Electromagnetic Energy Harvester Design for Power Transmission Line

M. Ş. Balcı,[1,*] *S. Sakar,*[2] *and A. Dalcalı*[1,3]

[1]Bandırma Onyedi Eylül University, Electrical and Electronics Engineering, Bandırma, Balıkesir, Turkey.

[2]Fredriksberg, 77010, Sweden.

[3]National Research University, TIIAME, 100000, Tashkent, Uzbekistan.

[*]Correspondence: M. Ş. Balcı, mbalci@bandirma.edu.tr

Parallel to the increase in energy demand, the importance of energy transmission lines is also increasing. In order for energy transmission to be carried out correctly, transmission lines must operate uninterruptedly. Therefore, it is important to inspect and monitor the lines and to intervene immediately in case of any fault. The use of Unmanned Aerial Vehicles (UAV) for the inspection and monitoring of these lines provides advantages in terms of both safety and cost. In the study, the design and analysis of electromagnetic energy harvesters have been made in order to provide energy to UAVs. Firstly, the mathematical modeling of the core has been presented. Electromagnetic energy harvesters designed based on this model have been analyzed using the Finite Element Method (FEM). The performances of toroidal magnetic energy harvesters have been investigated according to core size, material properties, air gap and line current. According to the results obtained from the analyzes, the harvester with the best size/energy density has been determined.

Keywords: Electromagnetic energy harvesters, transmission line, UAV, FEM.

1   Introduction

The importance of power transmission lines increases with the increasing energy demand nowadays. It is important to monitor and inspect power transmission lines for energy sustainability and quality. Most power transmission lines are located in places with difficult transportation and access. These lines are monitered by manpower, helicopters, or airplanes. UAVs are used in these duties due to costs and harsh environmental conditions. The most significant disadvantage of UAVs is their insufficient batteries. Therefore, when UAVs are about to run out of charge, they can be charged by harvesting magnetic energy from an appropriate nearby line instead of withdrawing them from their duty stations for charging or periodically changing the battery. Thus, the UAV, which will perform the duty, can continue to work from where it is left off after charging without leaving the duty area [1, 2].

Energy harvesting can be defined as the capture of small amounts of energy available by thermal, mechanical, and electromagnetic methods and its conversion into electrical energy [1]. An electromagnetic energy harvester can be likened to a transformer, with the transmission line being primary windings and

windings on the core being secondary windings [3]. In this harvester, voltage is induced using the magnetic field around the line, and energy is obtained from transmission lines. The method of energy harvesting from electromagnetic fields has some advantages over other energy harvesting methods. These advantages can be listed as not being dependent on weather conditions, not having maintenance costs, and working as long as current flows through the transmission line [4].

In electromagnetic energy harvesters, factors such as core material, core geometry, and core saturation are very important for the harvester's efficiency. Numerous studies have been conducted in the literature to optimize the harvester and overcome various problems [5, 6]. The saturation of the core material used in the harvester significantly impacts the output power obtained. Harvesting can be done effectively when the core is unsaturated, in other words, the core operates in the linear region. When the core is saturated, the output power decreases excessively with the reduction in the induced voltage. A comprehensive study investigating the effect of core geometry determined that a decrease in the magnetic flux leakage increased the output power due to the reduced inner radius of the core, the increased core height, and the air gap being as small as possible. Furthermore, it was revealed that windings should be optimized according to the line current value [7]. In the study in which harvesters using ferrite cores with different relative permeabilities were examined, the effects of 1000 and 2500 spiral windings and core material were investigated. The study found that the harvester having a core with a high relative permeability obtained the highest energy with the highest number of windings [8]. Therefore, it can be concluded that the obtained energy increased as the relative permeability of the core material and the number of windings increased. Different solutions have been proposed in the literature to prevent the core from reaching saturation in harvesters. A harvester with dual core was designed to avoid the magnetic resistance caused by the air gap added to the core to prevent the magnetic core's saturation. This two-piece core designed was compared with a single-piece core of the same size, with the same material and the same number of windings. Magnetic flux leakage was significantly reduced in the harvester with dual core compared to the harvester with single core, and more output power of up to 53% was achieved [9]. Another study, designed and tested an energy harvester with a desaturation controller. In this model, a secondary winding was added in addition to windings on the core to eliminate the saturation effect of the magnetic core, and it was attempted to eliminate the saturation effect by running the secondary winding while the core was about to be saturated. The study, obtained 13.8% more power than the harvester without secondary winding [10].

A magnetic energy harvester providing wireless charging for UAVs used in the monitoring and inspection of power transmission lines was designed in this study. In the structure to be designed, the system should be optimized in terms of size and high energy density to obtain energy from power transmission lines with an UAV. The optimum design was achieved in the study by focusing on factors such as core material, size, and core saturation while designing the harvester.

2   Energy Harvesting Methods

Energy harvesting is collecting of small amounts of energy available in the environment, such as solar energy, wind energy, mechanical energy, kinetic energy, and magnetic field energy, and its use by converting it into electrical energy. The term energy harvesting is used since the amount of energy obtained is low. Regarding energy conversion, people have long been using the current energy harvesting technologies in the form of windmills, watermills, geothermal and solar energy [11].

