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Energy Management through Electromagnetic Conversion

Eduardo Torres-Sánchez

Abstract

The global society has the responsibility to concern about environmental impact for energy purposes by replacing existing coal and hydrocarbon methods by sustainable and efficient energy systems. Hence, current power generation systems are bounded by the physical laws that tend to decrease the performance by converting most of the energy into heat. Likewise, the revolution and massive implementation of renewable energies around the world have demonstrated that the electromagnetic transduction presents a viable option to harness the induced mechanical energy provided by either wind or water into exergy. The exergy focuses on the efficiency of the second law of thermodynamics with the purpose to ensure availability and quality of energy within energetic management systems. Thereby, it is necessary to decrease the energy demand by making very efficient power-consuming devices and increasing the quality of energy with performed output power generation systems. This chapter addresses a single diagram to develop models and novel designs for power generation with the aim to develop variable efficiency power systems. Furthermore, an analysis is addressed on magnetism, electromagnetic induction, and magnetic materials to design, optimize, and implement into current power cycles.

Keywords: variable energy efficiency, electromagnetism, sustainability, energy quality, time-varying magnetic field

1. Introduction

Energy management mainly refers to developing systems with potential energy savings with a positive economic impact. The key relies on identifying energy saving opportunities [1], for instance, the accurate maintenance measures made on time and the necessary modifications of current power systems to ensure best operation at lower costs. Accordingly, renewable energies have opened an opportunity to increase power management efficiency without compromising the natural resources of future generations [2].

Nevertheless, the energy is classified by two variants stated by the quality of energy, named exergy and anergy. The term exergy was first mentioned by Zoran Rant in 1956 as the amount of energy that can be converted either into mechanical, electrical, or other work [3]. Thus, the anergy results as the remaining energy part without a practical utility. Moreover, the exergy is a measure of efficiency of an energy system into parameters of quality and availability [4]. In comparison, these statements are based on the second law of thermodynamics that establishes the

boundaries regarding the quantity of work that can be done. In addition, an exergy analysis compares different energetic performance to choose the most efficient alternative according to either storing, consuming or power generation application [5].

Likewise, the exergy determines the thermodynamic value in a quantitative manner by analyzing the energetic resource wasting to find out the causes of low efficiency. Thereby, once the causes are quantified, the exergy analysis can help to specify the necessary modifications on either the process or the design [6]. Thus, the exergy is stated as a thermodynamic property of a substance or a system that allows determining the useful potential work of an available amount of energy that can be acquired by the spontaneous interaction between a system and the environment that surrounds it [7].

On the other hand, the only way to operate larger systems is across electrical energy provided by electric power plants. Hence, electricity generation has been accomplished in the last century by nuclear methods, coal and fossil-fueled systems, largely designed to power supply to an endless number of power consumption devices [8]. However, regardless of these great energy structures that produce huge amounts of useful energy, they face environmental concerns by polluting the natural resources [9]. In addition, it is not only the pollution but the consequences of extracting oil more than what it is due, by triggering greater earthquake frequency and intensity [10]. The oil is the earth's lubricant. Moreover, the environmental impact of using the hydraulic fracking method to extract shale gas causes an irreversible damage to aquifers and subsoil [11]. However, an additional problem despite the power generation from hydrocarbons is the need of power supply systems to be independent from the grid.

In contrast, renewable energies have started to accomplish the energetic demands with the aim to stop polluting by converting the mechanical energy from natural sources such as wind, wave, geothermal, hydraulic, and tidal power into available electrical energy [12]. The energy conversion is made, thanks to the electromagnetic induction properties that are present in every time-varying magnetic field of current electric generators. Of course, while there is an existing mechanical energy, consequently, there will be energy for conversion. Indeed, if there is no energy to convert, then no energy is generated. This statement is underpinned in the first law of thermodynamics [13].

Otherwise, energy harvesting systems have become an alternative form of power generation over the last few years. The mechanical force induced by vibrations using piezoelectric materials, and even collisions, are examples of energy harvesting methods. However, electromagnetic induction is an especially promising means of energy harvesting, since only coils and magnets are needed for its functioning and efficiency increasing [13]. Thus, the electromagnetic transduction increases the performance of energy conversion more than hydrocarbons by the simple fact of combustion and excessive heat conversion energy lack. This change yields implicitly the performance of the second law of thermodynamics, which is the aim of the exergy, by developing more efficient power systems [14]. Another important fact to regard is that the increase in the energy demand is on the rise since the population is on the rise [15].

Accordingly, it is necessary to power supply medium and low power consuming systems by obtaining the energy from the environment instead of getting it from a big manager energy such as oil wells. Thus, the development of new energy systems technology must be every time more efficient to power supply without environmental impacts at the lowest cost.

In this chapter, a developing diagram has been addressed to design customized electric machines according to the desired applications. The applications are also focused to establish these generators in areas where it is difficult to supply energy

for common use electronic devices and in applications of everyday life. Of course, this effect would yield to create independent power grids per zones, roads, and streets. For instance, the sum of renewable energy applications will determine the approach to the creation of new energy systems.

Henceforth, these designs will open the possibility of developing configurable generators, according to the real-life applicable power generation systems. The effectiveness of the design depends on the architecture of the device, while the quantity of energy harvested depends on the lifetime of the magnets and on the continuation of the induced mechanical force.

Elsewhere, as the exergy focuses on the availability and the efficient application of energy, this statement yields to adapt current power generators into more efficient power cycles with the aim to reduce the energy transformation into heat. For instance, current induction generators of wind power stations may have the enhancement to vary the distance between the rotor and the stator with the objective to harvest the energy of wind velocities beyond the current operating limit. Therefore, the rotor would vary the distance from the stator every time there exists an up-or-down variation of the wind velocity. Therefore, at low wind velocity, the rotor will be set up farer from the stator to generate low output power and vice versa; at greater wind velocities, the rotor will be set up at a closer distance from the stator to generate high output power. Moreover, this variability allows velocity fluctuations to harvest energy any time there is an induced mechanical force. Namely, the outcome is a variable efficiency generator in accordance with the mechanical energy provided by the environment.

Further, there exist many energy systems that can be modified to increase efficiency by reducing the energetic losses with the induction of electromagnetism in a performed manner.

2. Energy management in energy harvesting

Renewable energies are an essential support to provide exergy in a clean manner to human life. Nowadays, an increasing number of smaller technologies are being powered by batteries, renewable energies, and complex control systems to save energy. Electromechanical applications are currently focused on energy harvesting, including the development of autonomous devices [16]. However, the current energy harvesting methods still rely on batteries or their equivalent. Namely, neither fossil fuels nor nuclear energy fall into this category. Thus, energy harvesting can play an important role if used properly in power systems.

