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Dynamic Analysis and Induced Voltage of an Electric Generator for Microgeneration

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--***ABSTRACT***--
In this work the mathematical modeling is done and the results of the simulation of a generator for microgeneration of electrical energy are presented. The induced voltage in the generator is calculated and compared with the voltage generated by the digital simulation model. This is done in order to analyze the viability of using a power generating system, driven by the continuous flow of passersby on a certain surface. The development of the analysis is based on the creation of a mathematical model and simulation with the help of software that operates with the finite element method. This is done in order to know and compare the voltage generated by the microgenerator and the one calculated with the mathematical model.
KEYWORDS: *Mathematical modeling, Electric generator, Induced voltage, Microgeneration, Simulation.*

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I. INTRODUCTION

Today, renewable energy technologies have shown great development in different global regions, with the presence of bioenergy, hydroelectricity, wind, among others, one of the most important being solar energy. Renewable energy sources are generally considered sustainable for the simple fact of being inexhaustible, and it is unlikely that the rate of exploitation carried out by man will approach the rate of replacement of nature. However, the use of this type of energy is subject to various technical limitations [1].

Renewable energies are favorable in the sense that their social and environmental impact is friendlier than that of fossil fuels, however, renewable sources are less concentrated than those of fossil fuels, so that large areas are required for their production. This entails a greater visual impact as is the case with wind turbines. Likewise, the monetary cost of some renewable sources is higher than traditional fuels, so it is necessary to reduce this economic gap directly affected by the increase in the price of fossil fuels, a situation that has been occurring in recent years. In this way, renewable sources begin to attract an important part of the world market [2].

Microgeneration is the development of small generation centers located as close as possible to the consumption center. It is the generation of electrical energy on a small scale that can be obtained mainly from the

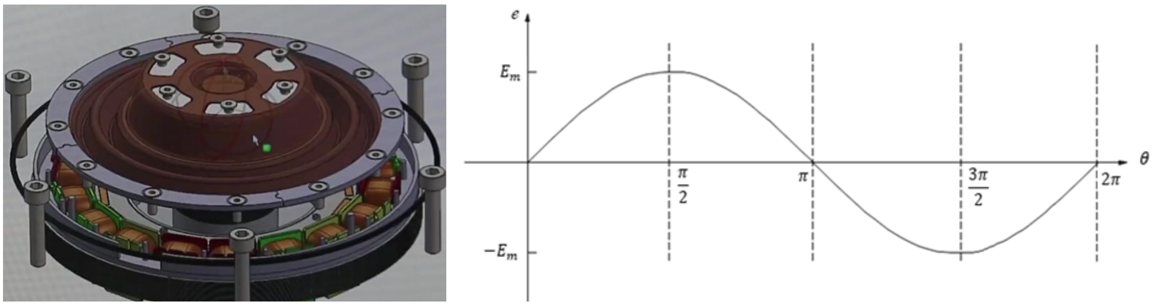
wind or the sun, however, there are other ways to obtain it, such as piezoelectricity. It includes small power equipment and the cost of installation, as well as the complexity of this is significantly lower than traditional methods. This type of generation manages to reduce consumption by up to *40%* since it eliminates losses in the transport of energy. It is a type of technology called distributed generation. Within the microgeneration of energy, there are different benefits for its application both for the user and for the electrical network, such as supply in remote areas, efficient use of energy, increased reliability, reduction of losses in transmission and distribution, reduction of polluting emissions, lower cost, among others [3].

The trend indicates that generators that produce electricity with fossil fuels will be obliged to gradually and on a scheduled basis replace their generation facilities that exceed the limits established by the regulations, with generation facilities that comply with the regulations on polluting emissions, giving rise to that new technologies emerge in search of satisfying this new niche of opportunity to promote the generation of pollutant-free energy. It is necessary to plan a future with a greater presence of distributed energy, where the growth trend points to the use of renewable energies in both developed and developing countries.

II. MODELED GENERATOR

Next, the type of generator that will be modeled is shown, considering an application of power generation by the flow of people in a given space.