Energy harvesting techniques have become highly important due to the limited availability of conventional power sources, increasing demands for systems such as wireless sensor networks, the increased number of in electrical devices working with very low power with the development of technology, and their environmental friendliness. With recent developments in wireless and micro electro-mechanical systems, energy harvesting stands out as an important alternative to conventional batteries [11]. Conventional batteries are used as power sources for portable electronic devices and wireless sensors with low power requirements. However, battery life is quite short compared to the working life of devices, and batteries must be replaced or recharged periodically, which is very costly, especially for sensors in inaccessible locations [12].

Numerous studies have been conducted on portable devices or wireless sensor network systems harvesting their energy independently of conventional batteries. In a study conducted to power UAVs, a mixed energy harvester containing radio frequency and solar energy was proposed, and an output voltage of 23.2 V, sufficient to meet the battery requirement of the aerial vehicle, was obtained [13]. A study on piezoelectric energy harvesters tested the designed harvester theoretically and experimentally. An output voltage of 5.99 V theoretically and 3.65 V experimentally at 35 Hz was obtained. This difference between theoretical and experimental results was originated from the fact that variables such as frequency and material properties differed from their real values in the simulation environment [14]. In the study in which energy was harvested from an electric field on a 765 kV high-voltage line, a Zigbee-based temperature sensor was successfully operated with the power obtained [15]. In a comprehensive study on thermoelectric energy harvesters, a low-power harvester was tested without any booster circuit, and a maximum power of 64.59 mW was obtained at a temperature change of 105 ℃. It was indicated that the power obtained could be increased significantly by increasing the amount of change in heat with better heat sink designs and using booster circuits [16]. A piezoelectric energy harvester allowing electrical energy to be obtained from low-frequency bridge vibrations was designed in another study. In the mentioned study, measurements were taken from an overpass used in the city, and the harvester was tested by generating the vibration measured in the laboratory environment. The test results, showed that 0.20 μW power was obtained at a frequency of 4 Hz and an amplitude of 4 V. Irregular structural vibrations were the reason for this low power [17]. In other words, continuous and regular vibrations are required to ensure the efficiency of this type of energy harvesters. Obtaining electrical energy from solar and wind energy, which are among the renewable energy sources, can be considered an energy harvesting method. However, energy harvesting from solar energy can only be performed in daylight. Wind turbines have been developed for large-scale energy generation with wind energy [18]. Since solar and wind energy is unavailable due to weather conditions and in some situations, such as indoor environments, vibrational energy comes to the forefront as an alternative to these sources. There are three conversion mechanisms, piezoelectric, electrostatic, and electromagnetic, to convert vibrational energy into electrical energy [19].

In particular, harvesting energy from the electric field is one of the energy harvesting methods studied to provide energy to sensors used in monitoring transmission lines. The method of harvesting energy from the electric field is one of the most appropriate techniques for transmission lines since electric fields around power lines are under open circuit conditions are independent of the line current and are relatively rich and continuous. An electric field is emitted when a certain voltage is applied to a conductor. The electric field energy harvesting technique is based on the principle of this emission. The capacitive displacement current flowing from the conductor to the ground can harvest this emitted energy [20]. The most significant advantages of energy harvesting from the electric field are not requiring current flow on the line and the ease of installation. The disadvantages of these harvesters are their large size and the necessity of being short-circuited under some conditions [21, 22]. Table 1 summarizes the comparison of energy harvesting techniques.

3 Methodology

In this study, the method of harvesting energy from the magnetic field, one of the energy harvesting methods, was chosen to charge UAVs. A toroidal model was preferred as the core geometry since it is easy to install on lines and allows higher power to be obtained than other geometric shapes [30]. In the design of electromagnetic energy harvesters, some analyses should be performed to achieve a design that meets the desired properties by taking into account some problems, such as core saturation, core geometry, and ease of installation. In this section, the harvester will be examined theoretically, and its analytical model will be derived. In the structures of electromagnetic energy harvesters, there is a core consisting of soft magnetic material and a conductor wound on the core, as seen in Figure 1. The windings on the core are secondary windings, and the line to which the toroid will be connected is primary windings. The equivalent circuit of these harvesters operating based on the current transformer logic is shown in simple Figure 2,

Table 1: Comparison of energy harvesting systems.