Building on single-source systems, Amanor-Boadu et al. [17] created a multi-energy system which simultaneously charged a Li-ion battery. This idea, however, could now be further improved by adding more energy sources to one energy harvesting system and not only charge one Li-ion battery or one capacitor but rather several batteries in less time.

A diagram of a multi-energy system is shown in **Figure 1** as an effective solution to combine multiple energy harvesting systems simultaneously for battery charging [17]. Evenly, this approach should have an effective management energy system such as a BMS (Battery Management System) to protect the batteries inside their safe operating functionality. Moreover, the effectiveness decreases, because energy is lost during the conversion processes. However, electromagnetic induction could increase the efficiency [18].

On the other hand, the exergy presents different qualities that depend on the possibility either to generate work or transforming one sort of energy into others. For instance, the heat quality depends on the temperature, where at greater

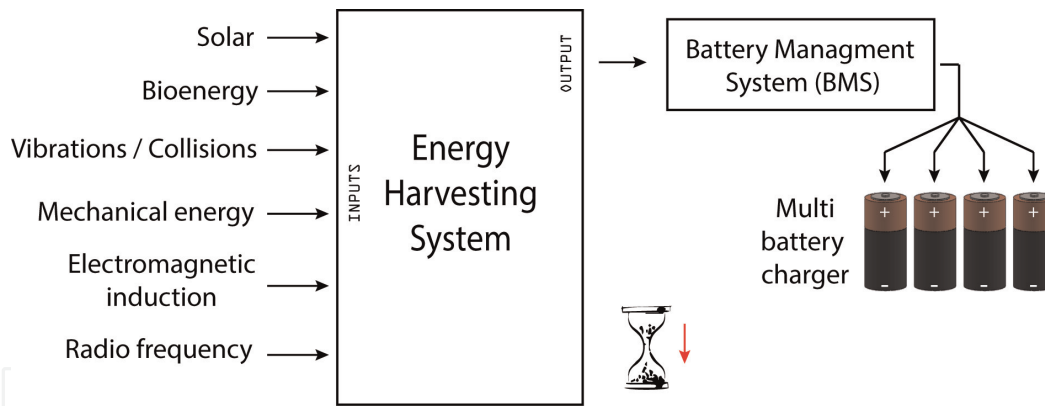


Figure 1.
Multi-battery charging system with multiple energy sources.

temperature, a heat source can transfer its energy more easily than at lower temperature [19]. Commonly, it is accepted as a measure of energy quality, the capacity of an object to produce work. Thus, for a thermal machine to perform work, the heat must be taken from a power source at high temperature, and part of that heat must be transferred into a low temperature environment while the thermal equilibrium is being carried out. In comparison with a thermal machine, if the environment temperature is very low (cold), therefore, it results more difficult to transform the heat of this source into work. Therefore, the reference level (the value of the low temperature) is very important when defining the exergy. This physical phenomenon is known as entropy, describing the irreversible for a thermodynamic system in equilibrium [20]. Consequently, as thermal machines usually work with the surrounding medium as a cold focus, the reference level is then taken from either a room or environmental temperature [21].

Accordingly, because of the lack of thermal equilibrium in the environment, the reference state cannot be completely defined but it is enough by defining the thermal equilibrium through temperature. The exergy of a substance can be divided into four main components: kinetic, potential, physical, and chemical exergy. The last exergies, physical and chemical, are grouped by the thermal exergy which is the sum of both. Conversely, the effect of energy losses during the energy conversion from mechanical to electrical through electromagnetic transduction is much more lower than in thermal machines [7].

Finally, researchers often compare the effectiveness of different methods based on the energy storage density inherent to each transducer type, demonstrating that electromagnetic induction demonstrates better performance than electrostatic [14]. The most effective transducer type depends on the specific structure design, the implemented materials, and its application.

3. Electromagnetic induction

In 1831, Michael Faraday and Joseph Henry discovered ways to produce electricity from magnetism—one, by using one long coil called an intensity magnet and the other by passing a magnet inside a short coil called a quantity magnet. These discoveries became the most important research on electric and magnet induction [22].

The multi-atomic arrangement of magnetic structures of the individual magnetic momentums of a group of atoms/molecules stays aligned due to a strong coupling named domains or magnetic dipoles [23]. The electron motion of the

atoms has several domains. Further, the intrinsic magnetic dipole moment is associated with the spin of the electrons. Thus, the alignment of magnetic dipoles parallel to an external magnetic field increases the field.

Equally, the difference by comparing the magnetic field lines of a magnetic dipole with the electric field lines of an electric dipole is the direction [24]. In other words, inside the current loop, the magnetic field lines are parallel to the magnetic dipole moment, whereas among the charges of the electric dipole, the electric field lines are opposite to the direction of the dipole moment. Thereby, inside a magnetically polarized material, the magnetic dipoles create a parallel magnetic field to the magnetic dipole moment vectors [25]. Nonetheless, if the magnetic flux across the stationary wire loop is changing, an electromotive force (emf) is induced in the loop.

The emf is distributed throughout the loop, which is due to nonconservative electric field tangent to the wire as shown in **Figure 2**. The flux across the loop is changing because the magnetic field strength is increasing, so an emf is induced in the loop. Since emf is the work done per unit change, we know that there must be forces exerted on the mobile charges doing work on them [25].

Otherwise, Lenz's law does not specify just what kind of changes cause the induced emf and current. The induced emf is in such a direction as to oppose or tend to oppose the change that produces it [26].

From **Figure 2**, when the bar magnet is moving to the right, an induced current is generated since an emf is induced into the loop. Likewise, the magnetic field through the induced current into the loop produces a magnetic field that exerts a force on the bar magnet by opposing its motion to the right. For instance, the yellow arrow is taken as if it were a bar magnet, where the magnetic moment of the loop $\vec{\mu}$ is such as to oppose the motion of the bar magnet due to the induced current. Indeed, the bar magnet is moving toward the loop, so the induced magnetic moment repels the bar magnet [25].

3.1 Permeability, reluctance, and magnetic susceptibility

When a magnetized material is placed in a strong magnetic field, such as a coil or solenoid, the magnetic field of the coil tends to align the magnetic dipole moments inside the core [25]. The magnetization occurs, thanks to the microscopic current loops inside the magnetized material. These current loops are a classical model for the orbital motion and spin of the electrons in atoms.

