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A CASE-STUDY VISION

Design of energy storage prototype based on elliptical bike

Diseño de prototipo de almacenamiento de energía en base a bicicleta elíptica

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ABSTRACT

The following article presents the design and fabrication of an energy storage prototype based on an elliptical bicycle and a 36 VDC brushless motor. The article also presents and explains measurements according to tests performed with different configurations in the control circuit and transmission.

Palabras clave:
Motor corriente directa
Circuito eléctrico
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RESUMEN

En el siguiente artículo se presenta el diseño y fabricación de un prototipo de almacenamiento de energía basado bicicleta elíptica y un motor sin escobillas de 36 VDC. En el artículo se presentan y explican de igual manera mediciones de acuerdo con pruebas realizadas con distintas configuraciones en el circuito de control y transmisión.

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1. Introduction

According to the RAE, energy is defined as "the capacity to do work". One way in which energy is expressed is through electrical energy. Electrical energy is one of the most required energies nowadays; electricity has allowed us to advance notably and together with technological advances, ideas that a century ago were thought impossible are made possible. Currently, there are different ways of generating electricity such as thermal energy, nuclear energy, solar energy, hydropower, wind energy, and nuclear energy, among others that are used for the same purpose, to generate electricity, "however, this type of conventional energy (fuel-based) are affecting the world today more than a while ago due to global warming, and we must find ways technologically friendly to the environment, generation of electricity for us and future generations". [1]. These different usual methods are implemented on a larger or smaller scale, but with the situation of now and the future we will focus on the subject that we will call alternative energy: "It is the energy coming from sources other than the usual ones such as coal, oil or gas." [RAE] This kind of energy, because they are those that affect the environment to a lesser extent, the world will increasingly use them to generate electricity. Mechanical energy is the type of energy that is used to generate movement in a body. It is further divided into two energies: potential energy and kinetic energy. Potential energy is that which defines the capacity of a body to generate movement, and kinetic energy is that which relates the mass and velocity of the same body to generate energy from that movement, in this case, electrical energy. An electric generator is a machine that from mechanical movement and thanks to Faraday's law can generate electrical energy; "this law states that for an electric current to be generated there must be a movement between the conductor and the magnetic field since the voltage induced in a closed circuit is directly proportional to the speed with which changes in time the magnetic flux that crosses a surface with any circuit as an edge". [2]. This means that, from the magnetic field, the generator will be responsible for producing the movement of electrons which translates into electrical energy. This change in the flow of the magnetic field is induced by the change of magnetic poles in the coils of the same, which are in the rotor, and as the speed and applied force increase, more energy will be generated. We are not only referring to energy generation in the industrial or residential field; one of the most used elements, but also one of the most questioned at present is the automobile. For this reason, hybrid vehicles are starting to be implemented in some places; "these vehicles are used taking advantage of the energy provided by an electric motor to complement the movement, helping the internal combustion engine on occasions when it is needed. These cars help the environmental impact by reducing environmental emissions." [3] With the above, we wish to communicate that the environment can be helped by small aspects such as an automobile. With this thought and also due to current regulations implemented in formula 1 or high-end vehicles the so-called regenerative braking. "Generative brakes are a braking mechanism for the vehicle that allows generating electrical energy from the kinetic energy involved in braking (In friction brakes it is released in the form of heat." [4].

As well as the regenerative brake, different ways of contributing to this topic of alternative energies are being sought and implemented more and more every day. For this reason, the idea of harnessing the kinetic energy produced by an individual when performing physical training by transforming it into electrical energy was thought of. "Fitness is one of the topics that are growing nowadays. People attend fitness centers to improve their physical appearance, but these machines can also be implemented to produce electrical energy." [5].

2. Methodology

"Over time, the world has exponentially increased its electricity demand, not only because of population growth but also because of the direction in which the world order is moving. This leads to an increasing need for additional resources to generate this energy and considering environmental conditions, fossil fuels are not a long-term solution. For this reason, renewable energies are thought of." [6]. However, in addition to conventional systems such as solar energy, wind energy, and geothermal energy, different alternatives that could help us in this aspect are not taken into consideration.