| Energy Harvesting Method	Advantage	Disadvantage
Solar Energy [22-24]	It has a high potential.	There is dependence on weather conditions. There is a need for storage. It cannot be used in closed environments. Photovoltaic cells have low efficiency.
Heat Energy [25-27]	Any system or device that generates heat in nature and industry can be utilized.	Thermoelectric materials have low efficiency.
Vibrational Energy [17]	It is easily available in the surrounding area.	Vibrations in the environment are usually not continuous and constant, which reduces efficiency.
Wind Energy [18,24]	It has a high potential.	There is dependence on weather conditions. The maintenance cost is high. It is difficult to install. It cannot be used in indoor environments.
Electric Field Energy [28]	It is always available on high-voltage lines or near the equipment.	It has low energy conversion due to high reactance.
Magnetic Field Energy [3,4,29]	Current is always present in every flowing conductor. Its efficiency is high, there is no maintenance cost, and the structure is quite simple.	The current flowing through the conductor should be sufficient. Energy losses occur inside the ferromagnetic core.
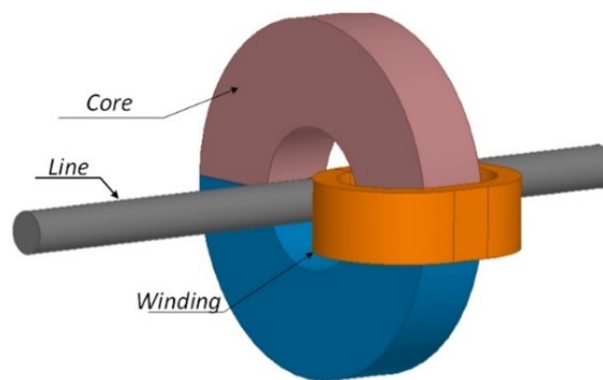
Figure 1: *Toroidal energy harvester.*

and these harvesters can be considered electrical machines.

The method of harvesting energy from the magnetic field works in line with the principles of Faraday's and Lenz's laws. The current flowing through a transmission line creates a magnetic field around the wire. Sufficient power can be obtained to charge the UAV by inducing voltage from this magnetic field.
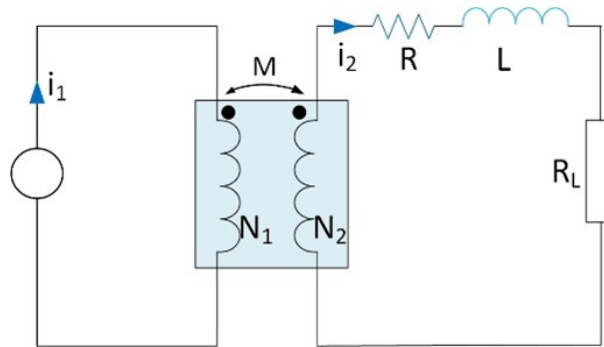
Figure 2: *Equivalent circuit of the electromagnetic energy harvester.*

3.1 Numerical Model

When Ampere's law is applied to the toroidal model, the magnetic flux density at any radius r inside the toroid is given in Equation 1 [8]:

$$\bar{B} = \frac{\mu i}{2\pi r} \tag{1}$$

where B represents the magnetic flux density, i represents the current passing through the line, μ represents the product of the magnetic permeability (μ_r) of the core material and the magnetic permeability of the air (μ_0). Based on the value of magnetic flux density, the flux in the toroid (ϕ_{21}), and based on it, the common inductance of the toroid and the line (L_{21}) and the self-inductance of the toroid (L_{22}) can be calculated. Through common and self-inductance, the voltage induced by the toroid (V_2) and the magnetic energy stored at the magnetic flux density in the harvester can be reached. Inductance can be expressed as an inductor's capacity to store energy as magnetic flux density. It can be said that there is a significant correlation between inductance values, induced voltage, power density, and energy obtained. The magnetic flux in the toroid;

$$\Phi_{21} = \int \vec{B}_1 \vec{ds}_2 = \frac{\mu i}{2\pi} \ln(b/a)h \tag{2}$$

Common inductance:

$$L_{21} = L_{12} = M = N_2 \frac{d\Phi_{21}}{di} = \frac{\mu}{2\pi} h N_2 \ln(b/a) \tag{3}$$

Self-inductance:

$$L_{22} = \frac{\mu}{2\pi} h N_2^2 \ln(b/a) \tag{4}$$

and the voltage induced in the toroid according to Faraday's law:

$$V_2 = N_2 \mu f i(t) \sin(wt) \ln(b/a)h \tag{5}$$

As seen from the equation, the voltage induced by a toroidal electromagnetic energy harvester is affected by the following variables [31];

Number of windings around toroid N_2,

Magnetic permeability of core μ,

Amount of the current flowing through transmission line$i$,

Inner and outer diameters of core a and b,

    Core height h.

The following equation expresses the magnetic energy stored at the magnetic flux density:

$$W = \frac{1}{2}Li^2 \tag{6}$$

    As mentioned previously and seen in Figure 2, toroidal electromagnetic energy harvesters operate based on a transformer logic in which the transmission line is considered the primary winding and windings on the toroid are considered the secondary winding. In this case, the magnetic energy stored at the magnetic flux density in the harvester can be expressed by the following relation.

$$W = \frac{1}{2}(L_{11}i_1^2 + L_{22}i_2^2 + 2Mi_1i_2) \tag{7}$$

    According to this relation, the energy obtained by the harvester is affected by the values of the current on the line (i_1), current induced in the windings (i_2), common inductance (M), and self-inductance (L_{22}). Therefore, it can be said that inductance values are very important for the harvested energy and power density. Thus, the common inductance and self-inductance values should be calculated to design the energy harvester most appropriately in terms of power density and energy obtained.