In the generator to be analyzed, the magnetic field is produced by a series of permanent magnets where the main advantage is that an external excitation system is not required, allowing the machine to be smaller and not show any type of energy consumption. In figure 1 you can see the distribution of the coils, where the induced *electromotive force (emf)* is found. The coils are positioned on the generator stator. A coil of a turn is posed, placed in a constant magnetic field established by two permanent magnets.



a) Scheme of the proposed electric generator [4]. **b)** Induced voltage in the coil.

Figure 1. Generator and induced voltaje.

Assuming that the coil has rotated *90* mechanical degrees from its initial position, the flux that links is minimal, however, the rate of change is maximum so the voltage at this point would be maximum. If the rotation continues, the flow will present an increase, so the rate of change will decrease until it reaches zero and it will repeat the same process with the difference that the polarity of the induced *emf* will be the opposite of the first phase. Thus, it is possible to generate alternating electrical voltage from the relative movement of a coil and a magnetic field [5, 6, 7]. Figure 1b) shows the voltage signal induced in the coil by the movement of the magnetic field. For more details on the proposed generator see references [4, 8].

III. MATHEMATICAL MODELING

According to the construction of the generator, figure 2 shows an illustrative diagram of the rotor and stator with concentrated coils. The generator has *18 magnets* on the rotor that alternate their polarity based on their location, and will directly affect *18 coils* wound in *18 slots* in the stator. The stator has a diameter of *16.5 cm* and *18 slots*, each *1.5 cm* wide, on which the coils are placed. The rotor has a *9.52 cm* diameter and *18 poles* each *1.5 cm* wide corresponding to the dimensions of the slots in the stator.

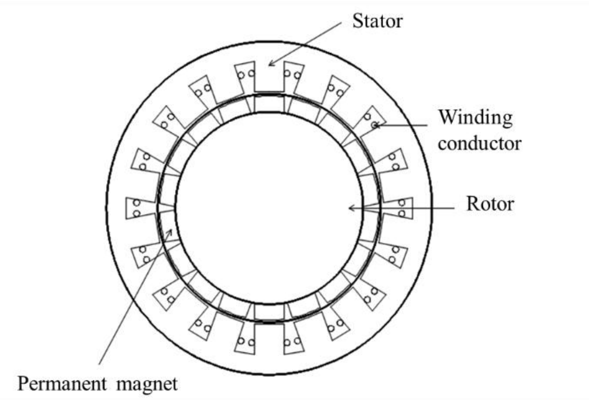


Figure 2. Constitution of the generator.

Because the rotating magnetic field in the machine will be generated by permanent magnets placed on the rotor, the magnetic field can be considered to be variable in time. It is proposed that since the complete coil is positioned below the area that each magnet subtends, the polar flux will be used to the maximum, allowing a higher magnitude *emf* to be obtained. Because the magnetic material is in series with the air gap, the reluctances of the rotor and stator are very small compared to that of the air gap, and the distance between the air gap is assumed to be very small.

For the development of the model, the following will be considered:

- *The flux per pole is constant in any nearby region under its subtended area.*
- *The magnetic flux will only circulate through the magnetic material without loss.*

- *The air gap is small, continuous and uniform.*
- *The magnetic flux density is uniform within the magnetic material.*
- *There is no type of flux dispersion.*

Since the induction phenomenon is produced by a dynamic event, it will be considered from the approach of *the emf equation of motion of Faraday's law*. In order to simplify the mathematical development and understanding it was decided to develop the equations from the analysis of a single turn coil.

Starting from the geometry of the generator and the aforementioned considerations, it is known that the rotor section of the machine is the magnetic field and the coil is stationary. The plane of the coil positioned perpendicular to the flux lines is momentarily affected during the rotation of the rotor by a north pole and later by a south pole. Given this principle, to facilitate the approach of the phenomenon, it will be assumed that the coil is the dynamic element and the field is stationary. In this way, the same event is posed in a different scheme where the proposed source of magnetic flux is bipolar.

In this case the magnetic field is constant and has a direction from north to south. It is stated that the turn is square. Given that the turn has a geometry in which each section of it is affected by the magnetic field in a different way, illustrated in figure 3a), each segment will be analyzed, the total induced *emf* being the sum of the emf of each section.

