Distributing the Generation of Electricity to Extreme Level

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***Abstract*—Energy harvesting is the process of converting low level ambient energy into electrical energy usually in the µW to mW range. Energy harvesting enables the distribution of the production of electricity to extremely localized in situ electricity generation. This paper briefly describes our research work and results in the field of energy harvesting. Energy harvesting in general is first shortly discussed and then the design, implementation and testing of our inductive harvester are presented.**

Keywords—distributed generation, energy harvesting, microgeneration, in situ generation

I. INTRODUCTION

The general interest towards the microgeneration of electricity has grown remarkable during the last ten years. Consumers are willing to small scale production of electricity for their own needs. Sustainable solar power generators can be found on the rooftops of single-family houses in ever increasing numbers [1]. Energy harvesting takes the idea further: the electricity is generated precisely where it is needed.

In situ electricity generation enables the consuming device to generate the electricity it needs to operate. Consequently, harvester powered electrical apparatus can be used in an environment where no grid electricity is available. Therefore, the harvester technology can significantly reduce the costs and amount of labour needed for wiring conventional electric devices. That can be a remarkable benefit for example in the smart homes of the near future where several hundreds of sensors and actuators might exist, or in any situation where the installation of wires is particularly tough or may not be even possible.

The energy harvesting technology reduces the usage of accumulators and batteries and the laborious replacement of batteries can be avoided. Consequently, the amount of produced toxic waste can be reduced.

This paper presents the design, implementation and testing of an electromagnetic induction harvester system. This paper is organized as follows. In Section II, the power sources, general architecture, and technologies used with energy harvesting are described. Section III explains the inductive harvester more carefully. The simulation tool used in the design and the results achieved by simulation are presented in Section IV. The implementation and the construction of the prototype harvester and the other components of the system are explained in Section V. The testing and the results are described in Section VI. Section VII provides the conclusions and describes the future work.

II. ENERGY HARVESTING SCHEMES

Several power sources and technologies are used in energy harvesting. The most used energy sources are kinetic energy (vibration or rotation), light and heat. The most preferred technologies include electrodynamic and piezoelectric, photovoltaic, and thermoelectric, respectively [2].

The general architecture of a harvesting system is shown in Fig. 1. The power source specific microgenerator converts the source energy to electricity. The generated voltage must be converted and rectified by the energy management electronics. The charging of the energy storage is also managed by the electronics. A low-capacity energy storage is usually needed and implemented by a supercapacitor. The consuming device is electrified by the management electronics.

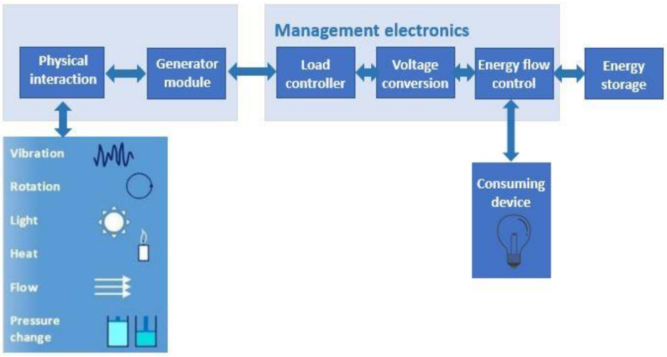

Figure 1. The architecture of a harvesting system.

The most widely used power source for harvesting is light. For decades there has been calculators and watches powered by light to electricity conversion. General shortcoming related to photovoltaics is evident in interrupted supply of light energy i.e., light is not available in all circumstances, and the surface needed by the photocell is relatively large [2].

A temperature gradient can be used to generate voltage by thermoelectric effect. If a temperature difference is maintained between two terminals of a thermoelectric module, electrical power is generated to the module's output terminals [3]. To get a satisfactory amount of power, considerable temperature differences are needed.

Pressure change can be used to harvest electricity by using three technologies: piezoelectric, electrostatic and magnetostrictive. These technologies are briefly presented in the following paragraphs.

