Design and Implementation of a Simulator of The Micro-Electromagnetic Generator Used to Power Medical Devices Implanted in The Human Body

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Abstract: The issue of obtaining sustainable energy to power small electronic devices that are difficult to power with batteries is considered one of the important research topics, such as Biomedical Implants, as it depends on the nature of these devices in order to power them themselves, noting that most of these devices are located in a vibrating medium, and thus energy can be secured. It has a micro-generator that converts ambient energy into electrical energy that is used to charge a small battery installed on the device implanted within the human body. Micro-electromagnetic generators are considered one of the most important types that convert vibration energy into electrical energy used to charge a battery. In this research paper, we conducted a theoretical study of the micro-electromagnetic generator, and deduced its mathematical equations, leading to the final model that links the vibrations to the generated voltage. This model was later modeled and simulated using MATLAB/SIMULINK, and we designed and implemented an emulator circuit for the generator that uses a dsPIC digital signal processor through which parameters can be adjusted via an interactive GUI interface to obtain the output of the micro-generator similar to the real one, with the aim of using it later in research into developing collection systems. Energy for Biomedical Implants. Finally, we applied practical designs of micro-generators found in previous research to the simulator that we designed to ensure the accuracy of the results.

Keywords: Micro-electromagnetic, dsPIC, micro-generator, Biomedical Implants, MATLAB GUI.

تصميم وتنفيذ محاكي للمولد الكهرومغناطيسي المكروي المستخدم في تغذية الأجهزة الطبية المزروعة في جسم الانسان

الملخص: يعتبر موضوع الحصول على الطاقة المستدامة لتغذية الأجهزة الالكترونية الصغيرة التي يصعب تغذيتها بالبطاريات من المواضيع البحثية الهامة، مثل أجهزة الزرع الطبية Biomedical Implants بحيث يُعتمد على طبيعة هذه التجهيزات من أجل تغذيتها ذاتياً، بملاحظة أن معظم هذه التجهيزات موجودة في وسط اهتزازي، وبالتالي يمكن تأمين الطاقة لها من المولدات الميكروية Micro-generator التي تقوم بتحويل الطاقة المحيطة إلى طاقة كهربائية تستخدم في شحن بطارية صغيرة مركبة على الجهاز المزروع ضمن الجسم البشري.

تعتبر المولدات الكهرومغناطيسية الميكروية generatorMicro electromagnetic من أهم الأنواع التي تحول طاقة الاهتزاز إلى طاقة كهربائية تستخدم في شحن بطارية. قمنا في هذه الورقة البحثية بإجراء دراسة نظرية للمولد الكهرومغناطيسي الميكروي، واستنتاج معادلاته الرياضية وصولاً إلى الموديل النهائي الذي يربط الاهتزازات بالجهد المولد. تم فيما بعد نمذجة هذا الموديل ومحاكاته باستخدام MATLAB/SIMULINK وقمنا بتصميم وتنفيذ دارة محاكي Emulator للمولد يستخدم معالج الإشارة الرقمية dsPIC يمكن من خلاله ضبط البارامترات عن طريق واجهة تفاعلية GUI للحصول على خرج المولد الميكروي مشابه للحقيقي وذلك بهدف استخدامه فيما بعد في أبحاث تطوير أنظمة تحصيل الطاقة لأجهزة الزرع الطبية Biomedical Implants. وأخيراً قمنا بتطبيق تصاميم عملية لمولدات ميكروية موجودة في أبحاث سابقة على المحاكي الذي قمنا بتصميمه للتأكد من دقة النتائج.

1.Introduction:

Developing and improving the output of the direct rectifier lever switch requires providing an input voltage that practically simulates the output of the micro electromagnetic generator. Therefore, in this research paper, we studied the working principle of the micro electromagnetic generator, modeled and built a simulation model of the generator, and then we designed a simulator using a digital signal processor microcontroller. dsPIC based on the deduced mathematical model. We carried out the practical implementation of the simulator, and applied the designs of the micro electromagnetic generator to previous research, and we obtained results close to the results of the practical designs.

1. Micro electromagnetic generator:

The adopted micro electromagnetic generator can be represented by a permanent magnet, a damper element, a spring, and a coil, where the permanent magnet is fixed by the spring to the base of the generator body and has freedom of movement within the primary coil as shown in Figure (1) [1]. For ease of study, we considered that the vibrations occur in a plane applicable to Generator axis.

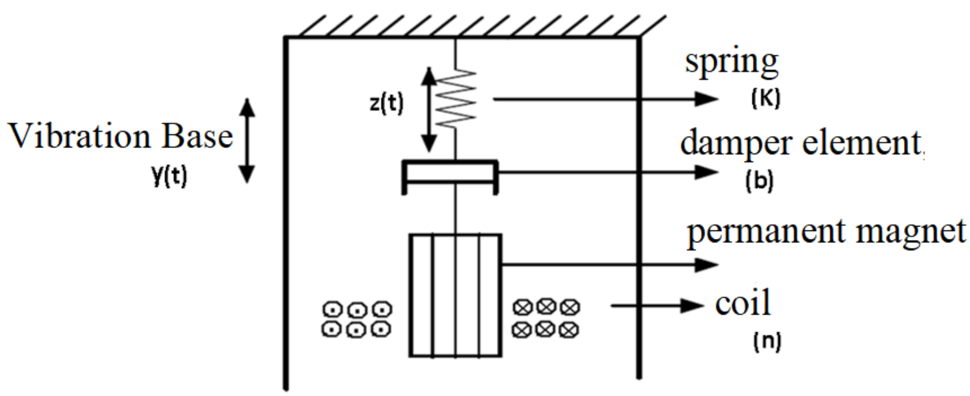

Figure 1. Micro electromagnetic generator

When the body of the generator is exposed to external mechanical vibration, the permanent magnet within the coil vibrates, and according to Faraday's law, an alternating voltage will be generated between the two ends of the coil. Its value depends on the number of turns of the coil, the type of permanent magnet, and the strength of the vibration. The form of the generator's output voltage is sinusoidal and of the order of tens of millivolts [2][1].