4   Design and Comparative Analysis

4.1   Designed Model

The electromagnetic energy harvesters designed were analyzed by FEM. This method is intensively used in many engineering fields such as electrical - electronic, construction, and biomedicine fields. FEM has been put forward to solve problems whose changes over a given area can be represented by partial differential equations. Through FEM, complex and time-consuming problems are solved with high accuracy and in a short time [32]. Thus, there is a significant advantage in terms of time and economy. Models were analysed using a magnetostatic and transient solution type in Ansys/Maxwell package program. Figure 3 displays the mesh model of the toroid core with a size of 30x10x10 mm. This core model, used 184309 tetrahedral mesh structures.
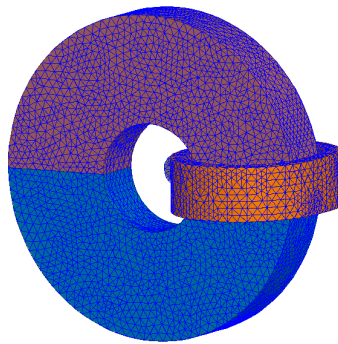

Figure 3: *Mesh structure of the core.*

    Toroidal cores were determined as the core geometry for analysis. These cores were analyzed separately with different magnetic materials and in different sizes. Since soft magnetic materials form the harvester's magnetic circuit, these materials are expected to have high relative permeability, high saturation, and low core loss. Mu Metal, Steel 1010, and M19 were used as core materials in the study. Figure 4 shows the B-H curves of these materials.
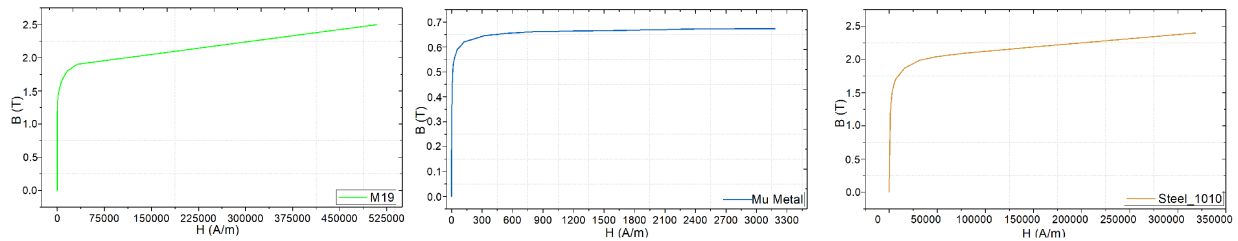
Figure 4: *BH curves of the materials used.*

Table 2: Common inductance and self-inductance values.

Core Dimensions(mm)		25x10x10	25x10x20	25x15x10	25x15x20	30x10x10	30x10x20	30x15x10	30x15x20
M19	L_{22} (mH)	820.13	1633.6	542	1070.5	1074.2	2158.9	792.34	1585.1
	M (mH)	1.6211	3.246	1.067	2.1214	2.124	4.2891	1.5631	3.1447
Mu Metal	L_{22} (mH)	418.18	828.46	280.87	552.61	555.71	1104.9	417.31	826.53
	M (mH)	0.81718	1.636	0.54488	1.0857	1.0871	2.1817	0.81301	1.6271
Steel 1010	L_{22} (mH)	436.42	864.52	248.43	489.47	517.79	1027	329.49	650.14
	M (mH)	0.85369	1.7066	0.8065	0.95968	1.0114	2.0266	0.63776	1.2751

Due to the weight problem, which can be considered the biggest disadvantage of UAVs, harvesters are limited size and weight during the design. Therefore, it is necessary to provide the most optimum design regarding harvester weight and performance. The sizes of the cores used for toroidal models in the study were chosen as 25x10x10, 25x10x20, 25x15x10, 25x15x20, 30x10x10, 30x10x20, 30x15x10, and 30x15x20, respectively. The variables represent the outer diameter (mm), the inner diameter (mm), and the height (mm) of the toroid, respectively.

4.2   FEM Analysis

In the analyses, the common inductance (M) and self-inductance (L_{22}) values of the harvesters were first calculated. While inductance values are important for the voltage induced by the harvester, with an increase in the inductance value, the voltage induced by the harvester and the power density in the harvester increase to the same extent. In this respect, there is a significant correlation between power density and inductance. Moreover, the power density in the harvester and the energy obtained depend on inductance values, as seen in Equation 7. However, the weight of the harvester limits the designs. A larger core provides higher inductance and power density, resulting in a heavier core. Therefore, it is necessary to compromise one of the weight or inductance values during design. According to Equations 3 and 4, the common inductance and self-inductance values depend on the core's height, inner and outer diameters, the number of windings, and the material's relative permeability. According to the results of the analyses conducted with cores of different sizes, the harvester with the highest inductance values was the harvester with a 30x10x20 mm sized M19 core with a small inner diameter, large outer diameter, and large height, as seen in Table 2. Therefore, this is the most appropriate model in terms of induced voltage and, thus, harvested energy. No air gap was used during these analyses, and the current value was determined as constant 60 A.