Piezoelectric effect refers to the capability of piezoelectric materials to generate electric charge when a mechanical strain is affecting to it. Piezoelectric harvesters are utilizing this effect to convert mechanical source energy to electricity [4]. The mechanical source energy can be in the form of pressure, flow, rotation, or vibration.

In the electrostatic harvester a capacitor is subjected to pressure changes from the environment which vary the distance between the capacitor's conductive plates and consequently alter the capacitance. The change of the capacitance is used to increase the electrical energy stored in the capacitor, and the energy can be collected by discharging the capacitor [5]. In addition to pressure change, vibration is also used as a source energy for electrostatic harvesters Although an ideal candidate for miniaturization, electrostatic energy harvesters cannot function without an initial power source, a battery, which maintains the capacitor plates charge separation.

When magnetostrictive materials are deformed, they induce changes to the magnetic field. This phenomenon is known as inverse magnetostriction and is used in energy harvesting. A time-varying pressure is applied to a magnetostrictive material, causing a time-varying magnetic field. The time-varying magnetic field induces current in a coil located in the range of the magnetic field [6].

Vibration and rotation as a source energy can be utilized by inductive harvesters. Rotation can be transformed to electricity by a traditional, but mini-sized generators. The utilization of vibration by an inductive harvester is presented in the next chapter. In addition to above mentioned power sources, also other sources of energy have been researched. For example, in [7] a harvester that uses the acceleration of a fired projectile as a power source is represented.

III. INDUCTIVE LINEAR HARVESTER

In our approach the electromagnetic induction is used to harvest electricity from mechanical vibration. The grounds are that the inductive harvester is quite uncomplicated and inexpensive to construct. Further, the operating principle is based on a phenomenon that has been recognized and researched for centuries. Furthermore, kinetic energy suitable for harvester excitation exists commonly as a consequence of running machines and human activity.

Faraday’s law of induction, published already in 1831 [8], is utilized by the inductive harvesters. In accordance the law of induction, time-varying magnetic flux generates electromotive force to a conductor that locates in the influence of the magnetic flux. The time-varying magnetic flux is generated by making a permanent magnet to move nearby the conductor, or the other way around, making the conductor to move nearby the magnet [9]. In inertial vibration harvesters the preferred solution is to make the permanent magnet to move relative to a coil. This solution results in fixed output wires from the coil, which simplifies the construction of the physical structure of the harvester [10]. The source mechanical energy (vibration) is used to excite the harvester, i.e., to get the magnet to move.

Our harvester is operating linearly, signifying that the magnet and the coil are moving relative to each other back and forth on one axis. The harvester is composed of a moving magnet and a coil. A permanent magnet rests on springs inside a plastic tube. When installed to a location where vibration occurs, the magnet starts to vibrate and consequently, current is induced to the coil winded around the pipe. The structure and the circuit diagram of a typical inductive linear harvester are illustrated in Fig. 2.

The harvester is used in locations where continuous vibration exists, like inside or on a machine casing, a vehicle or a living and moving creature. The external dimensions of the harvester can be adjusted, if needed it can be implemented in considerable small scale. However, the dimensions are almost directly proportional to the electric generating capacity as the generating capacity is dependent on the number of turns of the coil and the strength of the magnet, in addition to the velocity of the magnet. The harvester must be designed and adjusted based on the operation environment (available kinetic energy, space, and weight limitations) and on the power requirements (output energy needed).

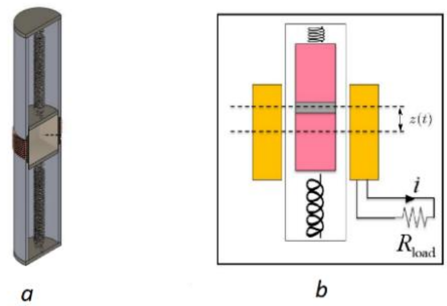

Figure 2. The structure(a) and the circuit diagram(b) of the harvester.

IV. SIMULATION

Designing an optimal device for a given application requires accurate simulation tools. For this purpose, a finite element method (FEM) based simulation tool was developed and implemented on MATLAB.

In this section, the utilized simulation approach and the simulation results demonstrating the electromechanical behaviour of the designed harvester are presented.