2.Modeling of the micro electromagnetic generator:

The force F applied to the micro-generator causes external vibration y(t), which in turn causes internal vibration z(t) of the mechanical system (spring, damper element, permanent magnet). Then the mathematical model of the micro-generator can be expressed by the following differential equation (1): [3]

$$\mathrm{F} = \mathrm{mz}''(\mathrm{t}) + \mathrm{bz}'(\mathrm{t}) + \mathrm{kz}(\mathrm{t}) \qquad (1)$$

Where:
m[kg] is the mass of the permanent magnet.
b[(N.S)/m] is the damping constant resulting from the sum of the mechanical damping bm and the electrical damping be, i.e. b=be+bm.
K [N/m] Stiffness of spring constant. F[N] The force applied to the mass and is given by the following relationship according to Newton's second law:

$$\mathrm{F} = \mathrm{my}''(\mathrm{t}) \qquad (2)$$

$$my''(t) = mz''(t) + \mathrm{b}z'(t) + kz(t) \qquad (3)$$

From equations (1), (2), (3) we get the following form for the generator model:

$$y''(t) = z''(t) + \left(\frac{\mathrm{b_m}}{\mathrm{m}} + \frac{\mathrm{b_e}}{\mathrm{m}}\right) z'(t) + \frac{k}{m} z(t) \qquad (4)$$

For ease of modeling, we assume that the force F applied to the micro-generator generates a sinusoidal vibration y(t), which is given by the following relationship:

$$y(t) = \mathrm{y}_{\mathrm{max}} \sin \omega \mathrm{t} \qquad (5)$$

Where:

y_{max}[m]: is the largest amplitude of vibration.
ω[rad/s]: The angular frequency of vibration.

$$y''(t) = -\omega^2 y_{\max} \sin \omega t = -\omega^2 y(t) \tag{6}$$

By replacing equation (6) with equation (4), we get equation (7):

$$-\omega^2 y(t) = z''(t) + \left(\frac{b_m}{m} + \frac{b_e}{m}\right) z'(t) + \frac{k}{m} z(t) \tag{7}$$

We consider that u(t) represents income and is given by equation (8):

$$u(t) = \ -\omega^2 y(t) \tag{8}$$

Therefore, the mathematical model of the generator becomes represented by Equation (7) according to Equation (9):

$$u(t) = z''(t) + \left(\frac{b_m}{m} + \frac{b_e}{m}\right) z'(t) + \frac{k}{m} z(t) \tag{9}$$

On the other hand, the vibration of the magnet produces an electrical force in the coil, which is given by the relationship (10):

$$e(t) = n \frac{\partial \emptyset}{\partial t} \tag{10}$$

Where:
Ø [wb]: Magnetic flux resulting from the movement of a permanent magnet.
n: Number of turns of the primary coil.
By converting equation (10) to a partial derivative in terms of ∂z:

$$e(t) = n \frac{\partial \emptyset}{\partial z} \frac{\partial z}{\partial t} \tag{11}$$

Equation (11) can be written as follows Equation (12):

$$e(t) = C_E \frac{\partial z}{\partial t} = C_E Z' \tag{12}$$

where:

$$C_E = n\frac{\partial \emptyset}{\partial z} \tag{13}$$

It is a constant whose unit [SV/m] is related to the number of turns of the primary coil and the composition of the permanent magnet. The generated electrical power PE is the result of converting the mechanical power Pm generated by work changes w[(N.m)/S] during one time:

$$P_E = P_m = \frac{\partial w}{\partial t} = F_{eb}\vartheta = F_{eb}z' \tag{14}$$

Where:

ϑ[m/S]: linear speed.

Note that the electrical damping force Feb [N] is given by:

$$F_{eb} = b_e z' \tag{15}$$

Substituting (15) into (14):

$$P_E = b_e z' z' \tag{16}$$

On the other hand, the instantaneous electrical power is given by equation (17):

$$P_E = EI \tag{17}$$

Where:

E[V] electric force generated at the output of the micro-generator.

I[A] The current passing through the load connected to the output of the micro-generator.

From relations (12), (16) and (17) the electrical damping constant can be deduced:

$$b_e = \frac{C_E I}{z'} \tag{18}$$

$$\mathrm{I} = \frac{\mathrm{E}}{\mathrm{R_L}} \tag{19}$$

Where:

R_L [Ω] is the resistance connected to the output of the micro-generator.

By replacing equation (19) with equation (18):

$$\mathrm{b_e} = \frac{\mathrm{C_E E}}{\mathrm{z' R_L}} \tag{20}$$

Substituting E from equation (12) with equation (20):

$$\mathrm{b_e} = \frac{\mathrm{C_E^2}}{\mathrm{R_L}} \tag{21}$$

By replacing equation (21) with equation (9):

$$u(t) = z''(t) + \left(\frac{\mathrm{b_m}}{\mathrm{m}} + \frac{C_E^2}{\mathrm{mR_L}}\right) z'(t) + \frac{k}{m} z(t) \tag{22}$$

From equations (22) and (8), the mathematical model of the micro-generator can be represented with the diagram shown in Figure (2), where:

$$C1 = \frac{k}{m} \tag{23}$$

$$C2 = \frac{\mathrm{b_m}}{\mathrm{m}} + \frac{C_E^2}{\mathrm{mR_L}} \tag{24}$$

$$A = -\omega^2 \tag{25}$$

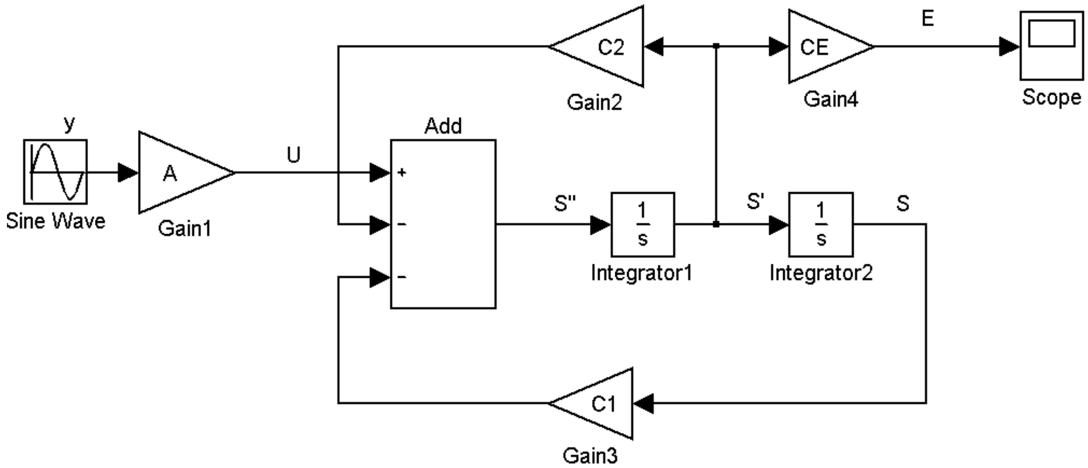

Figure 2. Box diagram of the mathematical model of the micro-generator

The transfer function can be obtained from the box diagram of the micro mathematical model shown in Figure (2) according to Equation (26):

$$H(s) = \frac{E(S)}{y(S)} = \frac{AC_E S}{S^2 + C1S + C2} \quad (26)$$

2. Frequency study of the transfer function of the micro electromagnetic generator:

In order to know the effect of the vibration provided to the generator on the gain, we will study the frequency response of the transfer function of the micro-generator, where the transfer function is given in standard form:

$$G(S) = \frac{aS}{S^2 + bS + c} \quad (27)$$

Figure (3) shows the frequency characteristic (Bode), from which the maximum value of the gain of the previous transfer function is given:

$$A_{Gmax} = \frac{a}{b} \quad (28)$$

Then the frequency is:

$$\omega_p = \sqrt{c} \tag{29}$$

Where ω_p is called the pole frequency, and it is the frequency at which the transfer function gain is maximum.

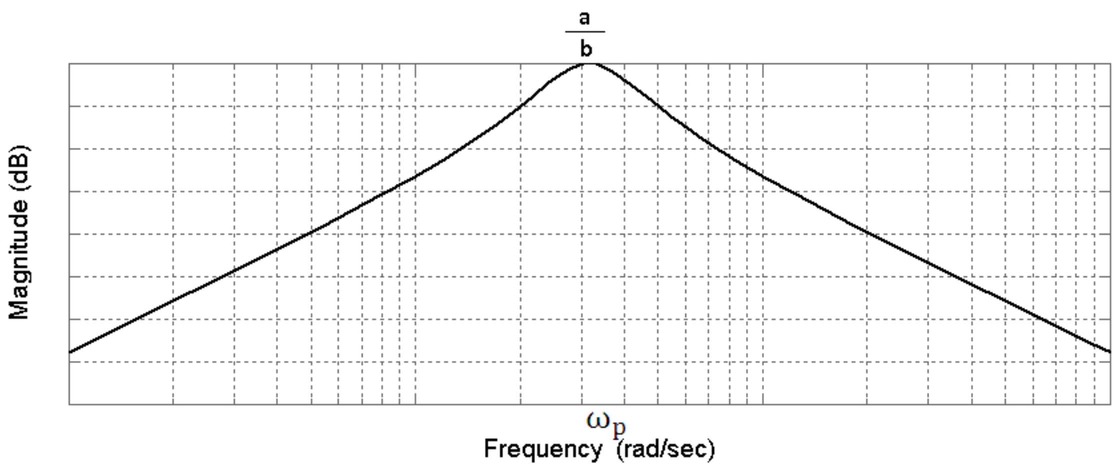

Figure 3. Bode frequency characteristic of the transmission function

By matching the transfer function of the generator given by equation (26) with the standard form equation (27), we find the values of:

$$a = AC_E \tag{30}$$

$$b = C1 \tag{31}$$

$$c = C2 \tag{32}$$

From this, the maximum value of the transfer function gain of the micro-generator is given:

$$A_{Hmax} = \frac{AC_E}{C1} \tag{33}$$

$$\omega_{Hp} = \sqrt{\frac{b_m}{m} + \frac{C_E^2}{mR_L}} \tag{34}$$

The generator output is given:

$$E = Hy \tag{35}$$

Therefore, from equations (5), (8), (33) and (35), the maximum output of the micro-generator when the vibration frequency ω_{Hp} is given by the relationship (36):

$$E_{max} = \frac{AC_E}{C1} y_{max} \tag{36}$$

From this, the maximum output power of the micro-generator is given:

$$P_{Emax} = \frac{E_{max}^2}{R_L} = \frac{\left(\frac{AC_E}{C1} y_{max}\right)^2}{R_L} \tag{37}$$

Through studying the frequency response of the transfer function, we conclude that the micro-generator has a maximum response at a certain vibration frequency. Therefore, the design values K, m, bm, and CE must be chosen to determine the polar frequency ω_p according to the working environment of the micro-generator, based on the frequency range of mechanical vibration provided to the micro-generator.

3.Micro-electromagnetic generator simulation:

In order to simulate the mathematical model of the generator, the design values of the generator given in Table (1) were chosen [3] [4].

Table 1. Design practical values for simulating the mathematical model of the micro-generator

k	**416[N/m]**
m	**0.005[kg]**
b_m	**0.00001[N.m/s]**

R_L	**100[Ω]**
C_E	**6.456[S.V/m]**

By taking the practical design values of the generator from Table (1) and from equations (23) and (24), we calculate the values of the constants C1 = 83200 and C2 = 83.3619. For a vibration frequency of ω = 282.7433 rad/sec for the input signal shown in Figure (4), the output of the micro-generator is E Shown in Figure (5) according to the simulation of the box diagram shown in Figure (2) in the Matlab environment.