As can be calculated from Equation 3, the outer diameter/inner diameter ratio affects the mutual inductance and self-inductance. A high ratio causes high inductances. Among the toroids with the same inner diameter, material, and height from Table 2, the inductance of the larger outer diameter is also higher.

In the continuation of the study, the effect of the current value on the harvester's performance was examined. The current values were analyzed by increasing 5 A at each step, in the range of 0-100 A. It was tried to reveal the effect of the current on harvesters by calculating magnetic flux density values at each current value. These analyses were based on the core design of a 30x10x20 mm size with the highest inductance value among the designs.

M19 was the material that reached the highest magnetic flux density value at the current values applied in the analyses. M19 also performed quite well in reaching saturation. As seen from the BH curves in Figure 4, Mu metal, with the highest relative permeability among the materials, started to reach saturation rapidly when the line current was just 10 A. When the flux density is examined by considering Equation 1, it is seen that mu metal with high magnetic relative permeability provides high flux density at low current compared to other materials. Although Mu metal yields quite good results at low current values, its use is limited due to saturation problems as the current value increases. Steel 1010 did not approach the saturation region at the applied current values, but it did not provide as good results as M19 at the magnetic flux density value. According to the analysis, the magnetic material that yielded the best results at low current values was Mu metal. In this study, M19 was the material that provided the best results for magnetic flux density at the applied current values, and steel 1010 came to the forefront at high current values. According to the analyses carried out by increasing the line current, as the amount of current increased, the magnetic flux density also increased in line with expectations, as seen in the graphs in Figure 5. However, the increase in magnetic flux density decreased, although the current increased after a certain point, and the core reached saturation. Hence, adding an air gap is one of the most common solutions for the core to operate in the linear region at high current values.
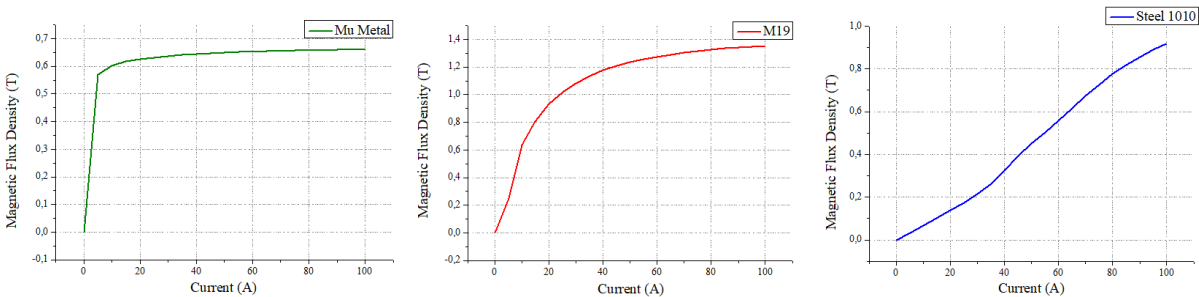

Figure 5: *Flux density with respect to excitation current.*

4.3   Air-gap Effect

In this section, analyses were performed to see how the air gap affected the harvester performance and saturation problem. The air gaps added to the cores were tested in the range of 0-2 mm by increasing them by 0.1 mm at each step. These analyses were also based on the design of 30x10x20 mm in size.

According to the analysis conducted by increasing the air gap in the core in 0.1 mm steps, as the air gap increased, the magnetic flux density decreased due to the increase in reluctance and took a constant value close to zero after a certain point, as seen in the graph in Figure 6. Therefore, attention should be paid to ensuring that the air gap should not be more than necessary to prevent core saturation. Figure 7 demonstrates magnetic flux density distributions of the cores with no air gap and an air gap of 0.1 mm at a 60 A. In this part, the effect of both material and air gap on the flux density distribution is obtained by magnetostatic analysis. In order to create an air gap in the toroid core, the core was designed in two parts and an air gap of 0.1 mm was created between the parts according to the first model.