The induced stress in each section can be calculated according to equation (1):

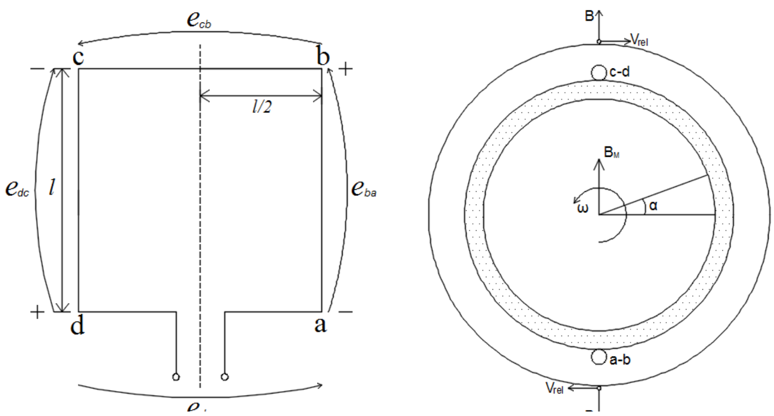
$$e_{ind} = (v \times B) \cdot l$$

1)

Where:

v: Movement speed.
B: Flux density.
l: Length of the turn.

However, this equation was derived for the case of a conductor moving in a stationary field, so it is necessary to make certain adjustments to be able to apply it to this particular case. First, it is stated that the single-turn coil is stationary and the magnetic field rotates as found in the study system. The air gap is small, continuous and uniform.



a) Induced *emf* in a square turn. **b)** Static field reference frame.

Figure 3. Induced *emf* and Static field.

Since the magnetic field is mobile, it is proposed that the magnitude of the vector $\boldsymbol{B}$ varies sinusoidally in the air gap with respect to a mechanical angle of rotation. Furthermore, this vector is always directed radially outside the machine. If $\boldsymbol{\alpha}$ is the angle measured from the direction of zero flow to the partial position of the rotor in the motion path, then.

$$B = B_M sen(\alpha) \tag{2}$$

Since the rotor moves at a specific angular velocity during its operation, the magnitude of the flux density vector $\boldsymbol{B}$ at any $\boldsymbol{\alpha}$ angle around the stator is given by:

$$B = B_M sen(\omega_m \mathrm{t} + \alpha)$$

3)

To apply the equation of *emf* of motion, it is required to be in a frame of reference where the field is static. When positioned on the field vector and it appears to be stationary, the sides of the loop will appear to move at a relative speed V_{rel}, as shown in figure 3b). Since the velocity and the magnetic field are stated from the point of view of a stationary magnetic field and a moving wire, the *Faraday* equation of motion can be applied. The total induced voltage in the coil will be the sum of the induced *emf* on each of its sides.

These voltages are determined as shown below:

1. ***Section ab***

For *ab* segment, $\alpha = 270°$. Considering that vector *B* is directed radially out of the rotor and the speed to be considered is the tangential speed of the loop, the cross product $(v \times B)$ generates a vector in the direction of *l* so that:

$$e_{ab} = (v \times B) \cdot l \tag{4)}$$

$$e_{ab} = vBl \quad \text{in the direction of } z \tag{5)}$$

given that

$$B = B_M sen(\omega_m \mathrm{t} + \alpha) \tag{6)}$$

then

$$e_{ab} = -vB_M lsen(\omega_m \mathrm{t} + 270°) \tag{7)}$$

Where the minus sign reflects that the polarity of the *emf* is the inverse of the assumption. In the direction of *b* to *a*.

2. ***Section bc***

For the *bc* segment, the vector $(v \times B)$is directed in the direction of the *z* axis, since the length of this section is in the *x* direction, $(v \times B)$is perpendicular to *l* and therefore the voltage will be zero.

$$e_{bc} = (v \times B) \cdot l = 0 \tag{8)}$$

3. ***Section cd***

For *cd* segment, $\alpha = 90°$. Considering that vector *B* is directed radially out of the rotor, the cross product $(v \times B)$ generates a vector in the direction of *l* as in *ab* segment, so:

$$e_{cd} = (v \times B) \cdot l \tag{9}$$

$$e_{cd} = vBl \quad \text{in the direction of } z \tag{10}$$

given that

$$B = B_M sen(\omega_m \mathrm{t} + \alpha) \tag{11)}$$

then

$$e_{cd} = vB_M lsen(\omega_m \mathrm{t} + 90°) \tag{12)}$$

4. ***Section da***

For the *da* segment, the vector $(v \times B)$ is directed in the direction of the *z* axis, since the length of said section is in the direction of x like the *bc* segment, $(v \times B)$ is perpendicular to and therefore the voltage will be zero.