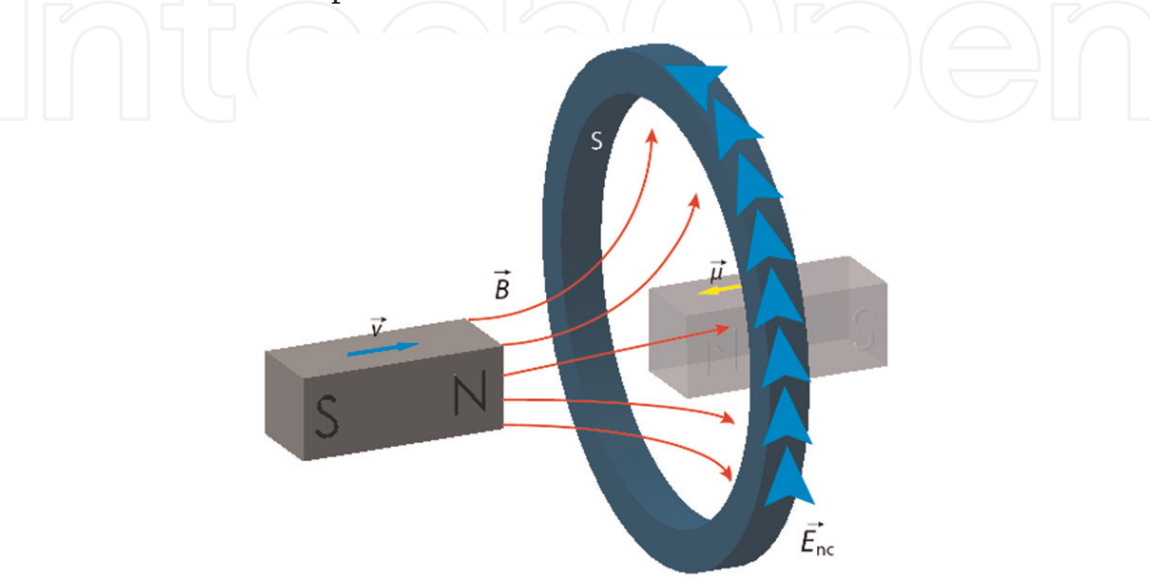


Figure 2.
Single stationary loop in a magnetic field.

The magnetic susceptibility X_m is a dimensionless proportionality constant that defines the susceptibility degree to the magnetization of a material influenced by a magnetic field. This term is related with the permeability of the materials. Thus, the magnetization of ferromagnetic materials exhibits magnetization even in the absence of an applied field. The magnetic susceptibility of the copper, implemented to make the coils, is $-0.98 \times 10^{-5} X_m$ at 1 atm. Moreover, silver and gold would be a better option as conductors to harvest energy with electromagnetic variations due to the values of their magnetic susceptibility which are -2.64 and $-3.5 \times 10^{-5} X_m$, respectively [24]. Additionally, the magnetic permeability μ is defined as the ability of a material either to attract or pass across magnetic fields [27].

Consequently, there exists an interaction between the density of the magnetic field and the magnetic induction that appears within itself. Likewise, the magnetic permeability of the medium can be defined as the capacity measure to establish lines of magnetic flux. Further, the greater the permeability of the medium, the greater the number of flow lines per unit area as shown in **Figure 3**.

Elsewhere, the magnetic permeability of the air or vacuum is $4\pi \times 10^{-7} \text{ Wb/Am}$, Tm/A or H/m , represented as μ_0 . Thereby, regarding the air permeability as a reference, the relative permeability μ_r of any material will be measured respect to it. For instance, copper has 0.9, iron is between 1500 and 7200, and NdFeB is over 100,000 H/m [27]. Thus, permeable materials are magnetized by magnetic induction, resulting in a much more intense magnetic field, and accordingly, the use of these materials increase the efficiency of power generation.

In contrast, the reluctance is the opposite of the permeability, in which, this applies resistance to the magnetic flux when influenced by an external magnetic field. The greater the reluctance of a material, the more energy will be required to establish a magnetic flux through it. Thereby, these properties allow an efficient conversation of energy by increasing the quality and availability of energy.

3.2 Magnetic materials

The magnetic flux produces electric currents and vice versa. The fields generated by magnetic materials are because of the orbital angular momentums and the electron spinning. The continuous movement in the material experiment forces ahead an applied magnetic field. The magnetic characteristics can vary by the composition of other elements, where the atomic interactions are modified [24].

The applied magnetic field always plays an important role over the regarded electrons individually, giving the effect known as diamagnetism. At an atomic level, the magnetic momentum is aligned with the induced field, giving place to

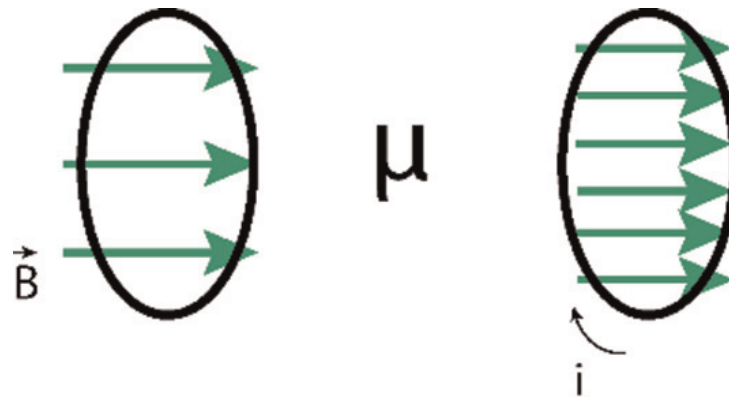


Figure 3.
Permeability behavior to magnetize the materials [27].

paramagnetism. Simultaneously, the present thermic energy orients in a random way the magnetic momentums. This interaction, as a relative intensity of all these effects, determines the definitive behavior of the materials [28]. According to the behavior of their magnetic moments in an external magnetic field, the materials fall into three categories, which are paramagnetic, diamagnetic, and ferromagnetic [25].

The diamagnetic materials have the property to induce very small magnetic moments compared with the permanent magnetic moments. This effect arises from the orbital magnetic dipole moments induced by the applied magnetic field. The magnetic moments are opposite the direction of the applied magnetic field [29]. The diamagnetism effect can be modeled by applying Lenz's law to the orbital movement of the electrons. Some examples for diamagnetic materials are copper and helium.

In comparison, paramagnetic materials arise from the molecular magnetic moments by an applied magnetic field. Equally, the magnetic dipoles interact with each other and they are oriented in a randomly way. The magnetic momentum has a parallel alignment to the applied field. Since the slow response, these materials are similar to the air ($\mu = \mu_0$) in the magnetic design. Moreover, the response intensity is very small, and the effects are practically impossible to detect, except at extremely low temperatures or very intense applied fields. For instance, aluminum and sodium present these characteristics [30].