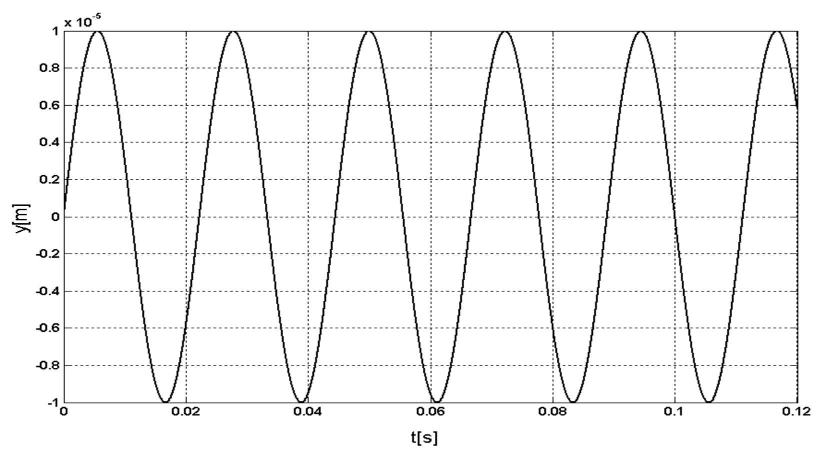

Figure 4. Microgenerator input signal

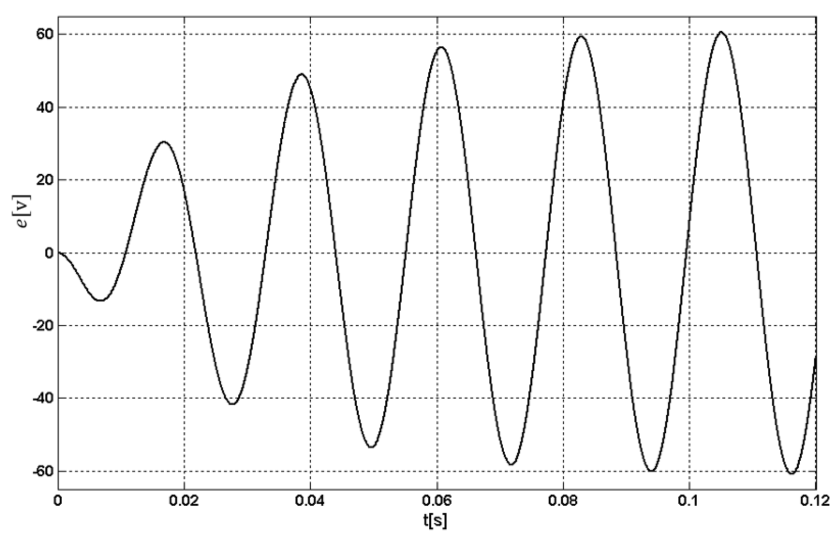

Figure 5. Microgenerator output signal

We notice from the simulation results that the amplitude of the generator output increases at the beginning of the vibration application and then stabilizes at a certain value as a result of mechanical inertia. Therefore, the energy harvesting system, the electronic part (switched), must be designed so that it tracks this change in the take-off phase to make the most of the energy provided to the micro-generator and increase the yield in particular. In an environment where the vibration provided is intermittent rather than continuous (the condition is more common).

3. Design a micro-generator simulator:

Designing a micro-generator simulator is one of the main steps in this research, as we designed a simulator circuit that uses a dsPIC digital signal processor to obtain the output of a micro-generator with certain design parameters that are entered through an interface available to the designer. The micro-generator simulator consists of the sections shown in Figure (6):[5]

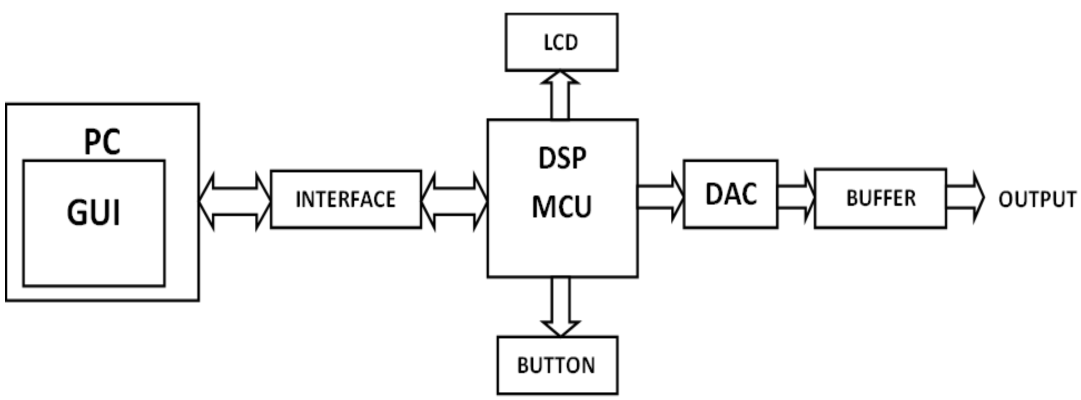

Figure 6. Block diagram of the microgenerator simulator

The work of this simulator is based on the mathematical model of the micro-generator shown in Figure (2) by mainly programming the dsPIC digital signal processor and the GUI program according to two modes of work:

- **Online mode:** In this mode, the mathematical model is simulated using dsPIC to obtain the output signal according to the requirements entered by the GUI interface. This mode is useful for studying the transient states of the micro-generator, but on the other hand, there is difficulty in changing the output parameters of the micro-generator directly.

- **Offline mode:** In this mode, the mathematical model is simulated using a GUI program according to the input parameters to obtain the parameters of the output signal, and this signal is generated by dsPIC. This mode is characterized by changing the output parameters of the micro-generator directly, but on the other hand, it is not possible to study cases through it. Trans.

The most important features of the simulator are:

1- It provides an easy design interface for choosing the values of the constants K, m, bm, and CE for the micro-generator.

2- It allows the researcher and designer of the energy harvesting system to test and simulate his design using the MATLAB environment and practically using the simulator circuit.

3- It allows the vibration and amplitude to be changed in several ways, which provides a simulation of the natural environment in which the micro-generator may exist.

4- It provides the possibility of studying the efficiency of the energy harvesting system accurately.

The simulated system can be divided into two parts:

3.1 Hardware:

It consists of the following parts:

3.1.1 Interface connection circuit:

It is the circuit that connects the computer and a dsPIC digital signal processor in order to match the logical levels of the RS232 protocol between the COM port of the computer and the UART unit of the processor and Figure (7) the linking circuit.