A. Approach

In the utilized simulation approach, we use FEM to accurately compute the electromagnetic quantities present in the system. For a given geometry, spline interpolation functions for induced voltage and magnetic force are created based on their pre-computed values at relevant magnet position and coil currents. This method makes solving the resulting time dependent problem extremely fast for a given harvester excitation.

In the FEM part of the simulation approach, a Maxwell’s magnetostatic problem is solved on an axisymmetric modelling domain. The problem to be solved reads

$$\operatorname{curl}\,(\boldsymbol{h}+\boldsymbol{h}_{\mathrm{pm}})=\boldsymbol{j}_{\mathrm{coil}} \quad (1)$$

$$\operatorname{div}\,\boldsymbol{b}=0 \quad (2)$$

$$\boldsymbol{b}=\mu\boldsymbol{h} \quad (3)$$

$$\boldsymbol{b}=\operatorname{curl}\,\boldsymbol{a}, \quad (4)$$

where (1) is the Amperes law where $\boldsymbol{h}$ is the magnetic field strength related to the magnetic flux density $\boldsymbol{b}$ by the permeability μ, as in (3). The magnetic flux density is required to be divergence free by (2). Furthermore, $\boldsymbol{b}$ is expressed by the curl of the magnetic vector potential $\boldsymbol{a}$ that is the unknown field of our magnetostatic problem. The source fields of the problem are the magnetic field $\boldsymbol{h}_{\mathrm{pm}}$, that is due to the magnetization of the permanent magnet, and the coil current density $\boldsymbol{j}_{\mathrm{coil}}$. Moreover, a linear relation between the magnet’s magnetic field $\boldsymbol{h}_{\mathrm{pm}}$ and magnetic flux density $\boldsymbol{b}_{\mathrm{pm}}$ is assumed, i.e., $\boldsymbol{h}_{\mathrm{pm}} = \mu_{\mathrm{pm}}\boldsymbol{h}_{\mathrm{pm}}$, where μ_{pm} is the permeability of the magnet.

Based on the solution of the magnetostatic problem, the total magnetic force F_{m} acting on the moving permanent magnet, due to the coil current or other magnetic objects, is computed using the virtual work principle [11].

In order to model an inductive vibration harvester, a coupled electrodynamical and mechanical problem is solved with a time-stepping procedure. The coupled problem thus consists of two equations to be solved with two unknows, i.e.,

$$\begin{cases} m\frac{\mathrm{d}^2 z}{\mathrm{d}t^2} + c\frac{\mathrm{d}z}{\mathrm{d}t} + kz + ma = F_{\mathrm{m}} \\ \frac{\mathrm{d}\Phi}{\mathrm{d}z}\frac{\mathrm{d}z}{\mathrm{d}t} + \frac{\mathrm{d}\Phi}{\mathrm{d}I}\frac{\mathrm{d}I}{\mathrm{d}t} + I(R_{\mathrm{coil}} + R_{\mathrm{load}}) = 0 \end{cases} \tag{5}$$

where m is the mass of the moving magnet, c the damping coefficient, k the spring constant and a the excitation of the housing. The resistances R_{coil} and R_{load} are the resistance of the coil wire and the resistance of the load, respectively. The magnetic force F_{m} is pre-computed with FEM as a function of the position of the magnet z, with respect to its housing, and the coil current I. The induced voltage, i.e., the time-derivative of the coils' total magnetic flux is expressed with the chain-rule as

$$\frac{\mathrm{d}\Phi(z,I)}{\mathrm{d}t} = \frac{\mathrm{d}\Phi}{\mathrm{d}z}\frac{\mathrm{d}z}{\mathrm{d}t} + \frac{\mathrm{d}\Phi}{\mathrm{d}I}\frac{\mathrm{d}I}{\mathrm{d}t} \tag{6}$$

where the derivatives of coils' magnetic flux Φ with respect to magnet position and coil current are pre-computed with FEM. For solving the time dependent coupled problem (5), ode45 (Matlab's ordinary differential equations solver function) was utilized.