Further, ferromagnetism is more complicated. The strong interaction among external magnetic fields and the ferromagnetic material causes a very large increase in the field. A high degree of alignment occurs even with weak external magnetic fields. The magnetic momentum of big atom groups remains aligned with each other due to a strong coupling.

A disadvantage with these materials is the high temperatures, in which it tends to misalign the domains. This temperature is named Curie's temperature T_c (K), becoming a paramagnetic material due to the disordered thermic effects greater than the alignment effects of the magnetic interaction among the domains. Therefore, to demagnetize a magnetized material, it is only necessary to heat up over the T_c [31]. For instance, the *Fe* can be demagnetized beyond 1043 T_c (K). Other examples of ferromagnetic materials are cobalt, iron, nickel, and most of the steels.

Hence, the permanent magnets have their magnetic poles aligned generating an external magnetic field. Many permanent magnets are made by metallurgic techniques, where the material is milled until it is converted into small dust particles. The magnets not only generate either an own or induced magnetic field but continue producing an induced magnetic field even after the applied magnetic field is retired. This property is neither altered nor weakened with time, except when the magnet is subjected to high temperature changes, demagnetized fields, and mechanical tensions, among other situations [24]. For instance, **Figure 4** shows the alignment of the magnetic field of a ring-shape permanent magnet with diamagnetic materials such as copper.

Elsewhere, only in the transition elements, such as Fe, Ni, O, and the rare earths elements, there exist incomplete deep orbitals that are not affected by the bonding forces when the atoms come together to form a solid. The atoms retain an important magnetic momentum and this effect yields to the origin of the phenomenon of ordering [32].

In contrast, the electromagnetic induction increases the quality and availability of energy harvesting by including permanent magnets and coils. Roughly speaking, magnetic materials are implemented because they have very large positive values of magnetic susceptibility. The reason is because in a changing magnetic field and in a changing magnetic flux, an emf is induced [22]. This feature helps harvesting the energy of the magnet in a singular manner by changing the magnetic flux in several

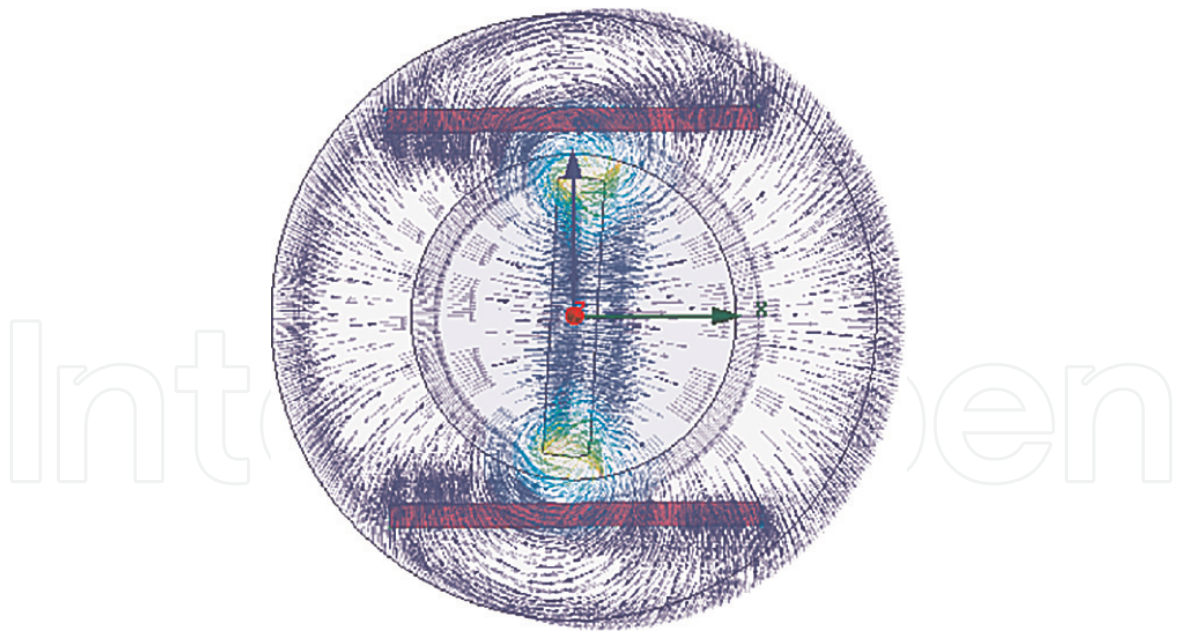


Figure 4.

Magnetic field distribution between a permanent magnet (center) and a diamagnetic material (top and bottom).

ways. Thus, the quantity and availability of exergy increase as a viable option to entirely substitute fossil fuel energies by renewable energies through the electro-magnetic conversion.

3.2.1 Ceramic ferrites and neodymium magnets

Ferromagnetic materials have been regarded as highly important electronic materials for more than half a century. During this time, the characteristics of commercial ferrite materials, both soft and hard ferrites, have come to approach theoretical values. The quality of commercial ferrites has been improved through accumulated scientific knowledge and advanced technology [33]. Further, when the ferrites reach the boundary magnetic saturation B_{sat} (**Figure 6**), is because the magnetic momentums of all the particles are entirely aligned. Consequently, so that it happens, it is necessary to induce much more energy to the material by increasing the cost. However, the advantage to magnetically saturate the whole material is low, since there exists a small difference by not to doing so.

The ceramic ferrites are made by using iron oxide powder. The formula is X_n (Fe_2O_3), where X can be either B or Sr. and $5.8 < n < 6.0$ to improve the alignment of the crystal structure. After the milling, the powder is compressed in a matrix with a magnetic field applied. The compacted powder is then synthesized at $1100\text{--}1300^\circ\text{C}$ [31]. Further, the permanent magnetism in ceramic ferrites is based on the anisotropy magnetocrystalline. **Figure 5** shows the demagnetization diagram of these materials.

On the other hand, the production of neodymium-iron-boron is cheaper than producing cobalt-samarium magnets. Indeed, iron is a transition metal much cheaper than cobalt, and neodymium is a rare light earth which is much more abundant than samarium. In various tests, boron formed a ternary compound with strong uniaxial magnetocrystalline anisotropy, demonstrating a higher operating temperature [34].

Additionally, the approximated formula is $\text{Nd}_2\text{Fe}_{14}\text{B}$, which states the best combination of magnetic and thermic properties. These magnets have different combinations in Nd and Fe proportions, producing a wide range of available properties.