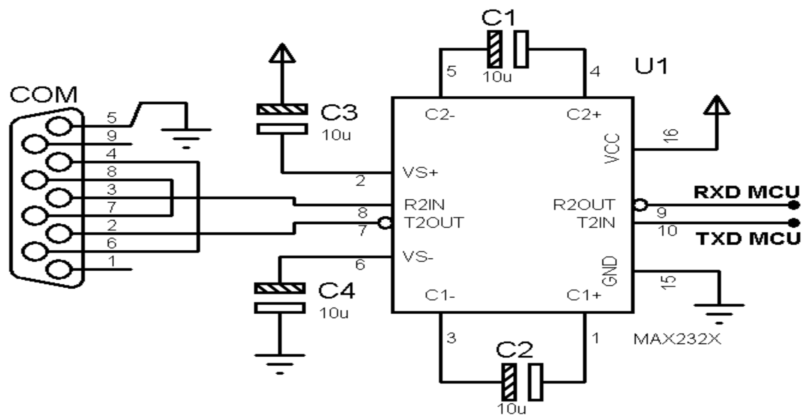

Figure 7. Interface circuit between the computer and the dsPIC digital signal processor

3.1.2 dsPIC digital signal processor circuit:

It is the main element in the simulator that generates the output signal in two modes, online or offline. The dsPIC30F3010 chip was chosen from the family of power inverters and motor control suitable for our research in terms of practical implementation because it has a high capacity in digital signal processing, as every instruction in the dsPIC digital signal processor is executed in One instruction cycle, which makes the dsPIC digital signal processor suitable for use in control systems that operate in real time, where the PWM motor control unit was used to build a digital-analogue converter (DAC) and a DSP core in order to perform mathematical operations. Figure (8) shows the digital signal processor circuit. dsPIC, where a screen is connected to show settings and working status.

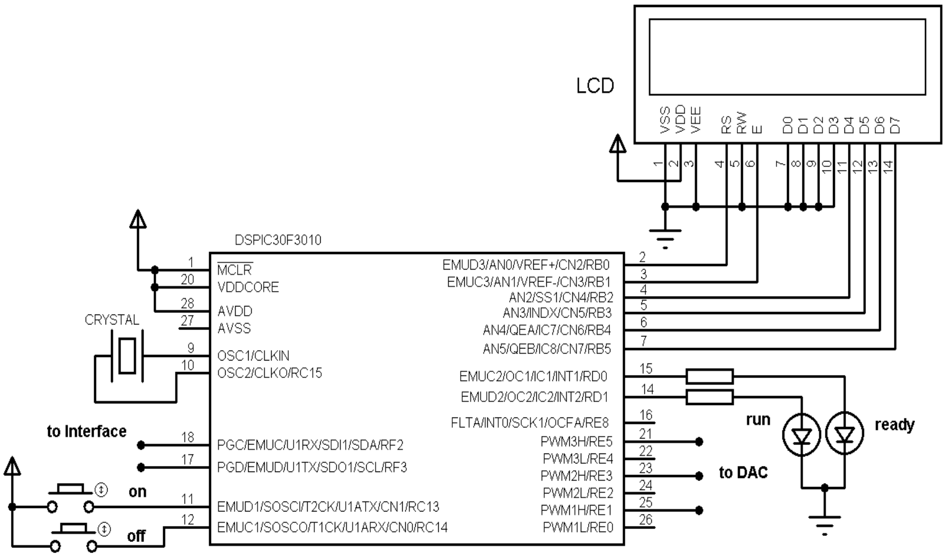

Figure 8. dsPIC digital signal processor circuit

3.1.3 DAC circuit:

Figure (9) shows the DAC circuit that we designed in order to convert the digital signal generated from the PWM ports into a signal expressing the output of the micro-generator. In this circuit, two RC low-frequency filters (PWM detector) were used with a cut-off frequency of Fc=159Hz, and the operational amplifier U2 combines the two part signals. The positive, negative, and U3 are for precise control of the amplitude. The transistors Q1, Q2, Q3, and Q4 are insulators on the one hand and a controller connecting the dsPIC digital signal processor and the filtering stage on the other hand.

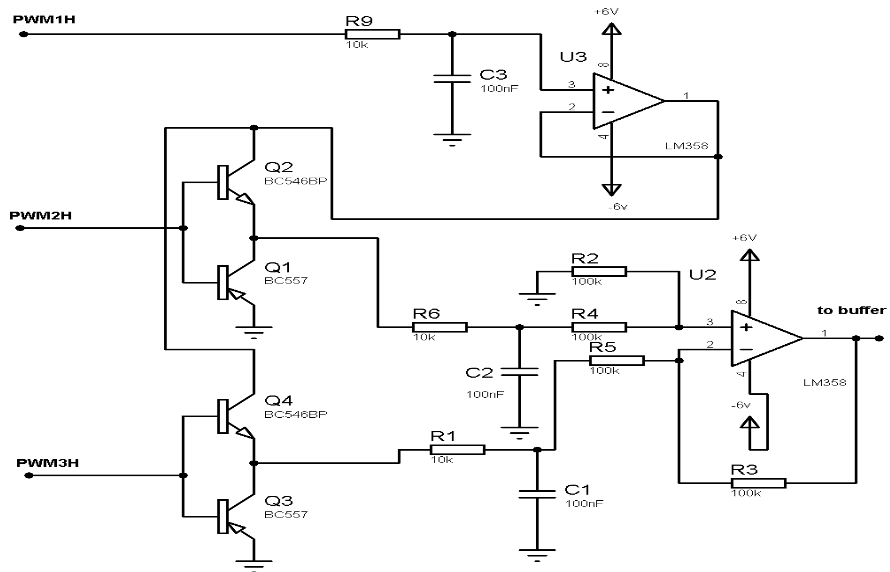

Figure 9. DAC circuit

3.1.4 Buffer circuit:

Figure (10) shows the Buffer circuit that we designed with the aim of eliminating the offset of the output voltage resulting from the inaccuracy of the elements, filters and operational amplifiers in the DAC circuit and obtaining the output voltage field of the order of millivolts, where the resistor RV1 is used to determine the output field and RV2 is used to cancel the offset of the output voltage.

