background

Since 2015, ‘Industry 4.0’ has evoked the growth of ‘Internet of Things’ technologies, which enables the connection and exchange of data among physical objects with the help of sensors and software over the internet or other networks. However, the main challenge is the periodic replacement of drained batteries for battery-powered wireless systems.

In recent years, energy harvesting has emerged as a solution to provide a lifetime power supply to the sensors [1]. In this work, we reproduce the electromagnetic energy harvester model (see Figure 1) introduced by Beeby et al. [2], which models the conversion of kinetic into electrical energy (Ansys Maxwell 3D). Find more electrodynamic energy harvesters in [3]. Furthermore, we present the workflow of exporting an equivalent circuit model from Maxwell 3D into ANSYS Twin Builder for system-level simulations, which enables modeling the interaction of the electromagnetic energy harvester model with both electrical and mechanical components.

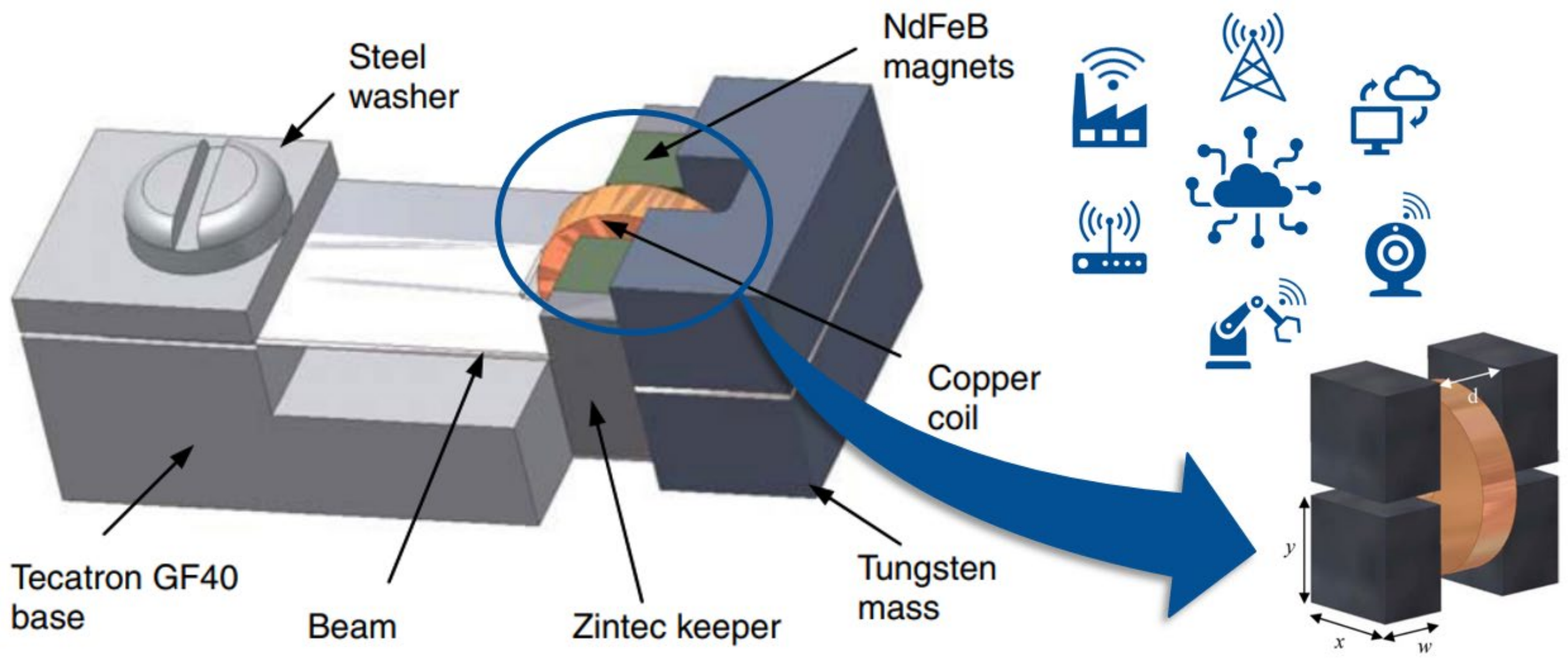

Fig. 1: Nowadays, ‘Internet of Things’ technologies enables connection and data exchange among physical objects via sensors or software over the internet. To overcome the drawback of battery-powered wireless systems, energy harvesting has emerged as a solution. This figure shows a drawing of the assembled electromagnetic energy harvester model introduced by Beeby et al. [2].

Modelling in Maxwell 3D

In this work, a magnetic model is built in Maxwell 3D on basis of the model setup introduced by Beeby et al. [2] (see Figure 2 and Figure 3). The structure of the electromagnetic energy harvester model consists of a copper coil and two pairs of magnets. The coil volume has an outside radius of 1.2 mm, an inside radius of 0.3 mm, and a thickness of 0.5 mm. It is configured with 600 turns of 25 µm diameter copper wire. The magnets are 1×1×1.5 mm³ in size and polarized along the long edge. Furthermore, they are surrounded by motion bands, which enable their displacement in Maxwell 3D in a transient analysis.