$$e_{da} = (v \times B) \cdot l = 0 \tag{13}$$

Therefore, the total tension in the coil will be:

$$e_{ind} = e_{ab} + e_{cd}$$

$$e_{ind} = -vB_M lsen(\omega_m \mathrm{t} + 270°) + vB_M lsen(\omega_m \mathrm{t} + 90°) \tag{14)}$$

15)

$$e_{ind} = -vB_M lsen(\omega_m t - 90°) + vB_M lsen(\omega_m t + 90°)$$

16)

Applying trigonometric identities:

$$e_{ind} = vB_M lcos(\omega_m t) + vB_M lcos(\omega_m t)$$

17)

$$e_{ind} = 2vB_M lcos(\omega_m t)$$

18)

Since the tangential velocity is defined by

$$v_{tan} = \omega_m r$$

19)

Substituting equation 19 into equation 18.

$$e_{ind} = 2(\omega_m r)B_M lcos(\omega_m t)$$

(20)

$$e_{ind} = B_M\ \omega_m l^2 cos(\omega_m t)$$

21)

If the coil has N_N number of turns

$$e_{ind} = N_N B_M\ \omega_m l^2 cos(\omega_m t)$$

22)

and

$$\omega_m = 2\pi f_m$$

23)

Substituting equation 23 into equation 22:

$$e_{ind} = 2\pi N_N B_M\ f_m l^2 cos(\omega_m t)$$

24)

From the equation of synchronous speed, the frequency is solved:

$$f = \frac{nP}{120}$$

25)

Where

n: Rotation speed in rpm.
P: Number of poles.

Substituting equation 25 into equation 24:

$$e_{ind} = \frac{\pi P N_N B_M n l^2 cos(\omega_m t)}{60}$$

26)

Because the generator has *18 poles*, simplifying equation 26:

$$e_{ind} = 0.3\pi N_N B_M n l^2 cos(\omega_m t)$$

27)

Where

e_{ind}: Induced voltage in the coil
N_N: Number of turns of the coil.
B_M: Magnetic flux density.
n: Machine rotation speed.
l: Length of a wound coil segment.

IV. CONSIDERATIONS OF THE DIGITAL MODEL

For the execution of the simulation, certain considerations were taken into account, in order to facilitate information processing and simplify the study:

- It is suggested that there is a wound coil per slot, so there are 18 coils in the stator. For simulation purposes, each coil has a single turn, which are connected in series to obtain a considerable voltage level.
- In order to be able to observe the behavior of the machine and the generated voltage curve, the speed at which the machine rotates is 60 rpm. This speed is a requirement for the model to function properly.
- It is considered that the generation occurs on the coil sides.
- The material selected for the stator and rotor cores will not present magnetic saturation and therefore there will be no losses.

Permanent Magnets: It was assumed that the permanent magnets that are the source of the magnetic flux that will allow the induction of an electromotive force in the coils, are made of neodymium, due to its high magnitude of remanence B_r and its high coercivity H_c.

According to the required dimensions and seeking to obtain the highest possible remanence, it is assumed that the rotor magnets are neodymium magnets, with dimensions of *15 mm* wide by *15 mm* long by *8 mm* high, block type, with nickel plating, B_r remanence between *1.29 to 1.32 Teslas[T]* and *N42* magnetization. The designation *N42* is a relative measure of the quality of the material used in the manufacture of the magnet. The 42 corresponds to the maximum energy product of the magnet being approximately $334\ kJ / m^2$ while the letter *N* refers to the maximum temperature of use, which in this case the magnet can be exposed to temperatures of up to *80° C*.