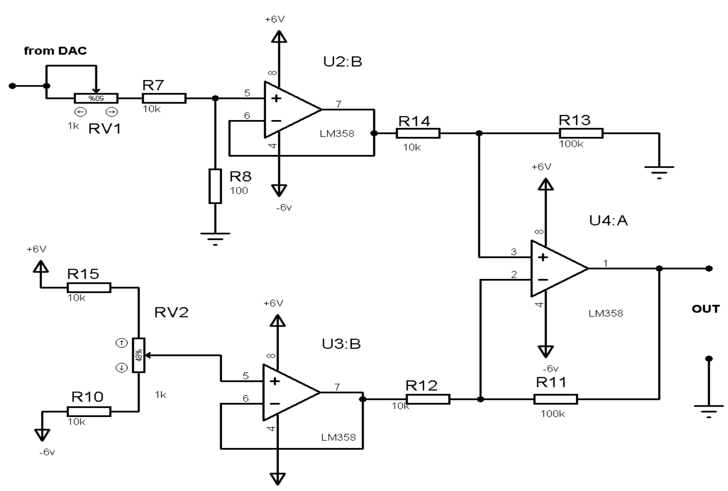

Figure 10. Buffer circuit

3.2 Software:

It consists of the following parts:

3.2.1 dsPIC digital signal processor software:

DSP instructions were used in two modes, online and offline, to achieve high speed of execution. We programmed the processor in C language using the mikroC PRO for dsPIC compiler. The program can be divided into the following parts:

- The first part: It receives parameters from the GUI program via the UART communication port at a speed of 138,000 Baud, according to the work mode and input parameters.
- The second part: It generates the micro-generator output in offline mode according to a fixed amplitude and frequency that are calculated by a GUI program according to a simulation in the MATLAB environment.
- The third part: It generates the micro-generator output in online mode based on the transfer function given in equation (27), where it is cut into a cut-off time T_s according to the backward difference method, so we get the following difference equation (38):

$$k1E(n) + k2E(n-1) + k3E(n) = k4(y(n) - y(n-1)) \qquad (38)$$

Where: n is the sample number.

$$\mathrm{k1} = \frac{1}{\mathrm{T_s^2}} + \frac{\mathrm{C1}}{\mathrm{T_s}} + \mathrm{C2} \qquad (39)$$

$$\mathrm{k2} = \frac{-2}{\mathrm{T_s^2}} - \frac{\mathrm{C1}}{\mathrm{T_s}} \qquad (40)$$

$$\mathrm{k3} = \frac{-1}{\mathrm{T_s^2}} \qquad (41)$$

$$\mathrm{k4} = \frac{\mathrm{AKe}}{\mathrm{T_s}} \qquad (42)$$

The previous constants are calculated by a GUI program through the input parameters and then sent to a dsPIC digital signal processor in order to obtain a fixed cutting time. Timer1 was used to generate an interrupt with a cutting time of TS=20us, which calls the interrupt service function, which calculates the output of the differential equation given by (38). We obtain the output voltage, which is converted to analog values by the PWM terminal and the DAC module.

3.2.2 GUI Program:

It is a program with a visual interface written in C language in the MATLAB environment through which the emulator is fully controlled, as it contains two visual interfaces:

• The main interface shown in Figure (11) through which the design values are entered, the results are simulated, the results are shown, and the simulated circuit is controlled.

• An interface for selecting and changing vibration parameters, shown in Figure (12), is used in offline mode only in two ways:

- ❖ Linear, as in this method the amplitude and frequency of vibration within a field are changed linearly and with increasing value over a specific period of time.
- ❖ Random: In this method, the amplitude and frequency of vibration within a field are changed randomly during a specific period of time.

The program performs the following tasks:

- Entering micro-generator parameters.
- Calculating the constants of the mathematical model from the microscopic input parameters according to equations (23), (24), and (25) and the discrete model according to equations (28), (29), (30), and (31).
- Simulating the micro-generator according to the mathematical model (Figure (2)) and showing the results.
- You can choose the online or offline work mode.
- Provides communication in order to transfer the constants of the mathematical model and the discrete model to the simulator circuit.

- Control the simulator circuit from turning it on and off.

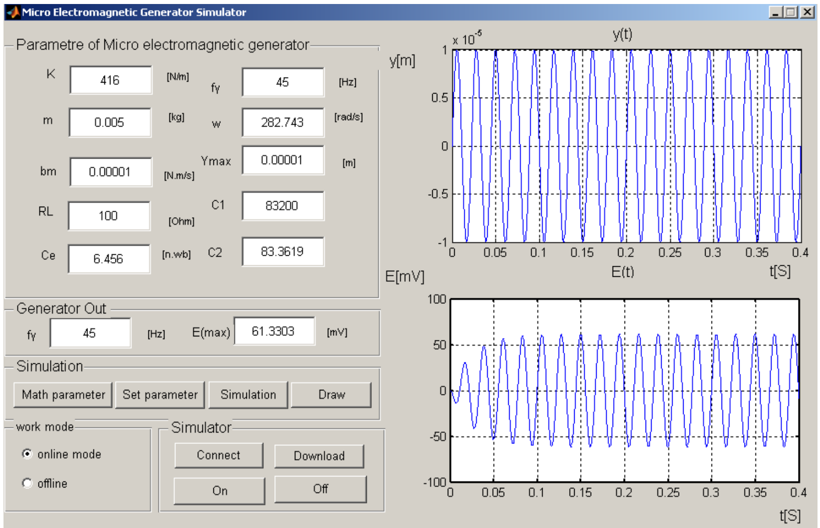

Figure 11. Main interface of the GUI program

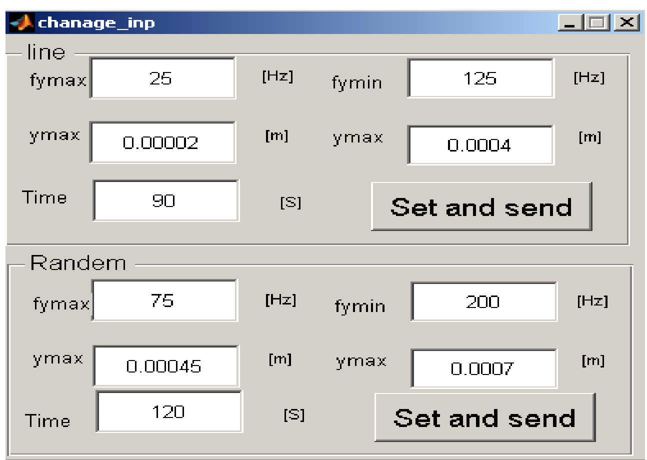

Figure 12. The interface for changing vibration parameters is used in offline mode

4.Testing and practical application of the simulator:

In order to test the simulator design, we applied two micro-electromagnetic generator designs that were implemented by previous research.