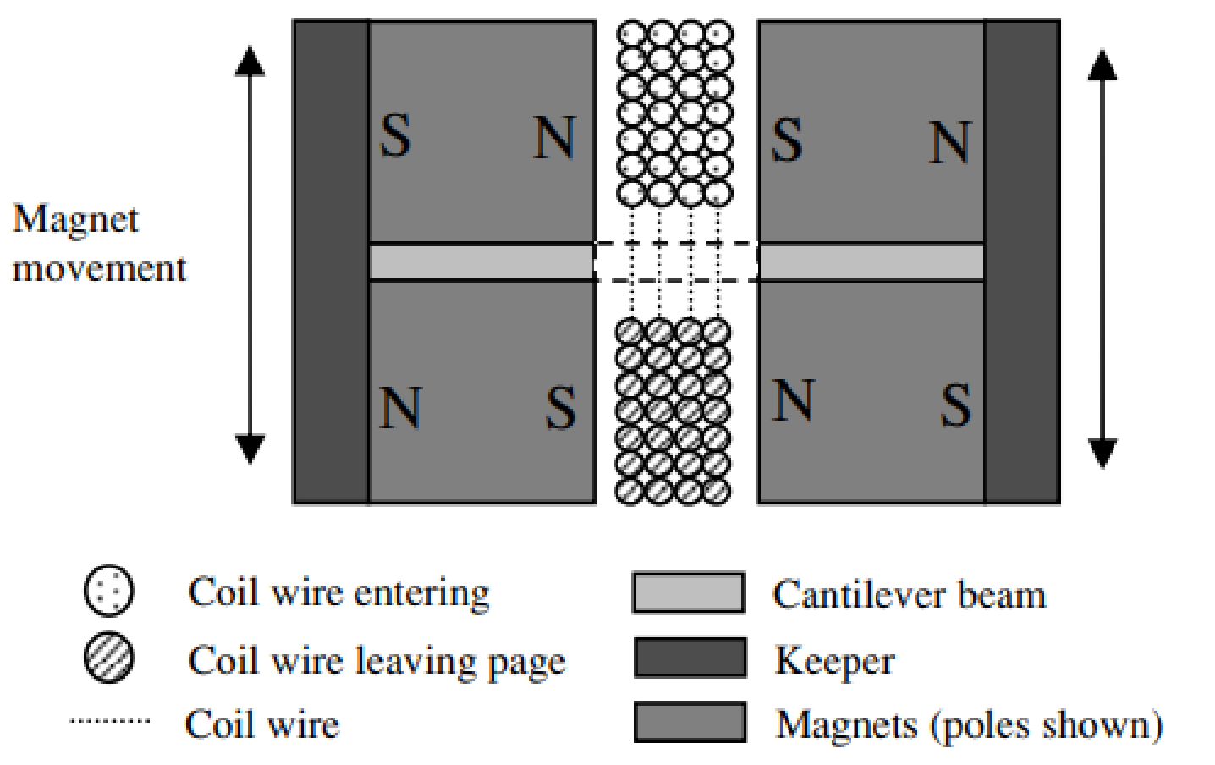

Fig. 2: Cross section through the four-magnet arrangement [2]. The magnetic poles are aligned as shown in this figure. A concentrated flux gradient through the stationary coil is produced with this arrangement as the magnets vibrate.

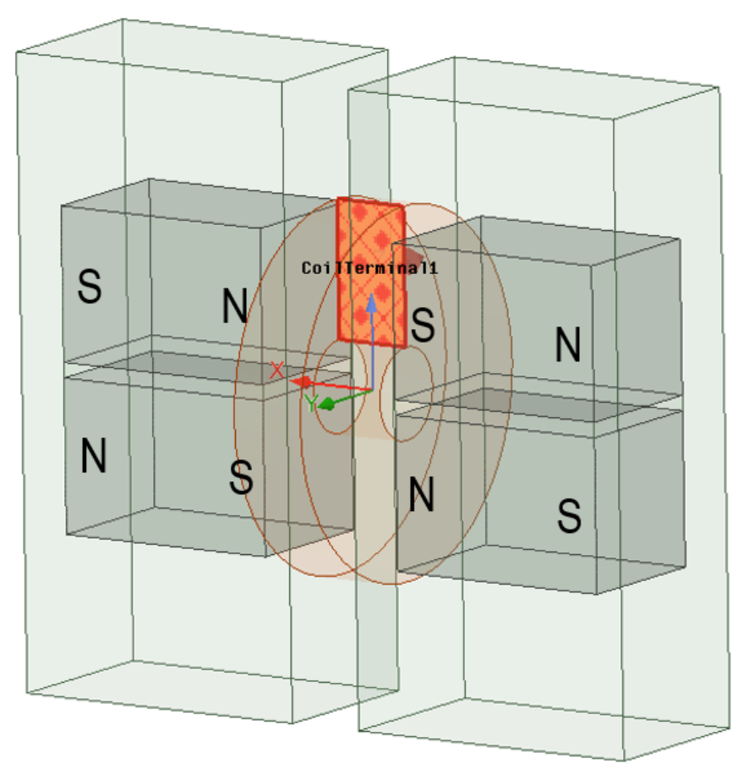

Fig. 3: Magnetic model built in Maxwell 3D. The position of the coil is fixed and two pairs of magnets are moved in the motion bands defined in a transient analysis.

The two magnets on each side are grouped and moved around the reference point in z direction between -0.57 and 0.57 mm and the initial resting position is at -0.57 mm (see Figure 4). A time-dependent force is applied to the magnets:

$$F = m\omega^2 A\cos(\omega t)$$

where m = 22.2 µg being the mass of two magnets, ω = $2\pi f$ with f = 60 Hz being the excitation frequency and A = 0.57 mm being the designated oscillation amplitude. The transient simulation result obtained from Maxwell 3D is consistent with the data presented in [2] as shown in Figure 5.