In regards of the development of the simulation tool, as a next step, the simulation tool will be made compatible with an electrical circuit simulator. Consequently, the FEM based model describing the magnetomechanical behavior of the harvester can be coupled with the electronics consisting of charging the energy storage and the components measuring and transmitting information at the harvester location.

B. Results

Using the simulation tool developed based on the presented simulation approach, a harvester design was optimized for our application of interest, i.e., to be placed inside a car tyre. The obtained design parameters are shown in TABLE I. The harvester design is presented in more detail in the following section.

TABLE I. OPTIMIZED DESIGN PARAMETERS

Parameter	Value
magnet radius	5 mm
magnet heigth	5 mm
magnet mass	3 g
magnet's remanent flux density	1.45 T
coil mass	2 x 4.5 g
turns	2 x 1000
coil heigth	4 mm
coil width	4 mm
spring constant	2.17 N/mm
optimal load resistance	310 Ω

The harvester was optimized based on the measured acceleration data shown in the top graph of Fig. 3. The data is measured in the radial direction and corresponds to car speed of 80 km/h. The radius of the tyre was 30 cm. The constraints for optimizing the harvester were: minimize the mass and volume of the harvester such that the minimum average load power is 1 mW.

Fig. 3 shows the electromechanical behaviour of the harvester when exciting the harvester according to the acceleration shown in the top graph. The second graph from the top shows the simulated displacement of the magnet with respect to its housing, as a function of time. Below that, the graph shows the simulated load voltage. The bottom graph shows the load power as a function of time. The average of the load power was around 50 mW.

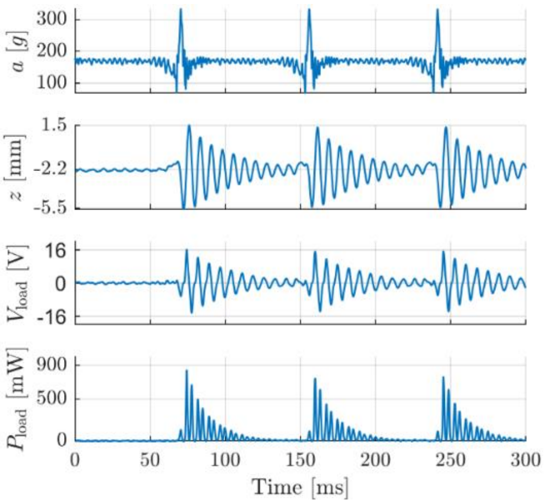

Figure 3. Simulation results.

V. PROTOTYPE IMPLEMENTATION

On the grounds of the results of the simulation, a prototype device was implemented. In addition to the actual harvester, also other components of the system (shown in Fig. 1) have got to be implemented to permit the properly testing of the harvester.

The housing of the harvester is implemented with a programmable turning tool with indexable insert. A Teflon bar was first used as a material, but it was noticed that polyacetal is easier to process. With Teflon, the coefficient of friction (between the magnet and the tube) would have been minor, but by using polyacetal, thinner wall thickness (between the magnet and the coil) was realizable, and that results a more critical effect to the amount of power generated by the harvester. The housing with the springs and the magnet is shown in Figure 4a, and Figure 4b presents the housing with the two coils. The coils are made of copper wire with a diameter of 0,1 mm and the number of turns is 2000 in both. The coils are winded in opposite directions.

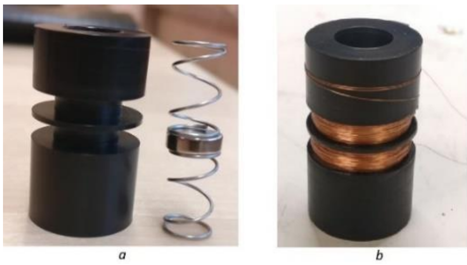

Figure 4. The housing of a double-spring design with the springs and the magnet(a) and with the coils(b).