• **First design**: By applying the parameters shown in Figure (11) and practical values for the constants c1 = 83200, c2 = 83.3619, and ce = 6.456 for the micro-electromagnetic generator (same simulation parameters for the mathematical model) that was designed by researchers Dwari, Dayal, Parsa, the practical laboratory picture of this generator is shown. Figure (13), where they applied a sinusoidal vibration with a frequency of 45 Hz from a controlled electric vibrator connected to the micro-generator with an amplitude Ymax = 100μm, so the maximum value of the microoutput voltage was Emax = 55mV, and using the analog signal analyzer connected to the output of the simulator circuit, we obtained the signal shown in Figure (14).)[6].

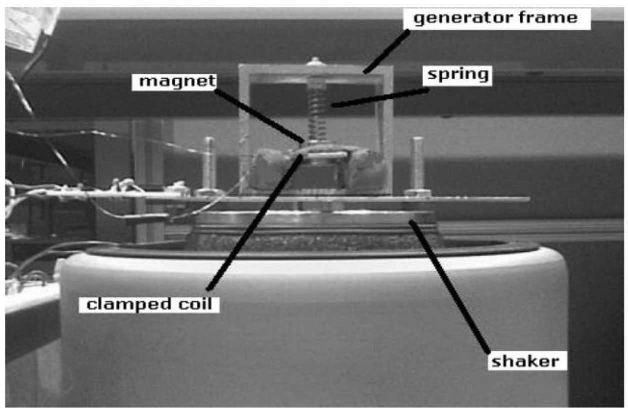

Figure 13. A practical picture of the micro-electromagnetic generator used in the simulator test

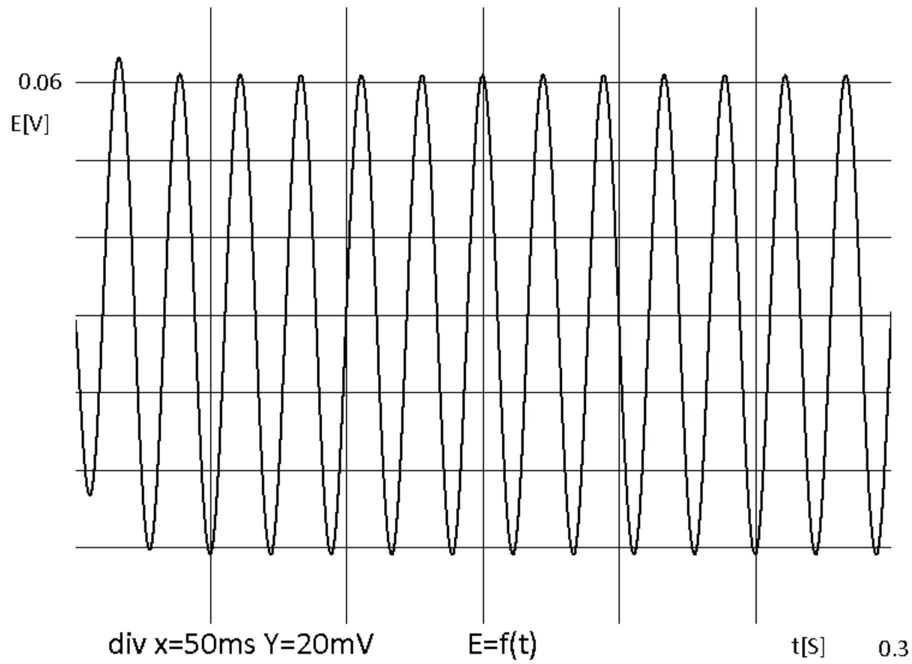

Figure 14. The output voltage of the circuit simulated for the first design of the micro-generator

We note from Figure (14) that the maximum value of the output voltage of the simulated circuit is Emax=61mV . It is close to the practical value of the designed generator.

• **The second design**: We applied the design of the micro-electromagnetic generator by researchers Cao, Chiang, Lee, with its parameters shown in Figure (15), to the simulator, where they obtained an output Emax=108.89mV by applying a sinusoidal vibration with a frequency of 42Hz and an amplitudeYmax=0.003m.[7]