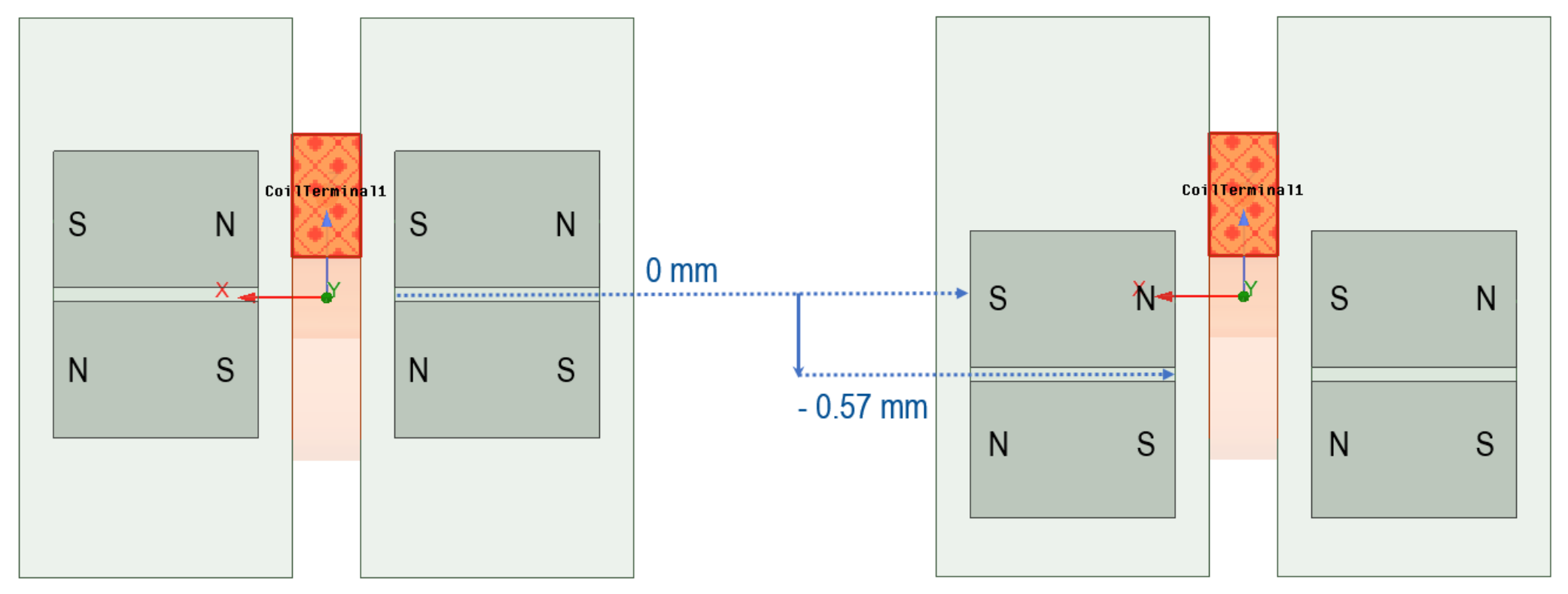

Fig. 4: The positions of the four magnets in the z direction. The magnets are at the reference position when the center line of the two pairs of magnets is at 0 mm (left) and the initial resting position of the two pairs of magnets in the z direction is at -0.57 mm (right).

The maximum voltage output from Maxwell 3D transient analysis is 65.4 mV, which is close to the simulation finding of 64 mV from [2] with a relative error of 2.2%.