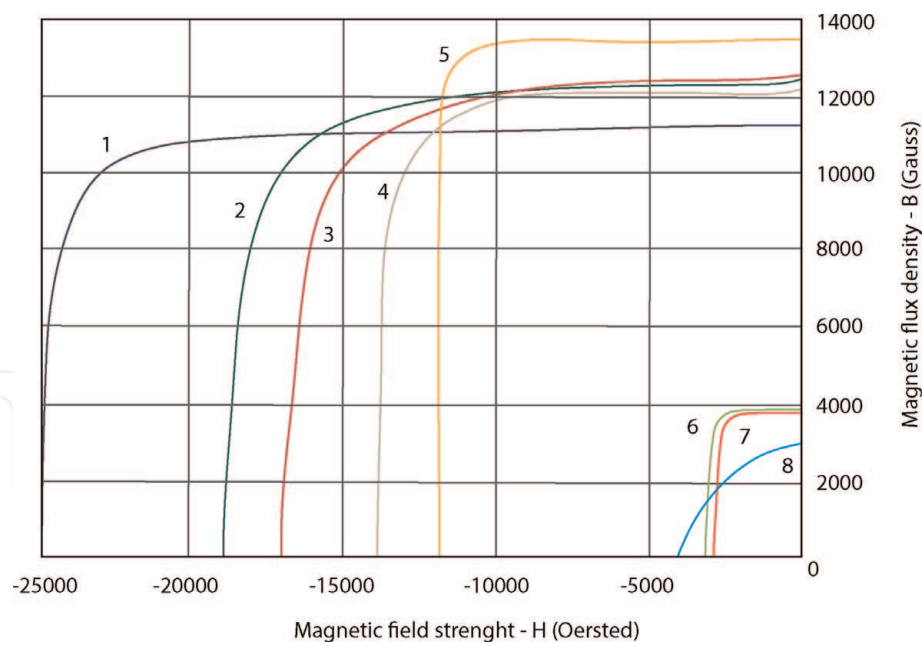


Figure 5.
Demagnetization graph of ceramic ferrites and NdFeB magnets [35].

These properties are presented in different values of magnetic flux (G) and magnetic field strength (Oe); **Figure 5** shows the demagnetization curves for various combinations of NdFeB [35].

3.2.2 Demagnetization of magnetic materials

The demagnetization of ceramic ferrites and NdFeB magnets is compared, where **Figure 5** shows the powerful magnetic flux density and magnetic field strength of NdFeB magnets against the ceramic ferrite magnets [36].

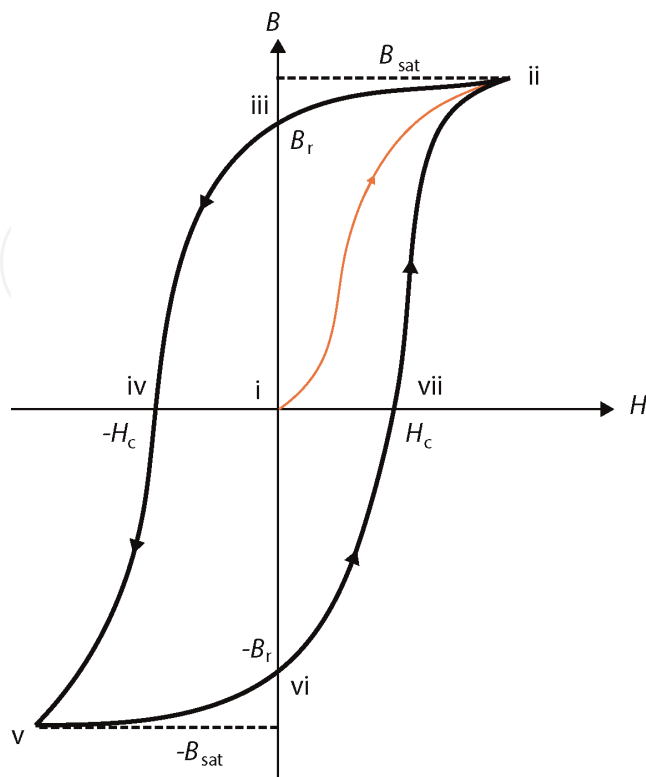


Figure 6.
Initial magnetization curve with magnetic saturation state [32].

According to the demagnetization graph, the materials represented by the numeric value are: (1) $\text{Nd}_{31}\text{Fe}_{25}\text{B}$, (2) $\text{Nd}_{35}\text{Fe}_{19}\text{B}$, (3) $\text{Nd}_{38}\text{Fe}_{17}\text{B}$, (4) $\text{Nd}_{40}\text{Fe}_{14}\text{B}$, (5) $\text{Nd}_{44}\text{Fe}_{12}\text{B}$, (6) $\text{SrFe}_{12}\text{O}_{19}$, (7) mild steel, and (8) molten iron. Meanwhile, to change the Gauss units to Tesla, it is only necessary to multiply it by 10^{-4} T. Thereby, it is necessary to regard that the maximum magnetic field B in a ferrite magnet $\text{SrFe}_{12}\text{O}_{19}$ is 3900 G with a magnetic field strength of 3450 Oe [37].

The normal magnetization curve determines the magnetic flux density B that the magnet generates according to the demagnetization force value H. As H is closest to the reversion value $-H_c$ (**Figure 6**), the flux density decreases until it drops quickly by passing the crest of the curve. Thus, in practical applications, the magnet should be kept over the crest to obtain a useful magnetic flux [32].

Nevertheless, when selecting a material for permanent magnet uses, the idea is to have three characteristics such as high remanence to obtain a greater magnetic flux, high coercivity to avoid the magnet from demagnetizing easily, and the maximum energy point to require less material to generate the magnetic flux [32]. Of course, it is not possible to possess these characteristics simultaneously. Likewise, a hard material with high remanence and coercivity presents a hysteresis cycle of great surface, implying high anergy. Therefore, this is the reason to use soft materials that use alternating current, resulting in narrow hysteresis cycles and lessen losses. Further, the hard materials are utilized in applications where the permanent magnets are not exposed to magnetizing-demagnetizing cycles.

4. Magnetic hysteresis

Demagnetized materials can be magnetized when the material is placed in an existing magnetic field space. Indeed, the magnetization varies when the applied field varies. Moreover, a magnetic domain rotation of the material starts as the magnetization process occurs. Thus, the rotation domains yield to align with the applied field. This process has lessened energy consumption; hence, the magnetization curve has a rapid increment of magnetic values. Additionally, the next step is the orientation of the magnetic domains which have not been completely aligned yet. The process involves a greater expenditure of energy, and thereby, the magnetization curve increases slower. Thus, it comes to a moment where all the domains of the material are aligned with the applied field and this final process is named magnetic saturation [24].