For the realization of the digital model it is required to follow a series of steps and program configurations in order to guarantee that the system converges correctly to the desired study. The following configurations are made:

- *Import of CAD (Computer Aided Design) file*
- *Definition of parameters*
- *Model couplings*
- *Material configuration*
- *Rotation settings*
- *Permanent magnet and core properties*
- *Mesh structure*
- *Establishment of variables*
- *Running simulation*

V. VOLTAGE CALCULATION PER GENERATOR UNIT

Starting from mathematical modeling, the corresponding calculations are presented to show the voltage produced by each generation unit. The calculation is referred to the voltage level and is developed in order to show the theoretical value of the induced electromotive force that must be presented by each generator. The voltage generated in a coil is given by equation 27, from which it is desired to calculate the magnitude of the peak voltage V_P. Therefore:

$$V_P = 0.3\pi N_N B_M n l^2 \tag{28)}$$

The magnitude of the variable $\boldsymbol{B_M}$ is obtained by taking an average of the flux density in the slot observed in the simulation based on the finite element calculation at time *0.03 [s]*, moment where the peak stress value occurs. Figure 4 shows the $\boldsymbol{B_M}$ distribution.

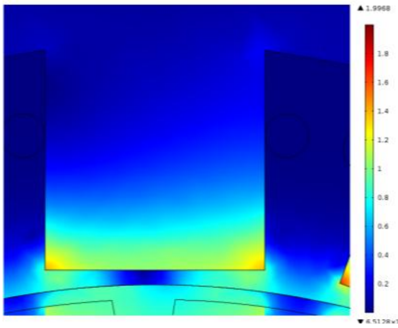


Figure 4. Flux density distribution in the slot when the peak stress value occurs.

Table 1 shows the magnetic flux density intensities in the slot when divided into 3 sections.

Table 1. Flux density in different sections of the slot.

SECTION	FLUX DENSITY [*T*]
lower	1.2
middle	0.6
upper	0.3

Determining the average magnitude present in the area enclosed by the coils:

$$B_M = \frac{(1.2 + 0.6 + 0.3)}{3} = \mathbf{0.7[T]}$$

Table 2 indicates the magnitudes of the variables for calculating the peak voltage per coil.

Table 2. Assignment of numerical values to model variables.

VARIABLE	VALUE
N_N	1 *turn*
B_M	0.7 [T]
n	60 [rpm]
l^2	2.25×10^{-4} [m^2]

Substituting these values in equation 28:

$$V_P = 0.3 * \pi * 1 * 0.7 * 60 * 2.25 \times 10^{-4} = \mathbf{0.0089}\ [\boldsymbol{V}]$$

As the generator has 18 coils of 1 turn connected in series, the peak voltage of the generator is given by:

$$V_{PG} = 18V_{PB} = 18 * 0.0089 = \mathbf{0.1603}\ [\boldsymbol{V}] \tag{29}$$

The peak voltage magnitude obtained by the calculation with the mathematical model is ***0.1603 [V]***.

VI. RESULTS

Once the mesh coupling tests in stator slots, permanent magnets and coils have been carried out, as well as the magnetic flux distribution of the generator over time, the dynamic analysis is made to know the induced voltage in the coil. Since the coil is completely wound in the slot, and the dimensions of the slot are the same as the length of the area subtended by the magnetic pole, the span in electrical degrees per pole is *180 °*. In order to obtain a complete cycle of the induced *emf*, it is necessary to pass two poles under each coil, generating a voltage of *360 °* electrical.

The main phenomenon starts from a rotational movement that moves a certain distance in a certain time, which gives rise to an induced *emf* as a function of time. This is why it is necessary to add a type of *Time Dependent* study, analyzing a time lapse that shows the generation of energy present in the coils. To define the time to be analyzed, it is necessary to know the period of the tension generated in the machine. The following equation as a function of the period of the electrical signal indicates that:

$$T = \frac{120}{nP} = \frac{120}{(60)(18)} = \mathbf{0.1111}\ [s]$$

With a rotation speed of *60 rpm* and the generator of *18 poles*, the analysis period will be from *0 to 0.11 [s]*, in intervals of *0.01 [s]* allowing to observe in *11 iterations*, the flux in the generator and the produced voltage signal. This is the time it takes to move the rotor to observe the flux variations in the area enclosed by the coils. The time of *0.01[s]* established in the programming represents the period in which the software captures the information of the phenomenon throughout the analysis. This time is sufficient to examine the flux and voltage in the machine without compromising the execution of the simulation due to hardware requirements. Figure 5 shows the state of the machine in the initial simulation time.