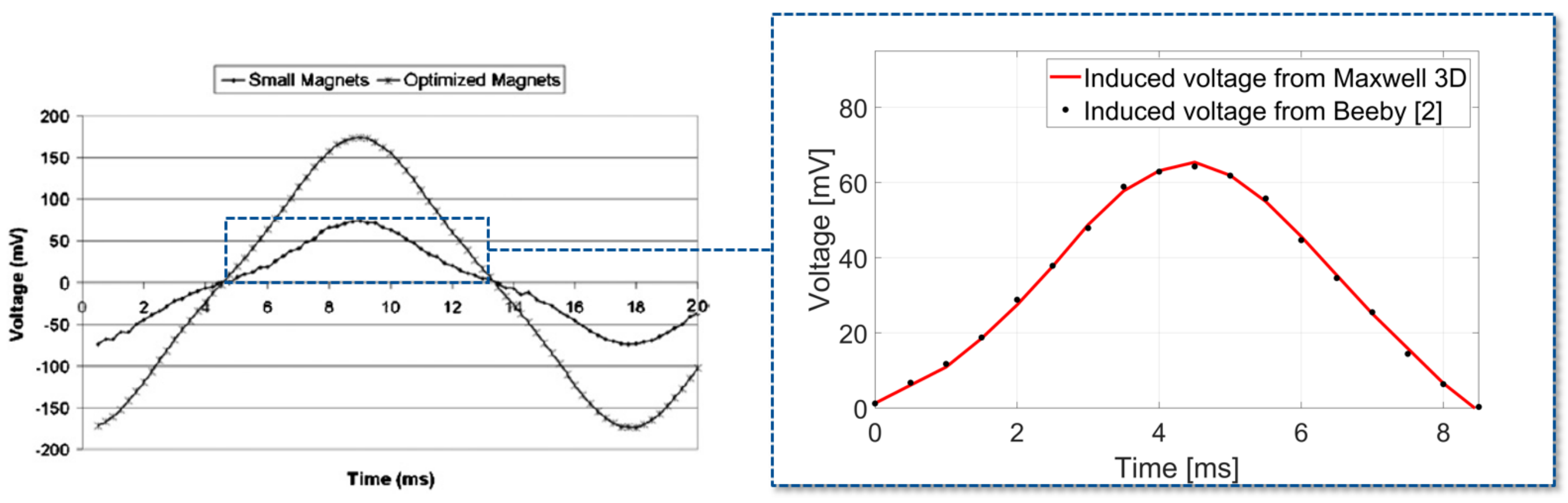

Fig. 5: Simulated output voltages from Beeby [2] (left) and comparison of the results from [2] and Maxwell 3D transient analysis (right). The matching of the results as shown in this figure verifies the accuracy of our model built in Maxwell 3D.

Equivalent Circuit Extraction (ECE)

The equivalent circuit model is generated in Maxwell 3D with a magnetostatic or electrostatic analysis setup, where the motion setups of the magnets are not allowed. Therefore, a parametric simulation setup is required, in which the position of the magnets is parametrized and the magnetic flux through the coil is obtained. The induced voltage can be calculated as:

$$EMF = -N \cdot \Delta\Phi/\Delta t$$

where N is the number of turns in the coil, $\Delta\Phi$ is the change of the magnetic flux through the coil in each time step Δt. The results of the parametric solutions are used to define a look-up table for the equivalent circuit model, which is imported into Twin Builder for system-level simulations. The dynamics of the harvester are implemented as a lumped element model in Twin Builder. Furthermore, a simple load circuit is connected to the equivalent circuit model (see Figure 6).