The nonlinearity magnetization curve consequently yields to magnetic domain deformation due to the thermodynamic characteristics as well as the interaction between each other [38].

According to **Figure 6**, the demagnetized state (i) indicates that every time the emf H arises, more domains are being parallelly aligned until all of them are aligned in the saturation state (ii) where there exists an induction field B_{sat} . At this point, if the emf is increased, then no more alignments will occur. In contrast, if the induced emf is decreased due to the saturation state (ii), the system does not follow the same trajectory. The reason is because the alignment domain mechanism, the border domain movements, and the thermal agitation are highly nonlinear mechanisms.

Equally, when the emf is equal to zero (iii), the material stays magnetized, generating a residual induction field B_r known as remanence. Hence, if the emf increases with negative values, the material is demagnetized effectively until reaching the coercivity value $-H_c$ (iv). Thereby, a new saturation is generated but in the opposite sense (v). This behavior is repeated over a symmetric curve in (vi) and (vii) sections [32].

The energy systems follow the same pattern, known as the hysteresis cycle. The material magnetization is made at the expense of energy, dissipated in heat form due to the border domain alterations. Furthermore, when a hysteresis cycle takes place in a material, it experiments an energy delivery by volume unit in heat form, equal to the hysteresis cycle [24]. However, the energy losses are much lower than in a thermal machine.

Additionally, the ferrite magnet keeps a magnetization $+B_{sat}$ until an inverse field of magnitude $-H_c$. Thus, the magnetization becomes unstable and decreases to $-B_{sat}$. Thereby, a new field $+H_c$ is required to apply so that the magnetization increases to $+B_{sat}$. Likewise, the first quadrant represents the initial magnetization region, whereas the second quadrant represents the region in which the magnet does the work against an applied reverse field with a lower value than $-H_c$ [32].

The presented plane in **Figure 6** has three main considerations for the technological application design [32]:

- Maximum energy point BH_{max} , which is exactly at half way between B_r and $-H_c$ over the second quadrant. This property has a value of $BH_{max} = \mu_0 (1/2 M_{sat})^2$. It also represents the maximum energy density that a magnet can stock.
- Coercivity H_c is the intersection of the curve with the $-H$ axis. An ideal material would be $H_c = M_{sat}$; however, an emf is required to set aside the magnetic flux inside the magnet. This property states the capacity of a magnet to stand demagnetizing factors.
- Remanence B_r is the intersection with $+B$ axis. An ideal material has $B_r = \mu_0 M_{sat}$. Nonetheless, B_r is the magnetic flux density value when the magnet has not emf ($B_r \rightarrow H = 0$). The remanence is an index of the capability of the material as permanent magnet.

Henceforth, the behavior of a magnet can be described and restricted to the second quadrant of the demagnetization curve.

5. Development diagram for electromagnetic systems

Ferromagnetic materials have a relative permeability of several hundred thousands over paramagnetic and diamagnetic materials. Indeed, these materials are strongly attracted by external magnetic fields. For instance, the permanent magnets and the iron structure (stator) in which the coils are placed inside an electric generator cause the effect to generate greater and denser time-varying magnetic fields according to the magnetic flux and electric fields characterized by the magnetic hysteresis and attributed to the magnetic alignment dipoles.

Namely, the main steps to design electromagnetic energy systems are shown in a cycling way in **Figure 7**. It is necessary to use all the physical laws and elements written inside the circle so that any design works properly. Usually, this scheme may regard either rotational or linear oscillatory velocities.

Specifically, each step is described as follows:

- Select the magnet type and magnet shape to use in the core. This is the most important step because from here, the rotation direction (if any), coil position, and basically the whole design are defined. Although the three magnetic characteristics are not possible to be present simultaneously, either select or if possible design a permanent magnet with the closest characteristics of high

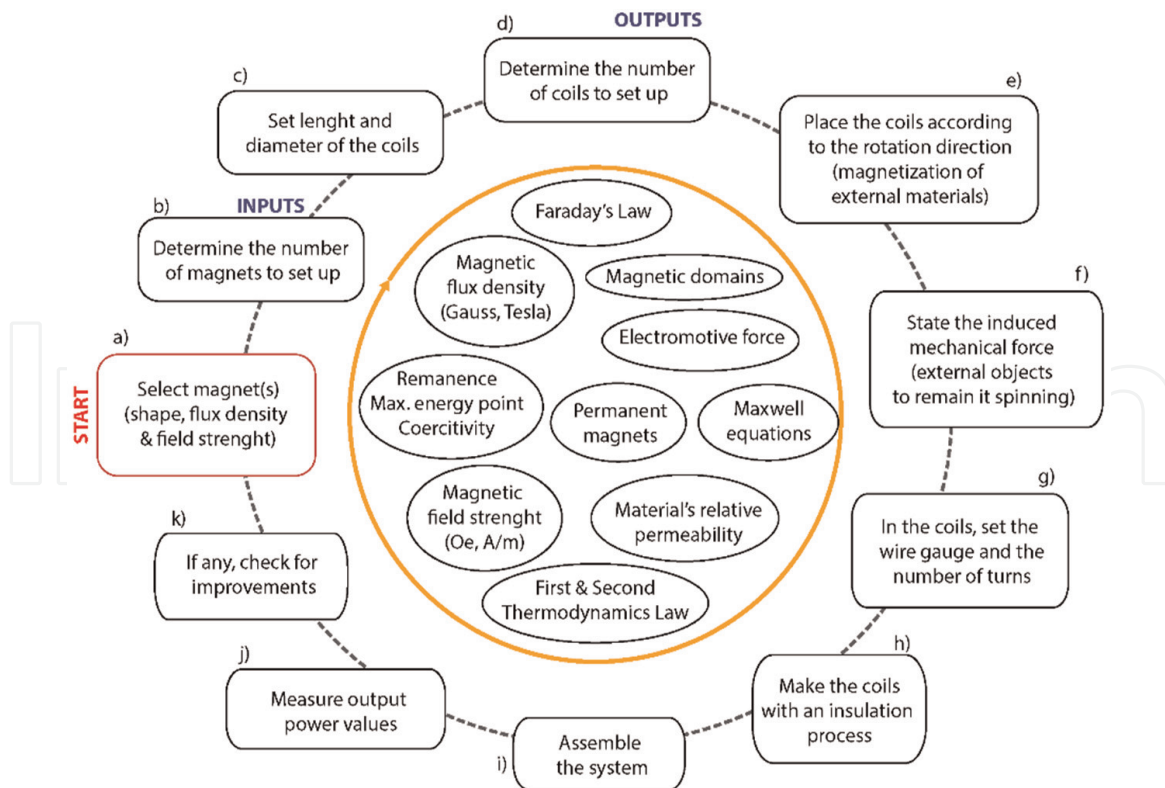


Figure 7.
Diagram for power generator design.

coercivity (to avoid the magnet from demagnetizing easily), maximum energy point (to require less magnetic material to generate a magnetic flux), and high remanence (to obtain a greater magnetic flux).