While the mu metal core was at saturation point in case of no air gap, it operated in the linear region when the air gap was added. Likewise, in case of no air gap, the M19 core operated close to this region, although it was not in the saturation region. However, it operated in the linear region with an air gap.
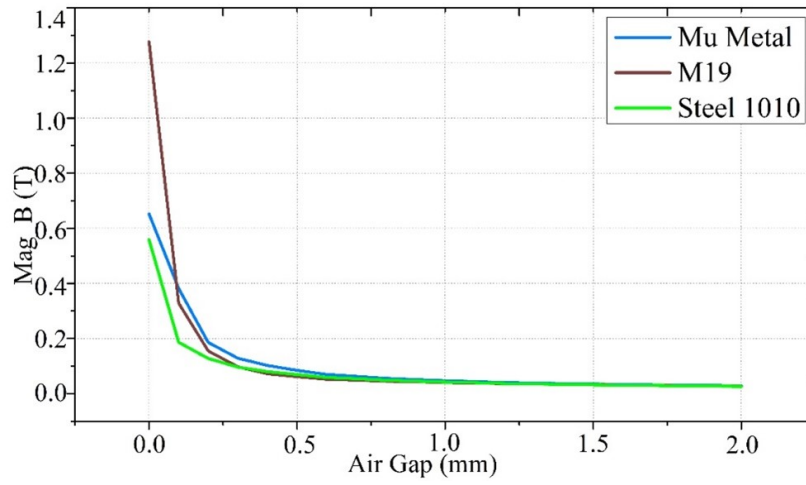
Figure 6: *Graphs of change in the air gap and magnetic flux density.*
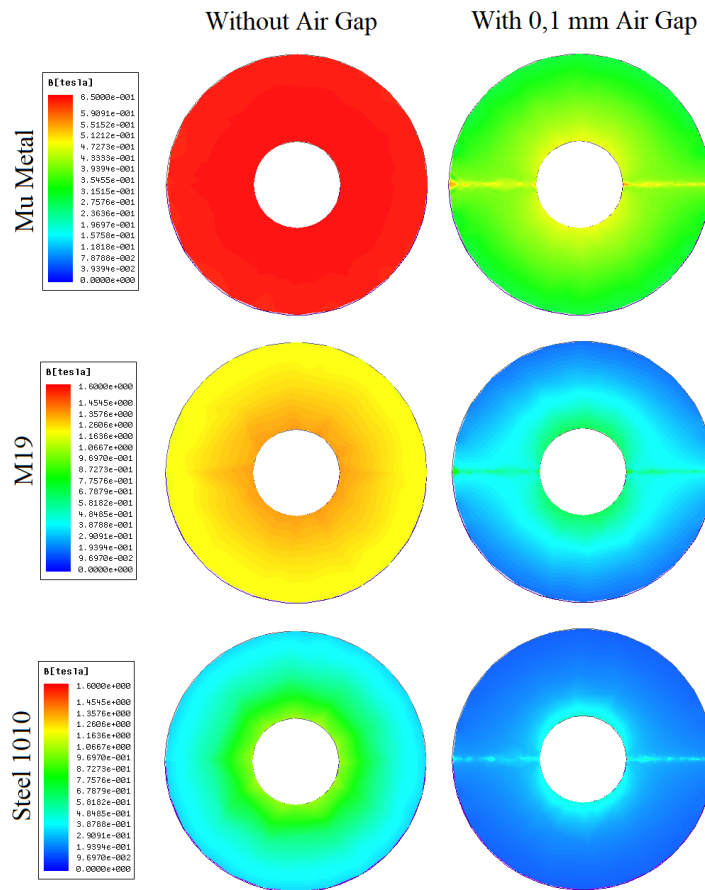

Figure 7: *Magnetic flux density distributions in the cores with and without air gap.*

Although the steel 1010 core had no air gap at this current value, adding an air gap did not make any sense since it was operating in the linear region.

5   Conclusions

In this study, magnetic energy harvesters providing wireless charging for UAVs used to monitor and inspect power transmission lines were designed. The harvesters were analyzed with M19, Mu metal, and steel 101 materials at different currents and air gaps. The design with the highest inductance values among the designs was the harvester with a 30x10x20 mm core having a self-inductance of 2158.9 mH and a common inductance of 4.2891 mH. According to the analysis carried out by increasing the line current in the range of 0 – 100 A with 5 A steps, the highest magnetic flux density value was obtained with the M19 core. The Mu metal core reached saturation rapidly, and the steel 1010 core lagged behind the M19 core in the magnetic flux density value, although it did not reach saturation. According to above-mentioned results, while Mu metal was the material that yielded the best results at current values less than 10 A, the steel 1010 core was the core that provided the best results at high current values. M19 had the best results in the 0 – 100 A current range.

According to the analyses conducted with air gaps, the magnetic flux densities of the cores decreased with the increase in the reluctance of the magnetic circuit as the air gap increased, and it approached 0 for each material when the air gap was above 0.1 mm. Mu metal, which reached saturation rapidly, and M19, which approached the saturation region, started to operate in the linear region when an 0.1 mm air gap was added. According to the results from the overall study, the harvester which had the highest magnetic flux density and inductance values and therefore could reach the highest voltage, power, and energy density values was the 30x10x20 harvester with a core of M19 material without adding an air gap. With the results from the analyses performed by FEM, the performance of toroidal magnetic energy harvesters was investigated according to size, material properties, air gap, and line current variables, and it was attempted to reveal the harvester with the best size/energy density.

Conflicts of Interest: The authors declare that they have no conflicts of interest.

Authors Contributions: This work is Mr. Balcı' thesis. Dr. Dalcalı is Mr. Balcı' advisor. In study literature review, model and analysis have been prepared by M. Şamil Balcı. Abstract, introduction, numerical model and conclusion have been prepared by Selcuk Sakar and Adem Dalcalı.

References

[1] Júnior, T., Rodriguez, Y., Melo, E., Santos, M., and Souza, C. (2013). Energy Harvesting Based on Magnetic Dispersion for Three-Phase Power System. *Energy and Power Engineering,* 5 (3B), 20-23. DOI: 10.4236/epe.2013.53B005.

[2] Özer, İ., Efe, S. B., & Özbay, H. (2021). CNN/Bi-LSTM-based deep learning algorithm for classification of power quality disturbances by using spectrogram images. *International Transactions on Electrical Energy Systems*, 31(12), e13204. https://doi.org/10.1002/2050-7038.13204.