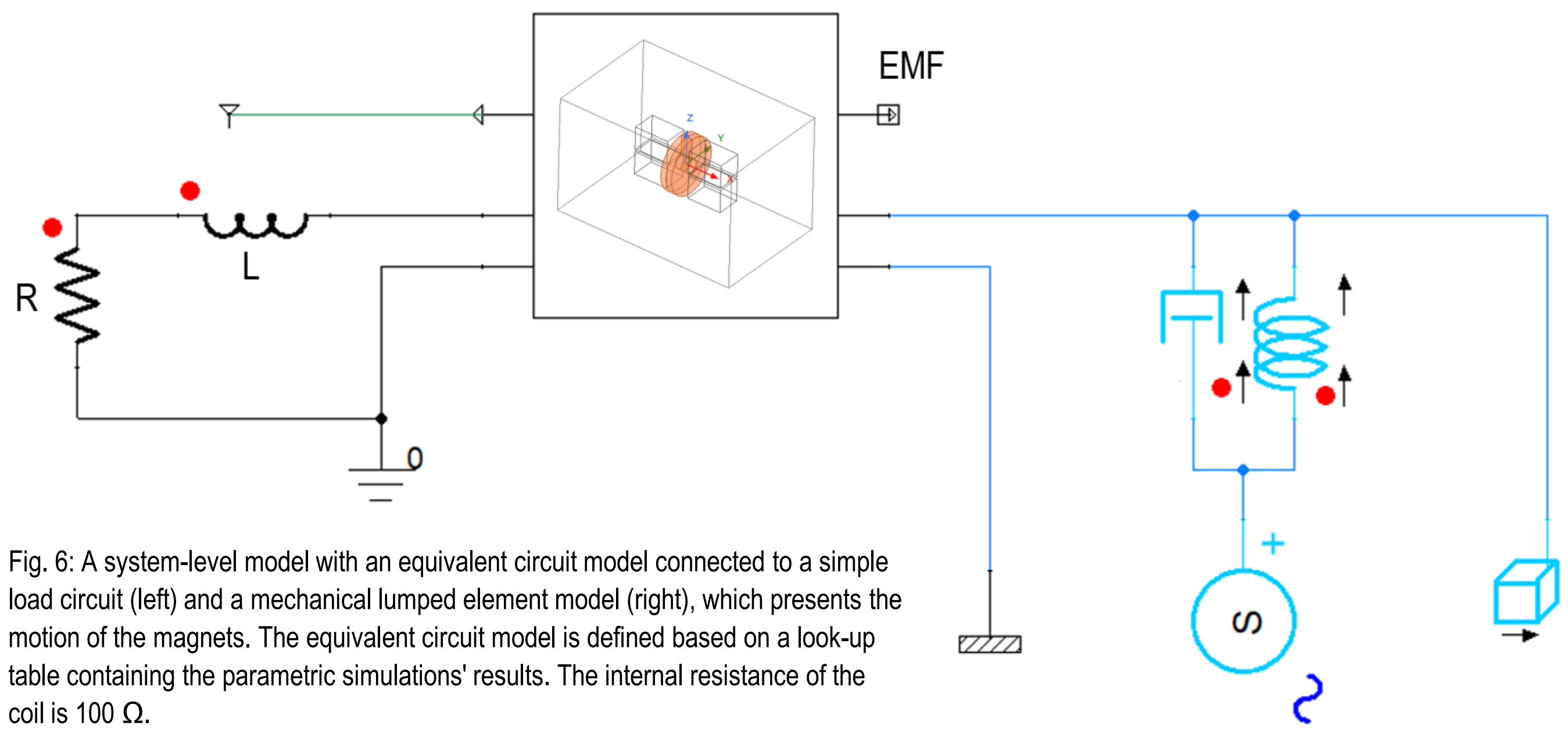

Fig. 6: A system-level model with an equivalent circuit model connected to a simple load circuit (left) and a mechanical lumped element model (right), which presents the motion of the magnets. The equivalent circuit model is defined based on a look-up table containing the parametric simulations' results. The internal resistance of the coil is 100 Ω.

Results

The simulations are carried out with an excitation frequency f = 60 Hz and an acceleration amplitude of a_0 = 0.59 m/s². The spring rate is calculated as $k = \omega^2 m$ = 3.16 N/m. A displacement amplitude of 0.57 mm is expected. Therefore, the excitation amplitude can be calculated as follows:

$$x_0 = \frac{a_0}{\omega^2} = \frac{a_0}{(2\pi f)^2} = 4.15\ \mu\text{m}$$

The resistance of the load resistor is defined as 10 GΩ, which sets an open circuit condition. The induced voltage from the equivalent circuit model is shown in Figure 7. A parameter study of the load resistance gives the results presented in Figure 8.