After the first prototype implemented it became aware that a harvester with smaller dimensions with the same power output would be possible to construct, if only one spring with a greater spring constant would be used. The values for the spring and the magnet were recalculated and a new housing was lathed. The housing of the second prototype has dimensions 20,10 mm x 26,00 mm, which is 7,0 mm lower than the first version. The dimensions are shown in Figure 5a, and the housing with the magnet and the spring in Figure 5b. The coils in single-spring version of the harvester are similar than in the double-spring version.

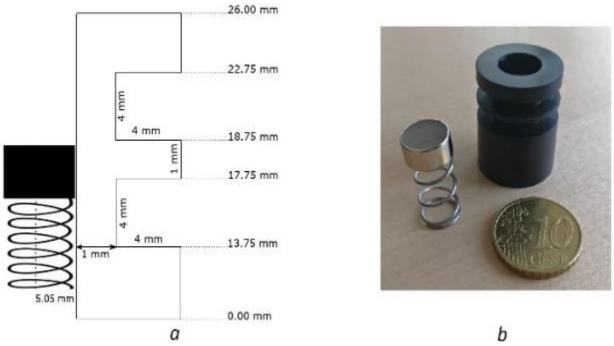

Figure 5. The dimensions(a) and the housing with the magnet and the spring(b) of the single-spring design. The coin is included to illustrate the dimensions.

The spring used in the single-spring design is a normal commercially available helical spring made of stainless-steel wire with a diameter of 0,81 mm. The diameter of the spring is 9,14 mm, the length of rest is 15,75 mm, and the spring constant is 2,17 N/mm [12].

The dimensions of the disc shaped nickel-plated permanent magnet, which is also a commercial product, are 10,00 mm x 5,0 mm. The strength of the magnet is 3,3 kg [13].

The friction between the magnet and the housing of the harvester decelerates the manoeuvring speed of the magnet and consequently the electric production of the harvester. During the construction of the third prototype, in pursuit to reduce friction between the moving magnet and the cylindrical housing of the harvester, we turned to the precision design principles and the principles of ball bearing operation. By employing three guides inside the harvester housing the magnet can be precisely aligned in space and by reducing the contact surface between the magnet and the housing, like in a ball bearing construction - the friction is minimized. The low-friction design is shown in Fig. 6. The method of manufacture was similar to that of the previous version, likewise the dimensions, the used magnet and the spring, and the coils are identical to the preceding version.

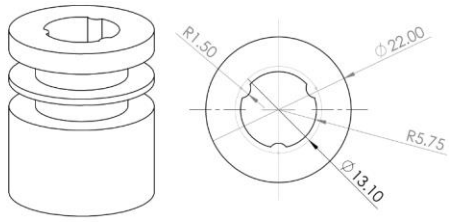

Figure 6. Low-friction harvester frame.

The energy management electronics was implemented based on Texas Instruments BQ25570 integrated circuit (IC). The IC is designed to operate with various harvesters, like for example solar panel or thermal energy collector [14], but in our approach it is optimized to work with an inductive harvester. Only a limited number of external components is needed, and due to the miniature dimensions of the IC (3,50 mm x 3,50 mm), it is appropriate for size optimized applications.

As an energy storage, a commercially available supercapacitor is used. On the grounds of the power requirements of the consuming device, a supercapacitor with 220 mF capacitance was selected. Supercapacitor has a nominal voltage of 5,5 volts that is sufficient for the loading system. The dimensions of the cylindrical capacitor are 11,5 mm in diameter and 5,0 mm in thickness [15].

Size of Printed Circuit Board (PCB) is 20 mm x 30 mm including all active and passive components. Supercapacitor is connected to the PCB by through hole pins. Other components are interconnected by surface mount technology.

Electrical current produced by the energy harvester is alternating and has got to be rectified before used by the boost charger. As a rectifying component, a Schottky diode-based bridge rectifier CBRHDSH1-40L is used. It is packaged in one solid IC case, and has a forward voltage drop of 440mV with the maximum current of 1A [16].

