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Effect of core material on induced voltage in electromagnetic harvester

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With the increasing demand for energy today, diversification of resources and meeting this demand has become crucial. Environmentally friendly alternative solutions have been the subject of research. Especially investments in renewable energy sources have increased in this regard. The power required by low-power sensor technologies can be met by harvesters. For this purpose, the design and Finite Element Analysis (FEA) of the toroid core electromagnetic harvester have been carried out in the study. The material of the toroidal core is determined by selecting Nickel-steel, M19, and nanocrystalline, and the effect of induced voltage and mutual inductance on the core material has been identified. In addition, the line current was determined as a variable and its effect on both flux density and voltage was determined.

Keywords: *Electromagnetic harvesters, Energy harvesting, Finite element method, Toroidal core*

1. Introduction

The importance of electrical energy is increasing day by day. The rise in automation systems, expanding population, and advancing technology contribute to an escalating demand for electrical energy. This has necessitated a focus on energy supply security and energy quality. Environmental concerns caused by the use of fossil fuels and the lack of known reserves have increased the popularity of renewable energy. The fact that renewable energy sources offer environmentally friendly local solutions and provide energy diversity is an important advantage. As with renewable energy sources, energy harvesting is an alternative application, especially for applications with low energy needs [1,2].

Energy harvesting is the extraction of small amounts of electrical energy from sources such as vibration, electromagnetic fields, solar and wind. Energy can be harvested from power transmission lines by means of electromagnetic fields. In this method, according to the transformer principle, the transmission line acts as the primary winding and the windings in the core act as the secondary winding. During energy harvesting from the transmission line, the magnetic saturation of the core affects the harvested power. [3-5].

Studies on magnetic energy harvesters that are found in the literature typically concentrate on air gaps, winding turns, geometric structure, and core material. [6,7]. In the study where the number of windings, winding configuration and core dimensions of the magnetic field energy harvester were extensively investigated, it was determined that the height of the core is positively correlated with the output power. [8]. However, especially in cases where weight is crucial, this situation can pose a problem. In a study investigating a similar effect, the influence of the primary current and core dimensions was experimentally extracted. For this purpose, the current value has been examined in the range of 0-10 A, and the geometry was investigated in four different diameters. As a result of the study, it has been determined that the harvested voltage is influenced by both the primary current and core dimensions [9]. In addition to dimensions, the material also affects the harvested power. In a study conducted to examine the material effect, induced voltage, core flux density, and core losses have been extracted for three different materials. It has been determined that the nano-crystalline structure induces the highest voltage [10]. As is known, if the core reaches saturation in the harvester, the harvested power decreases accordingly. Taking this into account, a study has proposed load voltage control as a method to enhance power density in magnetic energy harvesters. Critical saturation points for maximum power harvesting were determined by considering the primary current values [11] Another proposed method to prevent saturation involves a key system that short circuits the coil when the core is saturated. It has been stated that this method increases the harvested power by 27% [12]. In a different solution proposal, an artificial magnetic field was generated using an additional coil to manipulate the magnetic field. This way, the core has not easily reached saturation, and the obtained power value was increased [13]. Another method suggested to increase the obtained power involves using a low-power analog control circuit applying the maximum power point tracking (MPPT) technique. When compared to commercial circuits, it has been determined that the suggested method increases the output power in the 1-10 A current range [14]. In a different study for high power harvesting, a two-stage harvester is proposed. In the proposed structure, a clampable core and an air air-gap-free core form a two-stage cascade magnetic structure. The first part allows easy assembly, while the second part proposes a structure with high permeability for enhanced performance [15]. In the study carried out for the development of the proposed cascade structure, the size of the clampable core was optimized and the power obtained was increased [16].

In this study, the design of a toroidal core electromagnetic energy harvester for sensors operating at low power has been carried out. The impact of the material, using M19 steel, nanocrystalline, and nickel-steel, on the harvested voltage, mutual inductance and magnetic flux density in the toroidal core has been determined.

2. Design of Electromagnetic Energy Harvester

The mutual inductance and induced voltage values of the toroidal harvester have been extracted using materials with different BH curves and magnetic permeabilities. The designed toroidal magnetic energy harvester model is shown in Figure 1.

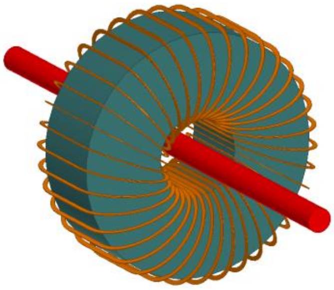

***Figure 1**. Designed toroid core.*

In the study, line (primary) current has been determined as variable. Limits of the specified variable:

- $2\ A < I_{line} < 40\ A$

The line current has been increased with a sensitivity of 2 A. In the designed core, the outer radius (b) is determined as 30 mm, the inner radius (a) as 10 mm, and the core height (h) as 20 mm. The number of windings is taken as 100 turns. In the study, M19, nanocrystalline, and nickel-steel materials have been used, and the BH curves of the materials used are provided in Figure 2.