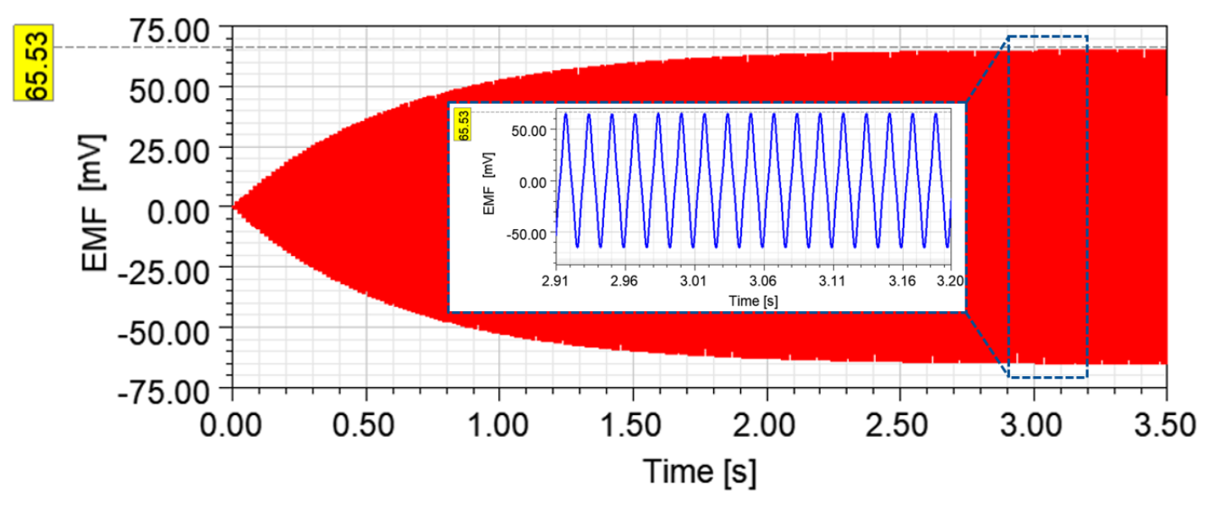

Fig. 7: Voltage output from the equivalent circuit model in an open circuit condition. The voltages between 2.91 s and 3.2 s are shown in the inner plot.

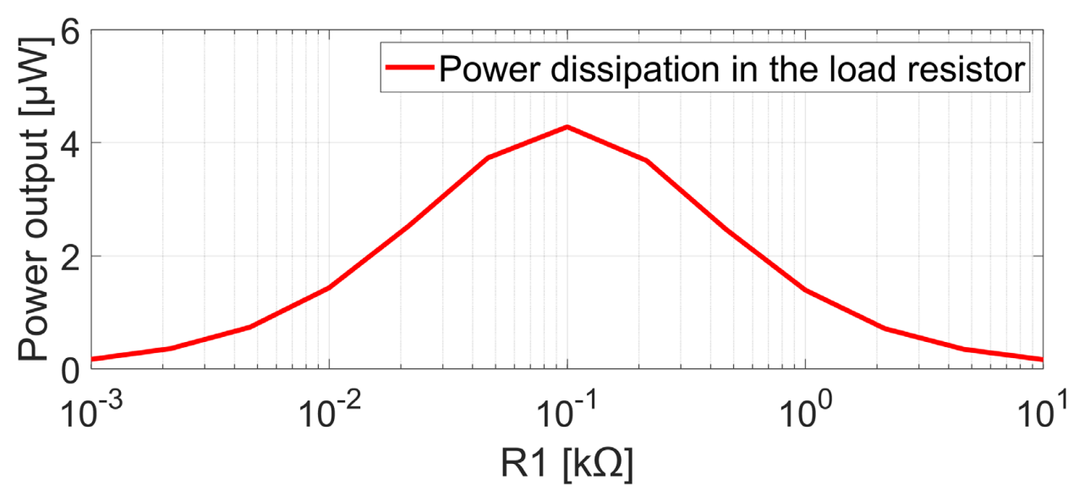

Fig. 8: Power dissipation in the load resistor with different values of load resistance. The maximum power is delivered when the load resistance equals the internal resistance of the coil at 100 Ω.

References

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