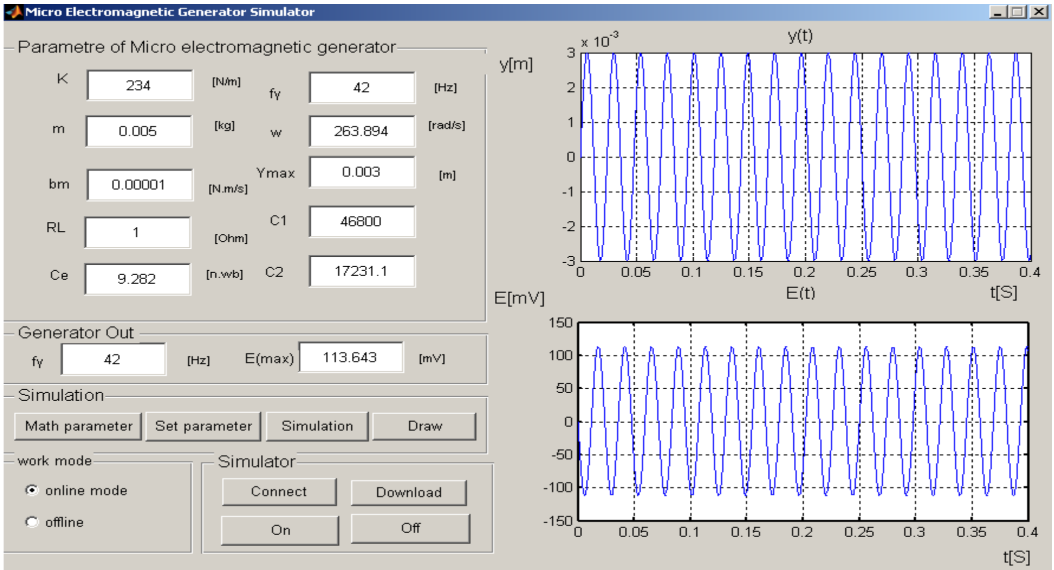

Figure 15. Parameters of the second design of the microgenerator

We note from Figure (16) the output of the simulator circuit that the maximum value of the output voltage of the simulator circuit is Emax=113.6mV, which is close to the practical value of the designed generator.

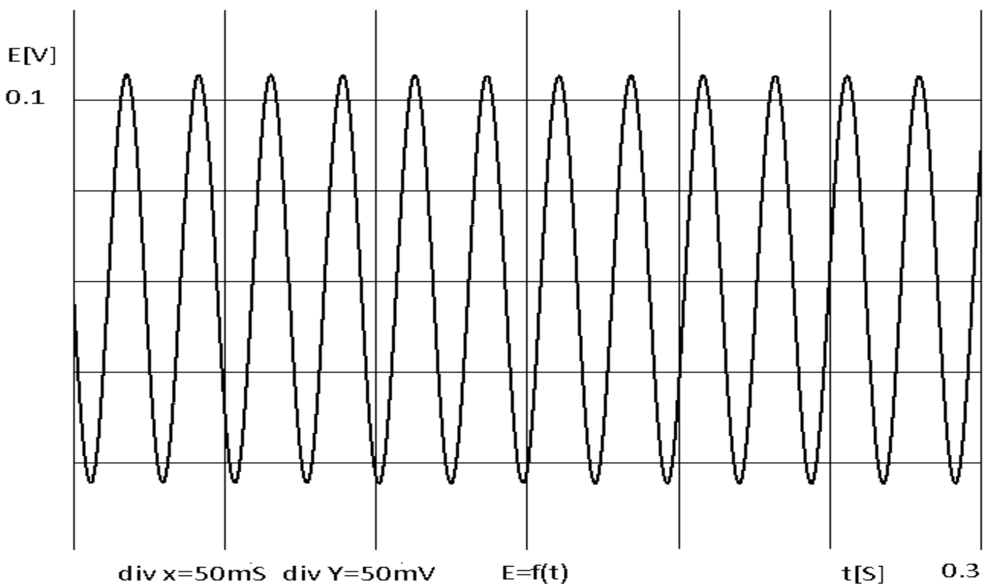

Figure 16. The output voltage of the simulated circuit for the second design of the micro-generator

5.Conclusion and discussion of results:

In this research paper, the micro-electromagnetic generator was studied, the main element in the microelectromechanical system for collecting energy from vibration. This study included the following:

1- Study the working principle of the micro-generator and its components.
2- Deducing the mathematical model of the micro-generator in several forms based on the basic mechanical and electrical equations.
3- Study the frequency response of the generator's transmission follower in order to know the effect of the vibration provided to the generator on the gain and output voltage and determine the best frequency for the generator to operate.
4- Building a simulation model in the MATLAB environment for the micro-generator.

A simulator was then designed based on the mathematical model derived using a dsPIC digital signal processor in online and offline modes (Figure 17), with the possibility of changing the amplitude and frequency of the vibration provided to the generator, which simulates the natural environments in which the microgenerator may exist.
In order to confirm the validity of the theoretical study and mathematical modeling, practical designs carried out by other researchers for the micro-generator were applied to the simulator that we designed. The practical results were close to the results of the researchers, which confirmed the validity of the theoretical study and the design of the micro-generator simulator.

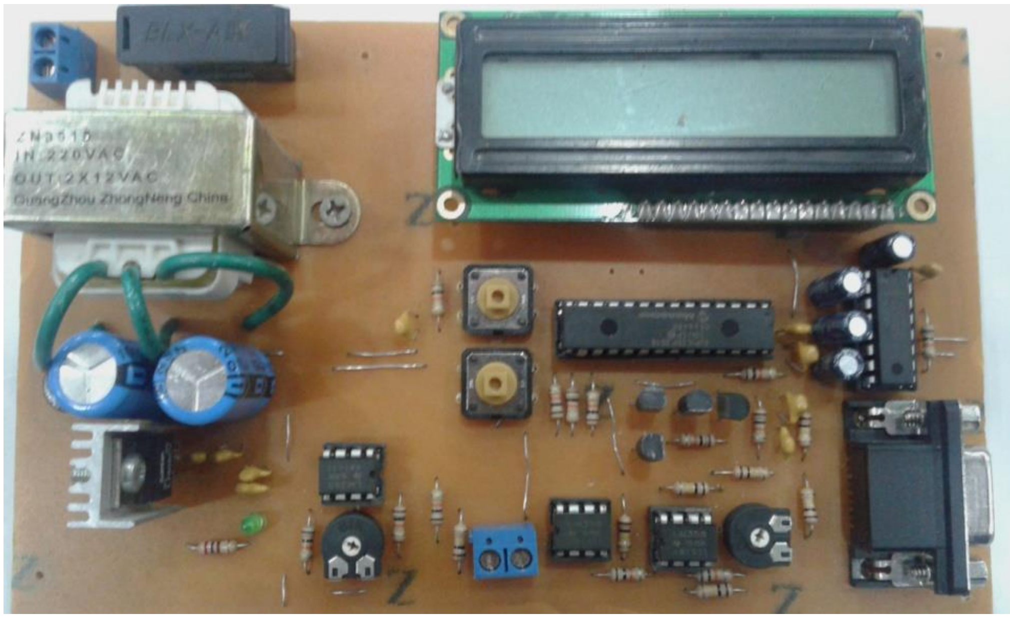

Figure 17. Practical circuit of the microgenerator simulator

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