- b. Determine the number of magnets (inputs) and poles. The selection validation is related with both, the desired values and design to satisfy the energetical necessities. If it is designed for low power generation, then, a small magnetic value is suggested and vice versa. At this point, the electromagnetic machine may be designed as a variable efficiency energy system to harness most of the induced mechanical energy as much as possible, for instance, the variable distance among the magnets and coils.
- c. Set the preferred diameter as well as the desired length of the coil. These measures are proportional to the magnet size. If in the simulation, the system has a low quantity of magnetic dipole alignment, then it is suggested to perform the design. Nonetheless, if it is designed for high power applications, then high magnetic values are desired as well as a greater mechanical energy. Of course, the design can be set by shunts instead of coils. This kind of design will deliver a very efficient energy system and therefore, good quality and availability of energy.
- d. Determine the total number of coils (outputs). This step will determine the number of preferred phases and the consecutive connection in which the energy system will be generating energy. In this point, an exergy analysis can be made to study the energy that will be lost during the hysteresis of the system. Both thermal conditions and turns of the induced coils must be regarded as well.

- e. Place the coils according to the rotation of the magnet. The coils can be placed either horizontally or vertically. The aim is to get the best position for the straightest magnetic alignment of the materials in each rotation.
- f. State the mechanical force induced to the system and the approximated time in which the system will remain functioning. Additional, either rotational or linear, movements of the material may apply.
- g. Set the wire gauge and the number of turns per coil. This step will determine the output resistance. In addition, use Ohm's law to determine the desired output voltage, previously set in step one.
- h. Make the coils with its respective insulating method to avoid losses by short circuit.
- i. Assemble the system by setting up the magnet in a desired distance from the coils without colliding. The distance will determine how efficient the system will be. For instance, if it is too close, then there will be a great magnetic interaction so that a great time-varying magnetic field is assured for a better mechanical energy conversion.
- j. Measure the generated output power values.
- k. If any, check for necessary improvements and start over.

Meanwhile, this diagram represents the predecessor of the design, before making accurate final measures. Of course, either simulating programs or CAD software designing is necessary to project the functionality of the system. **Figure 7** explains the feasibility to design electric machines according to the desired application. Equally, the electromagnetic transduction and thermodynamic laws apply for any power generator development.

Likewise, it is important to define the number of desired poles since this property determines the effectiveness of the designed system. Thus, a system with lesser number of poles can generate energy at greater velocities than if the system is structured with a greater number of poles since it would carry out to slow down the velocity caused by the Lorentz forces and low velocities would take effect. Moreover, the addition of poles in the design yields to change the magnet's shape with the aim to design freely a power generation system with the highest magnetic values, and consequently, a very efficient power source.

The aim of using any electric machine is to increase efficiency to generate much more energy to satisfy the increasing energy demand. Of course, the necessity to manufacture variable efficiency power generators can result in overcoming the power generation with the current rotational velocities permitted. In consequence, the results are the reliability and durability that these electric machines can provide, by designing a power generator since the beginning. Hence, there are a few options to regard:

- The development of a model according to the output power needed.
- Additionally, the sum of energy systems is permitted to reach the targeted power.
- The possibility to harness rotatory mechanical energy by connecting several generators serially.

- The option to connect different number of phases according to the power consuming application.
- Voltage fluctuations and rotational velocities are allowed but with the aim to harvest energy.
- A contribution to renewable energies by the creation of an environmentally friendly option to power supply. Furthermore, to generate exergy in places where it is difficult to supply energy.
- The conversion of mechanical energy beyond velocity ranges of current generators.
- The development of customized generators by implementing the development diagram to be assembled anywhere and by anyone.
- The result of creating an optional power source for real life situations.
- The possibility of low lifetime maintenance and costs.

These points must be accomplished with the aim to target energy necessities around the world. The use of renewable energies will cause an effect on reducing pollution eventually. Hereafter, the development of electric machinery instead of combustion generators is a step forward to evolve more efficient technologies.

5.1 Equivalent circuit

The design of electric machinery according to the diagram in **Figure 7** has implicitly an equivalent circuit. The electrical characteristics of the implemented circuit are described by the designer. The equivalent circuit is the general representation of usual designs by implementing the previously addressed materials. Indeed, it is stated that the output voltage made from a design would be a sinusoidal wave (AC Voltage— V_ϕ). Additionally, the permanent magnet is represented as a variability VAR, since in every time-varying magnetic field, there exist an electric current [39]. Moreover, the separation between the iron screw and the ferrite magnet is represented by the air gap, necessarily for both, to prevent the magnet from colliding and determine the efficiency of the system (**Figure 8**).

As the harvested energy is generated by the movement of a varying magnetic field, the electrical frequency is taken as

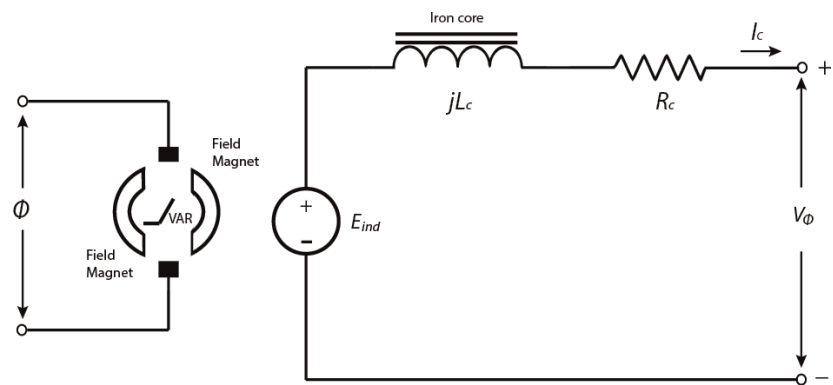


Figure 8.
Equivalent circuit of a modeled generator.

$$f_e = \frac{p \cdot \omega}{2\pi} \quad (1)$$

where p is the number of poles and ω is the angular velocity in radians. Of course, a single conversion can be made in Eq. (1) to calculate it with a linear velocity [40].