As an electric consuming device, we are using an acceleration sensor and a Bluetooth Low Energy (BLE) transmitter to transmit the data measured by the sensor. The measurements and the transmitter are implemented by using Apollo3 Blue microcontroller, whose power consumption is remarkably low. Apollo3 Blue has Arm Cortex-M4F core running at the frequency of 48 MHz, integrated Bluetooth 5.0 low energy with a dedicated processor and a fast 14-bit analog-to-digital converter (ADC) on chip. According to the manufacturer’s datasheet, the power consumption is 6 µA / MHz and 1 µA in microcontroller’s deep sleep state [17]. We tested the power consumption by making 900 measurements at a frequency of 15 kHz and by sending the measured data to the receiver. This test process was performed 60 times, the minimum current was found to be 3,6 µA, the maximum 4500 µA, and the average 240 µA. On the grounds of the measured power consumption and the features provided, Apollo3 Blue microcontroller was discovered to be appropriate for our purpose.

Requirements for the accelerometer consists of the frequency response to be at minimum 15 kHz and the measurement range to be plus-minus 200 g. The requirements are caused by the final testing environment (inside a car tyre at velocities up to 100 km/h) and by the intentions to utilize the measured data. A single axis analogical output accelerometer ADXL1003 [18] was selected grounds on the requirements.

The microcontroller was programmed with Ambiq Software Development Kit [19], and a custom BLE profile Ambiq Micro Data Transfer Protocol [20] is used for the data transmission. The software measures 900 samples with the accelerometer at the frequency of 15 kHz once per second and transmits this sample bundle to the receiver. The receiver is connected to a serial port of a PC, and the data is transferred to the PC to be further processed and to be displayed to a human user. The software runs on FreeRealTimeOperatingSystem (FreeRTOS) [21] provided with the software development kit, and utilizes services provided by the FreeRTOS in timing of the tasks and to put the microcontroller into the deep sleep state when possible and profitable.

VI. TESTING AND RESULTS

The preliminary testing of the harvester was performed by a muscle maintenance hammer. An adapter to connect the harvester to the hammer was manufactured by 3D printing. The frequency and the amplitude of the vibration provided by the hammer are adjustable. This apparatus, shown in Fig. 7, was used to quickly and unlaboriously test the fundamental operation of the harvester.

Figure 7. The harvester connected to a muscle maintenance hammer.

The second phase of the testing was completed in the laboratory. The measurements were adjusted and performed, and the results gathered by Signal Express measurement and data-logging software running on a laptop computer. National Instruments USB6251 Data Acquisition Module was used to connect all the test and control points. The device to generate the source energy was Vibration exciter system 4805 manufactured by Brüel & Kjaer, and the control signal to the exciter was amplified by Veneable Linear Amplifier VLA 1000. The harvester was connected on the exciter between two plastic plates. The acceleration of the harvester was measured by an PCB 355B02 acceleration sensor, with a 10 mV/g sensitivity, connected next to the harvester, and PCB 480C02 Signal Conditioner was used to condition the accelerometer signal. Adjustable electrical load was implemented with three resistors and one potentiometer and connected to the harvester. The test configuration and devices are presented in Fig. 8.

The electric load was adjusted to 390 Ω, as this equals to the actual load provided our consuming device. The low-friction version of the harvester was used, the preliminary tests provided that the electric production capacity of it is considerably higher than the production capacity of the previous harvester versions.

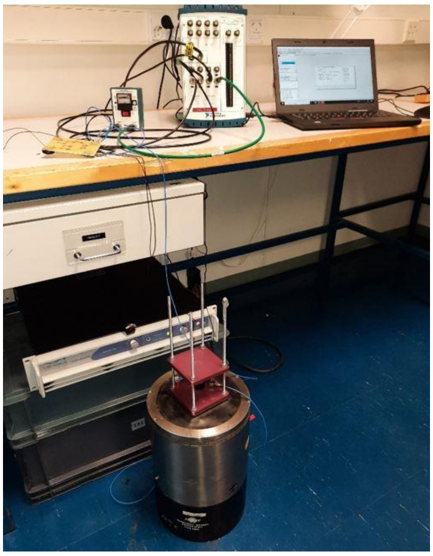

Figure 8. The testing equipment.