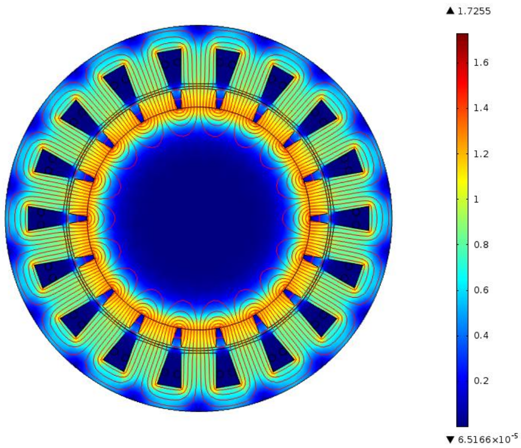
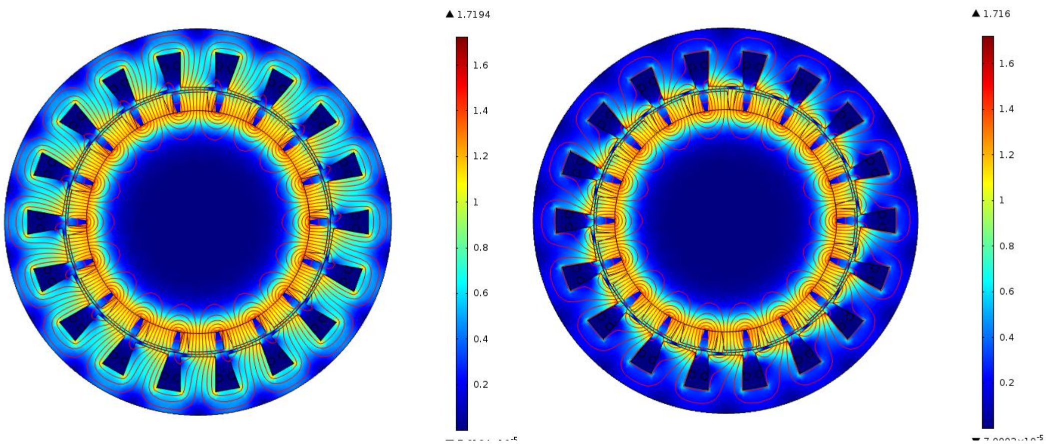


Figure 5. Generator State at *t = 0 s*.

Once the rotor starts to move counterclockwise, the magnetic flux lines begin to distort and the flux density layer on the stator varies in the different regions of the grooves. Figure 6a) shows the behavior of the machine at time *0.01 [s]*.

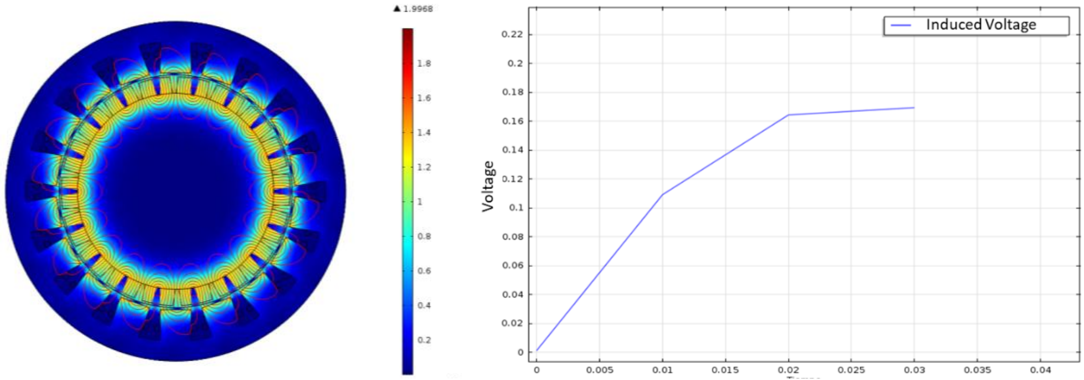
For the time 0.02 [s], the magnetic flux density in the groove decreases, as does the distribution of the flux lines, since they are not aligned with the slot tooth, they begin to deform, propagating in the air of the air gap and not being used by the magnetic circuit, figure 6b).



a) Generator in *t=0.01 s*. **b)** Generator in *t=0.02 s*.