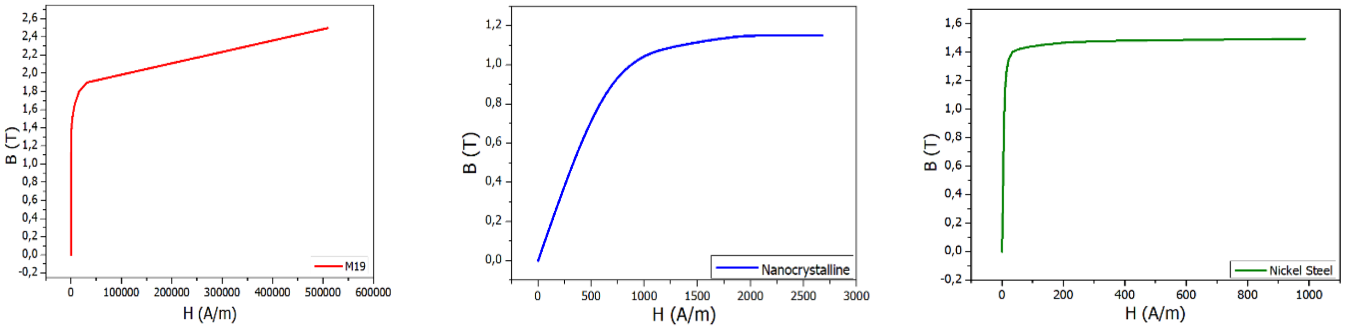

***Figure 2**. BH curves of the materials.*

A. Mathematical Model

Electromagnetic energy harvesters consist of a core with different geometrical structure and material and a winding on the core. These harvesters generate energy by inducing voltage from the magnetic field around a current-carrying conductor. In the harvester, the transmission line functions as the primary, and the core windings operate like secondary windings in a transformer [7,17].

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

In toroidal-shaped magnetic energy harvesters, the magnetic flux density *B* at any radius is influenced by the current in the coil and the relative permeability μ, as seen in Equation 1.

$$M = \frac{\mu}{2\pi} h \, N_2 \ln\left({}^{b}\!/_{a}\right) \tag{2}$$

For toroid model magnetic energy harvesters, the mutual inductance value is shown in Equation 2 and the voltage value induced in the windings is shown in Equation 3.

$$V_2 = N_2 \mu \, f \, i \sin(\omega t) \ln\left({}^{b}\!/_{a}\right) h \tag{3}$$

The mutual inductance and induced voltage value can be expressed together as in Equation 4.

$$V_2 = M \; f \, i \sin(\omega t) \; 2\pi \tag{4}$$

As can be seen, the induced voltage value is affected by the mutual inductance M, line frequency *f* and line current *i* values. The value of the mutual inductance is important for the voltage induced by the harvester. The equivalent circuit of the designed harvester is given in Figure 3. The mutual inductance *M* given in Figure 3 has been analyzed for each current and core material. The induced open circuit voltage has been calculated using Equation 4 [7].

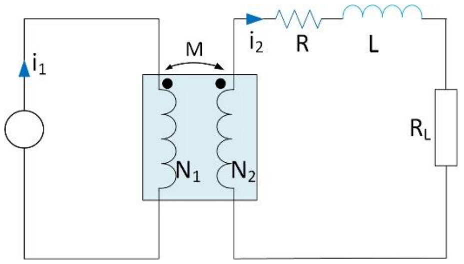

***Figure 3**. Equivalent circuit of harvester.*

3. Voltage and Mutual Inductance Analysis

In electromagnetic harvesters, various parameters such as line current (primary current), core material, geometric variables, and more, affect the harvested power. A lot of investigation is needed to meet criteria such as cost, weight and efficiency. The Finite Element Method (FEM) can be utilized to accurately determine magnetic flux density, harvested voltage, and inductance parameters. FEM can be employed in various fields, including electric machines [18], healthcare industry [19], and automotive applications [20]. This method provides advantages in terms of both time and cost. FEM involves the solution of equations in which quantities that can be expressed by partial differential equations are divided into a finite number of small regions and chained together [21]. The mesh structure of the designed harvester is given in Figure 4.

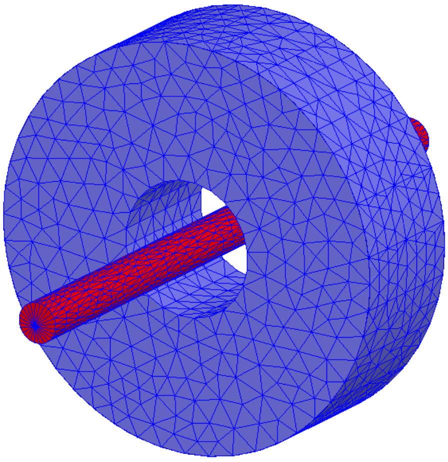

Figure 4. *Mesh structure.*

Mutual inductance values according to FEM analyzes using three different materials are given in Table 1.