By knowing the N_c turns in a coil, where it is placed around a magnetic field \emptyset , the induced energy in the coil will be

$$e_c = N_c \emptyset \omega \cos \omega t \quad (2)$$

Accordingly, the peak voltage can be calculated as

$$V_{peak} = N_c \emptyset \omega = 2\pi N_c \emptyset f_e \quad (3)$$

Thus, the induced energy in RMS is stated as

$$E_{ind} = \frac{2\pi}{\sqrt{2}} N_c \emptyset f_e = \sqrt{2} \pi N_c \emptyset f_e \quad (4)$$

Therefore, as the stator is considered as the armature structure in the designs, the internally generated voltage in a single phase E_{ind} (from one to n -number of serially connected coils) is not usually the output voltage V_{\emptyset} , due to the resistance of the materials and the distortion caused by the air gap magnetic field [40] and in this case, the space between the permanent magnet and the armature (**Figure 8**).

According to **Figure 6**, the load current I_c generates a magnetic field B in the coil that will generate a voltage reaction named E_{coil} . Furthermore, a voltage reaction E_{ind} is induced by the time-varying magnetic field every time there exists an alignment of the magnetic domains [41].

Hence, the output voltage per phase is stated by

$$V_{\emptyset} = E_{ind} + E_{coil} \quad (5)$$

Thereby, the induced energy in the circuit can be modeled by

$$E_{coil} = -jL_c I_c \quad (6)$$

where V_{\emptyset} represents the voltage generated. Because of Eq. (5) and Eq. (6), the output voltage is

$$V_{\emptyset} = E_{ind} - jL_c I_c \quad (7)$$

Thus, the equivalent current regarding the output resistance of the connected coils is

$$V_{\emptyset} = E_{ind} - jL_c I_c - R_c I_c \quad (8)$$

Therefore, the output voltage per phase results to be

$$V_{\emptyset} = \sqrt{2} \pi N_c \emptyset f_e - I_c (jL_c + R_c) \quad (9)$$

In contrast, it is assumed that in each interaction, a time-varying magnetic field crosses the coils, so that the magnetic flux is uniform and the emf is distributed evenly throughout each coil.

The efficiency of any electric machine can be immediately perceived on the hardness to move the magnets in accordance with the coils, for instance, the harder, the more efficient, and vice versa. Although the electromagnetic generators are a simple application of Faraday's law, they are a useful tool to satisfy present needs for energy source applications for dynamic systems without pollution.

One great advantage of these electromagnetic systems is that they are frictionless, so there is no weathering of the pieces, excepting the friction on the axis where rotation occurs and Lorentz damping forces. Thus, the cost-benefit increases, thanks to lower lifetime maintenance expense and long endurance. This is the future drive technology of the next years to come for a better-quality energy and more availability every time the energy is required as a tool to the energy shortage. Therefore, these designs are the benchmark for configurable generators, making a step forward in the evolutions of power system generators immersed in novel power cycles.

Finally, it is important to apply an exergy analysis at the process and component level. In consequence, it allows identifying, locating, and quantifying the main irreversible causes of thermodynamics of a system or process, through the study of exergy destruction and efficiency. Moreover, as the exergy is the available part of the energy used to produce useful work, it represents a powerful tool to determine potential improvements and optimization of processes with electromagnetic transduction application, as well as the mitigation of environmental concerns which results in a measure of the imbalance with the environment.

6. Conclusions

An exergy balance is the combination of the energy balance and entropy, since they are derived from the first and second principles of thermodynamics. However, it is an additional tool to make efficient the second law of thermodynamics.

Meanwhile, as an alternative to the increasing principle of entropy, the second law can state that the only processes that an isolated system can experience are those in which the exergy of the system decreases.

The balance of exergy is a very useful method of analysis when assessing the energy performance of a system by giving a broader vision than a thermal performance. Further, it allows evaluating the losses of energy in a process, the energy that will be utilized from outgoing flows in an open system and the advantages of regenerative methods in machines that get heated up easily. If a thermal machine is not performing with additional procedures to increase efficiency, then the option to replace it by a new technology that accomplishes energy necessities will take effect.

Nonetheless, since electromagnetic transduction has demonstrated to have a better performance than thermal machines, renewable energies and efficient power-consuming systems may replace them in its whole. For instance, ferromagnetic materials have a relative permeability of several hundred thousands, and they are strongly attracted by magnetic fields. This is the reason to employ ferromagnetic materials instead of paramagnetic and diamagnetic materials, causing the effect to generate time-varying magnetic fields, according to both, the magnetic flux and electric fields characteristics of ceramic ferrites. However, it has been outlined that neodymium magnets are magnetically three hundred times denser and stronger. This effect is possible, thanks to the relative permeability and magnetic susceptibility properties of these rare-earth magnets.

In recent years, the necessity to develop and to design novel renewable energy systems has been on the rise due to environmental impact by fossil fuels and the eventual depletion of the reserves of this hydrocarbon. In the meantime, these

materials are more adaptable for electric field distribution. Further, by harnessing the mechanical energy, it is possible to power supply in a practical form several real-life applications. The required material is by implementing either coils or shunts and magnets in the system designing.

In contrast, the resulting output power depends crucially on the design, the covered area among the magnet and coils, the lineal or angular velocity induced, the relative permeability of the implemented materials, and the time-varying magnetic field generated, as well as the magnetic flux density and magnetic field strength of the magnets. The designs can be a part of a larger mechanical conversion energy system as they require an external mechanical force to harvest the energy from wind, tidal, or hydraulic energy systems. Furthermore, the characteristics of the implemented materials may either increase or decrease the performance of the power generation systems.

The electromagnetic transduction represents a modern background among renewable energy power systems, exergy analysis, and the electromagnetic engineering concepts to ensure long endurance, instant energy generation, efficiency, performance, and optimization of the energy. The applications would primarily be focused on low power consumption but projected to be for high power applications with the aim to enable more effective systems than current technologies over the 30 to 50 years to come.

Conflict of interest

The author declares no conflicts of interest.

Appendices and nomenclature

B	magnetic field
BMS	battery management system
E	electric field
emf	electromotive force
G	Gauss—magnetic flux density
H	magnetic field strength
M _{sat}	magnetization saturation
NdFeB	neodymium magnet
Oe	Oersted—magnetic strength
Ø _m	time-varying magnetic field
rpm	revolution per minute
T	tesla
μ	air permeability
μ ₀	relative permeability
V	output voltage
W	Watt
W/kg	specific power
W/m ³	power density
X _m	magnetic susceptibility

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Author details

Eduardo Torres-Sánchez
Tecnológico de Monterrey, Mexico City, Mexico

*Address all correspondence to: e89.torres10@gmail.com

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