Figure 6. Generator States.

Figure 7a) shows the flux distribution in the stator when the rotor poles are below the region where there is no permeable magnetic material for conducting the field lines. This occurs at time *0.03 [s]*.



a) Minimum flux density in the slots, *t=0.03 s.* **b)** Induced peak *emf* in the coils.

Figure 7. Flux density and *emf* of the Generator.

At this moment the flux density change ratio as a function of time is maximum, going from a maximum value to a minimum value. Therefore, the magnitude of the induced emf is maximum. Figure 7b) shows the induced *emf* up to time *0.03 [s]*.

At time 0.04 [s] the movement of the rotor begins to align the poles again under the area subtended by the magnetic material slots, which causes the flux density in the stator slots to increase again and as a consequence the *emf* in the coils begins to decrease. Figure 8 shows the flux density increase in the slots.

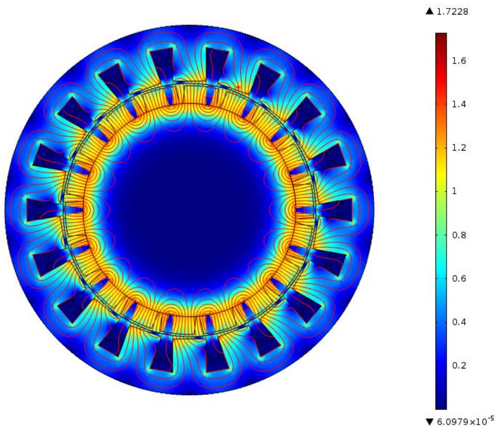
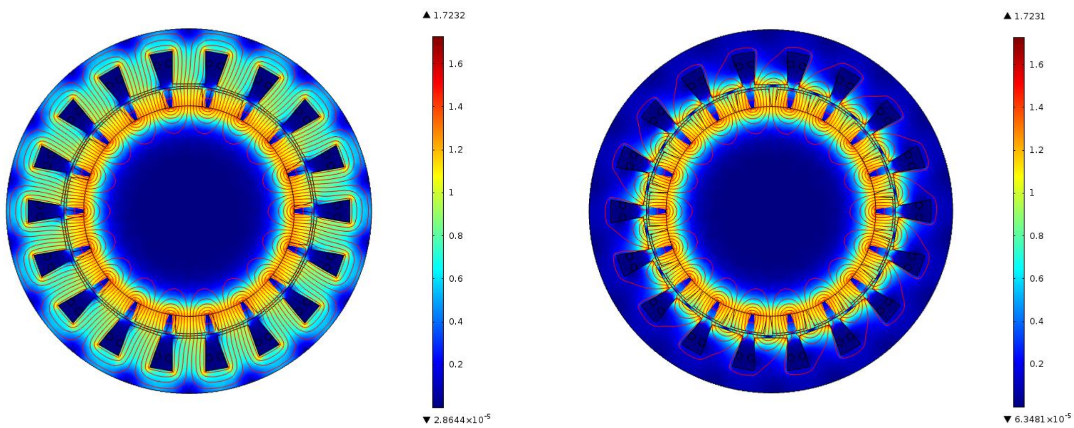


Figure 8. Generator State in *t=0.04 s.*

In time *0.06 [s]* a pole has moved from one slot to the adjacent slot, inducing a voltage of *180 °* electrical in the coils wound on the stator teeth. Since the flux is again maximum in the area enclosed by the turns, the voltage at this point is minimal and continuing with the rotation of the magnets the voltage with reverse polarity is manifested in the coils, figure 9a).