[3] Kabakulak, M. (2020). Energy harvesting from electromagnetic fields around overhead power lines. M. Sc. *Thesis, Harran University.*

[4] Zhuang, Y., Xu, C., Yuan, S., He, C., Chen, A., Lee, W. W., and Huang, Y. (2017). An improved energy harvesting system on power transmission lines. Paper presented at Wireless Power Transfer Conference, Taipei, 10-12 May 2017. https://doi.org/10.1109/WPT.2017.7953847.

[5] Dos Santos, M. P., Vieira, D. A., Rodriguez, Y. P. M., de Souza, C. P., de Moraes, T. O., and Freire, R. C. S. (2014). Energy harvesting using magnetic induction considering different core materials. Paper presented at International Instrumentation and Measurement Technology Conference, Montevideo, (pp. 942-944). DOI: 10.1109/I2MTC.2014.6860881.

[6] de Moraes Júnior, T. O., Rodriguez, Y. P. M., de Souza Melo, E. C., and de Souza, C. P. (2013). Experimental results on magnetic cores for magnetic induction-based energy harvesting. Paper presented at IMEKO TC 4 Symposium and 17th IWADC Workshop Advances in Instrumentation and Sensors Interoperability, Barcelona, (pp. 625-630).

[7] Wang, W., Huang, X., Tan, L., Guo, J., and Liu, H. (2016). Optimization design of an inductive energy harvesting device for wireless power supply system overhead high-voltage power lines. *Energies,* 9(4). https://doi.org/10.3390/en9040242.

[8] Gaikwad, A. A., and Kulkarni, S. B. (2019). Energy harvesting based on magnetic induction. *Smart Innovation, Systems and Technologies,* 106, 363–370. https://doi.org/10.1007/978-981-13-1742-2_35.

[9] Zhang, J., Tian, X., Li, J., and Yan, D. (2020). A Novel Electromagnetic Energy Harvester Based on Double-Ring Core for Power Line Energy Harvesting.*Journal of Circuits, Systems and Computers,* 29(16). https://doi.org/10.1142/S0218126620502655.

[10] Wang, J., Kim, J., and Ha, D. S. (2021). Powerline Energy Harvesting Circuit with a Desaturation Controller for a Magnetic Core. Paper presented at International Midwest Symposium on Circuits and Systems, Lansing (pp. 220–223). https://doi.org/10.1109/MWSCAS47672.2021.9531890.

[11] Kim, H. S., Kim, J. H., and Kim, J. (2011). A review of piezoelectric energy harvesting based on vibration", *International Journal of Precision Engineering and Manufacturing,* 12(6), 1129–1141. https://doi.org/10.1007/s12541-011-0151-3.

[12] Li, S., Peng, Z., Zhang, A., Luo, D., and Wang, F. (2016). Dual resonant structure for energy harvesting from random vibration sources. Paper presented at 11th Annual International Conference on Nano/Micro Engineered and Molecular Systems, Sendai, (pp. 255-259). DOI: 110.1109/NEMS.2016.7758245.

[13] Quyen, T. V., Nguyen, C. V., Le, A. M., and Nguyen, M. T. (2020). Optimizing Hybrid Energy Harvesting Mechanisms for UAVs. *EAI Endorsed Transactions on Energy Web,* 7(30), 1–8. https://doi.org/10.4108/eai.13-7-2018.164629.

[14] Jayarathne, W. M., Nimansala, W. A. T., and Adikary, S. U. (2018). Development of a Vibration Energy Harvesting Device Using Piezoelectric Sensors. Paper presented at Moratuwa Engineering Research Conference, Moratuwa, (pp. 197-202). DOI: 10.1109/MERCon.2018.8421913.

[15] Kang, S., Kim, J., Yang, S., Yun, T., and Kim, H. (2017). Electric field energy harvesting under actual three-phase 765 kV power transmission lines for wireless sensor node.*Electronics Letters,* 53(16), 1135–1136. https://doi.org/10.1049/el.2017.1794.

[16] Nadaf, N., and Preethi, A. (2021). Review on Waste Heat Energy Harvesting using TEG: Applications and Enhancements. Paper presented at 8th International Conference on Smart Computing and Communications, Kerala, (pp. 334-339). DOI: 10.1109/ICSCC51209.2021.9528196.

[17] Balguvhar, S., and Bhalla, S. (2018). Green Energy Harvesting Using Piezoelectric Materials from Bridge Vibrations. Paper presented at 2nd International Conference on Green Energy and Applications, Singapore, (pp. 134-137). DOI: 10.1109/ICGEA.2018.8356282.

[18] Wen, Q., He, X., Lu, Z., Streiter, R., and Otto, T. (2020). A comprehensive review of miniatured wind energy harvesters. *Nano Materials Science,* 3, 170-185. https://doi.org/10.1016/j.nanoms.2021.04.001.