Table 1. *Mutual inductance.*

Current (A)	**Ni-Steel (mH)**	**M19 Steel (mH)**	**Nanocrystalline (mH)**	**Current (A)**	**Ni-Steel (mH)**	**M19 Steel (mH)**	**Nanocrystalline (mH)**
2	5.350722	1.844877	0.5517898	22	0.05760229	0.702498	0.5215241
4	0.9846277	3.894447	0.5521176	24	0.05099567	0.6117317	0.5160483
6	0.3453183	3.383536	0.5501394	26	0.04517263	0.5371847	0.510092
8	0.1868043	2.614646	0.5475768	28	0.0399214	0.4791331	0.5036541
10	0.1410093	1.985241	0.5448835	30	0.03522143	0.4350556	0.4968334
12	0.116456	1.462616	0.5419923	32	0.03102485	0.3962506	0.4894318
14	0.09891724	1.181511	0.5387634	34	0.02746448	0.361648	0.4815466
16	0.08573164	1.043108	0.5351444	36	0.02453033	0.3310291	0.4731936
18	0.07468986	0.9217168	0.5311725	38	0.02217187	0.3033489	0.4643291
20	0.06539337	0.8056171	0.5265209	40	0.02026539	0.2785705	0.4549705

When Table 1 is examined, it is observed that for currents of 2 A and lower values Nickel-embedded steel material provides the highest mutual inductance. Up to 28 A, M19 exhibits the best mutual inductance, while beyond 28 A, nanocrystalline material achieves the highest mutual inductance values. To obtain the magnetic flux distributions on the core, analyzes have been carried out at 2 A, 20 A and 40 A values. The obtained flux distributions have been given in Figure 5.

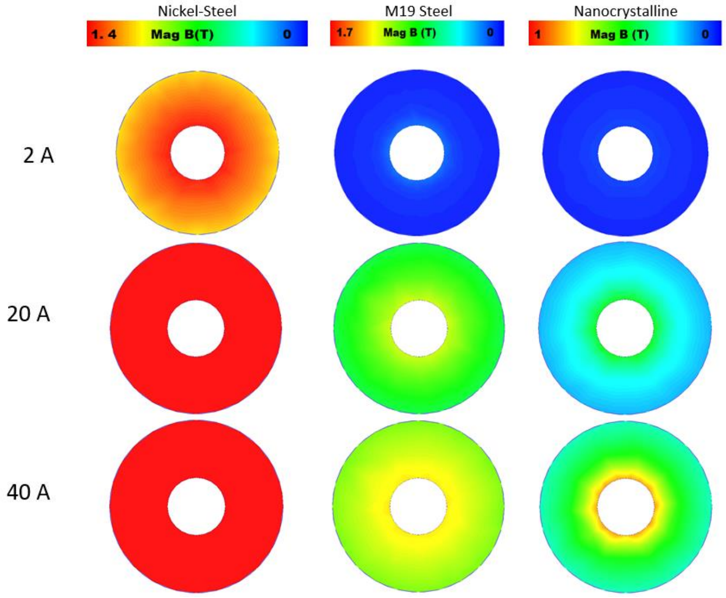

***Figure 5**. Magnetic flux density.*

As seen in Figure 5, the Nickel-steel material approaches the saturation region at a current value of 2A. At 20A, it is already in the saturation region. However, the other two materials have not reached saturation even at 40A. The obtained voltage values can be seen in Figure 6.

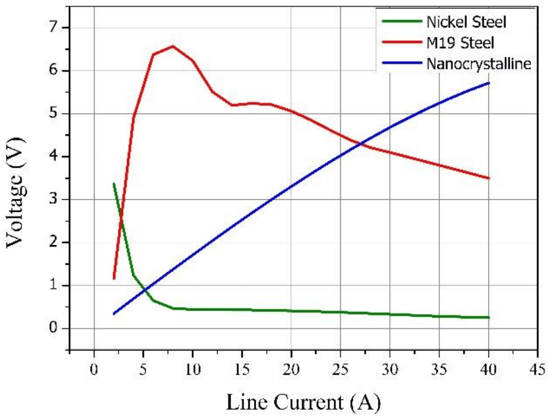

***Figure 6**. Induced voltage.*

While the line current was still 2 A, the highest voltage was induced by the Nickel-steel material harvester. Since this material reaches saturation at subsequent current values, it is observed that the induced voltage value decreases. While the line current is in the range of 2A to 26A, the highest voltage value is induced by the harvester with an M19 steel core. After 26A, even higher voltage is induced in the nanocrystalline material.

3. Conclusion

Electromagnetic harvesters offer a good alternative, especially for low power values. However, the harvested voltage value is influenced by various parameters such as core material, number of turns, core size, and line current. In this study, the geometric variables of the toroidal core were kept constant, and the influence of material and line current was determined. The line current has been varied in the range of 2A to 40A, and the saturation state of the core has been investigated through 3D analyses. At 2 A line current the highest voltage was induced by nickel-steel. But after

2 A the nickel-steel core has already reached the saturation region. M19 and nanocrystalline cores have not reached saturation in the applied currents. Between 2 A and 26 A line currents M19 core has induced the highest voltages. Beyond 26 A line currents the nanocrystalline core exhibited the highest induced voltage due to its high saturation point. In case the core material becomes saturated, adding an air gap can be offered as an alternative solution.

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