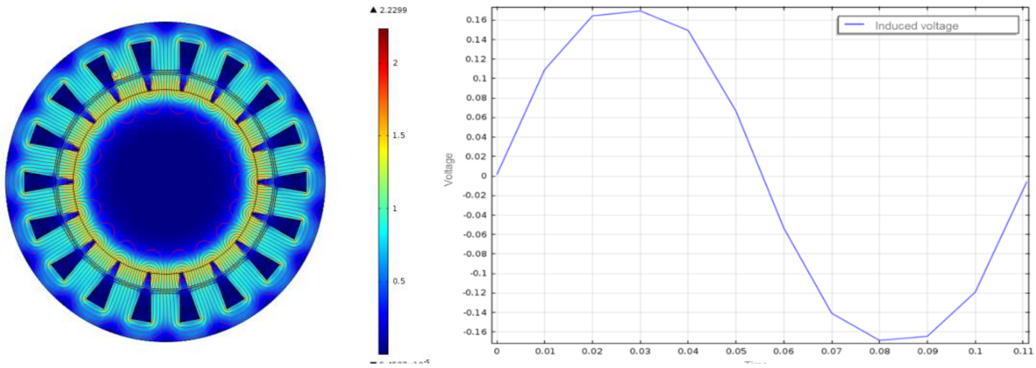


a) Generator in *t=0.06 s.* **b)** Generator in *t=0.08 s.*

Figure 9. Generator States.

Figure 9b) shows the rotor at the displacement time *0.08 [s]* where again the flux density in the area of the coils is minimal causing a maximum induced *emf*. The polarity of the voltage in the coils is negative because the direction of the current is such that it opposes the decrease in flux in the region comprised by the turns.

For the simulation time *0.11 [s]* the rotor aligns the poles again under the slots area, positioning the magnets as at the beginning of the study. The maximum flux in the slots is observed in figure 10a), where the *emf* at this point is again minimal so that, as the poles continue to rotate, more cycles will be generated in the coils.



a) Generator in *t=0.11 s.* **b)** Voltage in series connected single turn coils.

Figure 10. Generator after the generation of a voltage cycle in the coils.

The voltage signal in the coils connected in series after generating a cycle in time of *0.11 [s]* is observed in figure 10b). The peak magnitude of the voltage signal generated is *0.1694 [V]* for the generator of *18 coils* of *one turn* each, connected in series and with a steel stator that does not present losses.

The peak voltage magnitude obtained by the simulation of the generator is ***0.1694 [V]***, and the one obtained by the calculation with the formulated mathematical model ***0.1603 [V]***, it can be seen that they are approximate values.

VII. CONCLUSIONS

It was possible to compare the voltage levels obtained based on a mathematical model generated from the construction and operation characteristics of the analyzed generator and from the computational simulation.

The difference between the values calculated using the mathematical model and the simulation is that the software obtains a numerical solution based on differential equations that divide the geometry into a large number of subdomains, offering greater precision in obtaining data. Since the result obtained with the mathematical model is very similar to that of the simulation, it is verified that the voltage generation will be around these values.

The simulation allowed to graphically observe the voltage generation. Based on the results obtained in the work, it can be concluded that, according to the construction of the machine, the materials used, the geometric arrangement of the coils and the established flux levels, the microgeneration of electrical energy is viable. In this way, it is possible to create arrangements between generators on a given surface to increase the voltage and current level as required by the load to be supplied. The energy produced by the flow of people in a given space is viable according to what has been analyzed.

REFERENCES

[1]. Gregorio G. García, “Energías del siglo XXI: De las energías fósiles a las alternativas”, Madrid: Mundi-prensa, 2013.
[2]. Fenercom, “Guía básica de microgeneración”, Madrid, 2012.
[3]. A. Tapia, “Microgeneración de electricidad”. Available: https://e-management.mx/2015/04/15/microgeneracion-de-electricidad/
[4]. Pavegen, “Pavegen”. Available: http://www.pavegen.com.
[5]. B. Guru, “Máquinas eléctricas y transforamdores”, 3 ed., Oxford, 2003.
[6]. Stephen J. Chapman, “Máquinas eléctricas”, 5 ed., Mc Graw Hill, 2012.
[7]. Fitzgerald, A.E; Kingsley, C.Jr; Umas, S.D. "Máquinas Eléctricas". 6a Ed., Mc Graw Hill, México, 2004.
[8]. M. Torres. Sabino; Y. Astudillo B; M. Águila M. “Simulation and Analysis of the Magnetic Flux of an Electric Generator for Microgeneration”, 2021.