The tests were performed by regulating the frequency of the vibration used as a source energy and by measuring the voltage and the current from the load powered by the harvester. The electric power rms value was calculated from the voltage and the current. A representative sample of the tests results is shown in Fig. 9.

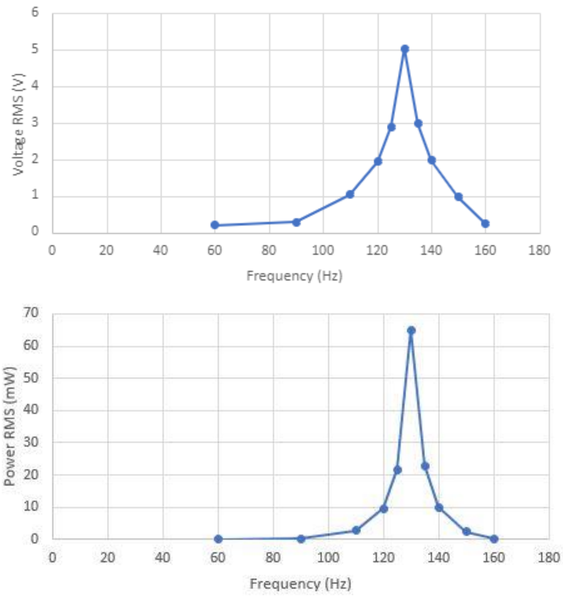

Figure 9. The output voltage (top graph) and power (bottom graph) at different frequency.

The test results strongly indicate the characteristic of frequency dependence of inductive linear harvester. The output power has the maximum value at the resonance frequency, and the value of the output power decreases rapidly when dislocating from the resonance frequency. The resonance frequency was observed to equal 131 Hz, in the results of the simulation the value was 134 Hz. The difference between the simulated and the measured values are mainly caused by the mass of the sealing compound used to secure the springs to the magnet, which was not acknowledged in the simulation.

The measured output power was on an expected level on the grounds of simulation and adequate to power our consuming device when operating in the vicinity of the resonance frequency. Indeed, tests were also successfully performed to power the measurement and the data transmission by the harvester. The harvester produced adequately electricity to power the consumer device and to load the energy storage simultaneously. The consuming device was capable to operate five and half minutes powered by the fully loaded energy storage after the source energy was disabled.

A car tyre will be used as the final testing environment. More accurately, the testing environment will be inside a tyre of a van. A van tyre was selected as there is adequately kinetic energy available (greater amount than in a heavy-duty tyres), but the rotation speed and exertion forces are lower than in the tyre of a passenger car. A tyre is a potential operation environment for a harvester as it would be useful to be able to measure numerous quantities from the tyre, in particular when developing self-driving cars. Further, due to the tyre being in constant rotation, it is demanding to provide cabling inside a tyre.

VII. CONCLUSIONS AND FUTURE WORK

The development of microelectronics during the last years has resulted with a significant drop in dissipation of electric energy [22]. This enables the implementation of self-powered devices, that are generating the electricity needed to operate by using energy harvesting. Energy harvesting provides environmentally friendly renewable electricity in situ. This is extremely profitable in surroundings where no grid electricity is available, and batteries are not an appropriate solution.

We have designed an inertial inductive harvester using a simulation tool. We have also designed and implemented several prototypes of the harvester system on the strength of the results of the simulation and performed initial and functional testing with the prototypes in the laboratory environment. The test results indicate that the harvester is capable to provide the operating electricity to a low powered device in suitable environment. The next step will be the testing of the proto device in a real-world use case. An agreement has been reached with a leading road vehicle tyre manufacturer to perform further tests. They will supply us with the tyres and the technology needed to mount the harvester system inside a tyre. Further they will provide us a testing environment, in which the tyre will be rotated, and different kinds of road surface can be simulated.

Our future research on inductive harvesters will deal with using magnetic springs, i.e. permanent magnets instead of mechanical springs. The research will investigate if a more robust structure is achievable by using magnetic springs. Further, it will be investigated if an adjustable magnetic spring force can be implemented, and how this adjustability could be utilized on the electricity output capability of a harvester.

VIII. ACKNOWLEDGEMENTS

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