[19] Uddin, M. N., Islam, M. S., Sampe, J., Ali, S. H. M., and Bhuyan, M. S. (2016). Design and simulation of piezoelectric cantilever beam based on mechanical vibration for energy harvesting application. Paper presented at International Conference on Innovations in Science, Engineering and Technology, (pp. 1-4). DOI: 10.1109/ICISET.2016.7856532.

[20] Rodríguez, J. C., Holmes, D. G., McGrath, B. P., and Wilkinson, R. H. (2014). Maximum energy harvesting from medium voltage electric-field energy using power line insulators. Paper presented at Australasian Universities Power Engineering Conference, (pp. 1-6). DOI: 10.1109/AUPEC.2014.6966633.

[21] Moghe, R., Yang, Y., Lambert, F., and Divan, D. (2009). A scoping study of electric and magnetic field energy harvesting for wireless sensor networks in power system applications. Paper presented at Energy Conversion Congress and Exposition, San Jose, CA, USA, 20-24 September 2009. DOI: 10.1109/ECCE.2009.5316052.

[22] Najafi, S. A. A., Ali, A. A., Sozer, Y., and De Abreu-Garcia, A. (2018). Energy Harvesting from Overhead Transmission Line Magnetic fields. Paper presented at IEEE Energy Conversion Congress and Exposition, Portland, (pp. 7075–7082). https://doi.org/10.1109/ECCE.2018.8558356.

[23] Yuan, S., Huang, Y., Zhou, J., Xu, Q., Song, C., and Thompson, P. (2015). Magnetic Field Energy Harvesting under Overhead Power Lines. *IEEE Transactions on Power Electronics,* 30(11), 6191–6202. https://doi.org/10.1109/TPEL.2015.2436702.

[24] Roscoe, N. M., and Judd, M. D. (2013). Harvesting energy from magnetic fields to power condition monitoring sensors. *IEEE Sensors Journal,* 13(6), 2263–2270. https://doi.org/10.1109/JSEN.2013.2251625.

[25] Zhou, J., He, L., Liu, L., Yu, G., Gu, X., and Cheng, G. (2022). Design and research of hybrid piezoelectric-electromagnetic energy harvester based on magnetic couple suction-repulsion motion and centrifugal action. *Energy Conversion and Management,* 258. https://doi.org/10.1016/j.enconman.2022.115504.

[26] Yeesparan, S., Bin Baharuddin, M. Z., Din, N. B. M., and Haron, M. H. (2018). A review of energy harvesting methods for power transmission line monitoring sensors. *International Journal of Engineering and Technology* (UAE), 7(4), 153–161. https://doi.org/10.14419/ijet.v7i4.35.22348.

[27] Camboin, M. M., Baiocchi, O., Villarim, A. W. R., Catunda, S. Y. C., de Souza, C. P., and Moreira, C. D. S. (2019). An Automatic Emulation System for Environmental Thermal Energy Harvesting. Paper presented at International Instrumentation and Measurement Technology Conference, New Zealand, May 2019, (pp. 1-6). DOI: 10.1109/I2MTC.2019.8827004.

[28] Yuan, S. (2019). Magnetic Field Energy Harvesting for Smart Grid Application. PhD thesis, University of Liverpool.

[29] Najafi, S. A. (2019). Energy Harvesting from Overhead Transmission Line Magnetic Fields. M. Sc. Thesis, Graduate Faculty of the University of Akron.

[30] Zhang, Y., Wang, Z., Li, Y., Tian, B., Huang, X., and Zhang, P. (2021). Optimized Design and Simulation Study of Helical Core Suitable for Non-invasive Energy Harvesting. Paper presented at 16th Conference on Industrial Electronics and Applications, Chengdu, (pp. 1016–1019). https://doi.org/10.1109/ICIEA51954.2021.9516123.

[31] Park, B., Kim, D., Park, J., Kim, K., Koo, J., Park, H. H., and Ahn, S. (2018). Optimization design of toroidal core for magnetic energy harvesting near power line by considering saturation effect. *AIP Advances,* 8(5). https://doi.org/10.1063/1.5007772.

[32] Dalcalı, A. (2019). Influence of Rotor Magnet Material and Stator Winding Geometry on Output Torque in Spherical Actuator. *Journal of Engineering Sciences and Design,* 7 (1), 145-151. DOI: 10.21923/jesd.437980.

About the Authors

M. Şamil Balcı received the B.Sc. degree from Kırıkkale University in 2015. He is M.Sc student and Research

Assistant with the Department of Electrical-Electronics Engineering, Bandırma Onyedi Eylül University, Türkiye. His research interests are electromagnetic fields and electrical machinery.

Selcuk Sakar received the B.Sc. and M.Sc. degrees from the Graduate School of Natural and Applied Sciences, Gazi University, Ankara, Türkiye, in 2010 and 2012, respectively. In 2021, completed his Ph.D. degree in electrical power engineering at the Lulea University of Technology, Sweden. He is currently working in Hitachi Energy as an R&D engineer.

Adem Dalcalı received the B.Sc. and M.Sc. degrees from Gazi University in 2010 and 2013, respectively, and the Ph.D. degree in electric and electronics engineering from Karabük University in 2017. His research interests include wind energy and the numerical analysis of the electromagnetic field in electrical machinery.