Most people who own an elliptical trainer use it for the sole purpose of improving their conditioning and fitness, but if we think about it, we are using energy that is only transformed into heat within the bike system. "The elliptical trainer is one of the most widely used fitness machines around the world because it can work different parts of the body, incorporating large and medium muscle groups both upper and lower, allowing a balanced and aesthetic development compared to other types of machines that we usually see in a fitness center." [7]. This means that the elliptical trainer is one of the favorite machines when it comes to physical training, but what if we take advantage of the energy used in something more than heat inside the mechanism? There are different types of elliptical bikes, from the simplest mechanisms where the movement is constant and without resistance [Figure 1], to digitized systems where there is a more complex electro-mechanical design that allows a better feeling for the user. [Figure 2].

Figure 1. Elliptical bikes with simplest mechanisms.

Source: own.

Figure 2. Elliptical bikes with digitized systems.

Source: own.

For the proposed project approach, a type of elliptical bicycle was used Figure 2.

Elliptical bikes of this type employ a resistance system that can be controlled by the user to apply more or less effort and thus perform a greater workout.

Why implement it on an elliptical trainer?

To find out which machines are mostly used by people attending a fitness center, three different gyms in Bogotá were visited on random days over a period of three months to identify which machines are mostly used by users. After some surveys with personal trainers, the results were the following: First, the elliptical trainer followed by the exercise bike, and then the treadmill as a general workout. For our benefit, the elliptical machine besides being the most used is also the one that presents a movement that is the most usable for the project. In all the machines it is possible to implement, with some modifications, an electrical generation system, however, in these others, the movement is not constant, and being used by a specific group, this resource would not be so useful. After conducting a joint analysis with the trainers it was concluded that: "The elliptical trainer is the most complete par excellence, where almost any individual can achieve the results required with this single machine if it is adjusted to the needs of each one". Already knowing which machine will be used, we entered the engineering field to analyze the types of existing generators and select which one is most suitable for the project.

2.1. Generation of electrical energy from kinetic energy

At present, there are different ways to generate electrical energy, but the way to deal with this article is the transformation of mechanical energy into electrical energy. The basis of an electric generator as the one we will use is the creation of a magnetic field that will try to reach the induced magnetic field; the movement generated by the external source, in this case, the axis of the elliptical bicycle creates flow through the turns of the generator and these by its constructive configuration (direction and poles) will generate a current that will induce the aforementioned field.

Kinetic energy is a branch of mechanical energy that is associated with motion, which is given as a function of the mass and velocity of the body in motion, this behavior is described by the following equation:

$$EC = \frac{m * v^2}{2} [J] \quad (1)$$

By the principle of conservation of energy, we know that energy is neither created nor destroyed, it is transformed; based on this it was noticed that the energy implemented in moving an elliptical bicycle is not used as it could be if it is only reflected in the physical conditioning of the person who uses it and heat in the mechanism of the bicycle. Faraday's law states that a magnetic field causes an electric current, this current is formed if you move a magnet through a loop, and this magnetic field in time will produce an electromotive force (generated energy). This behavior is described as follows:

$$\mathrm{FEM} = \frac{\mathrm{d}\Phi\mathrm{m}}{\mathrm{dt}} \qquad (2)$$

Where dΦm is the derivative of the magnetic flux which we can rewrite as:

$$\mathrm{d}\Phi\mathrm{m} = \int_{s}^{t} \mathrm{B.dS} \qquad (3)$$

Where B is the magnetic field and S is the area of interest.

2.2 Alternating current generators

In terms of AC motors, there are single-phase, three-phase, and polyphase motors in the industry. The most commonly used are the three-phase motors categorized between synchronous motor and asynchronous motor. "The alternating current generators are usually called synchronous generators or alternators. A synchronous machine, either as a generator or motor, operates at a synchronous speed, that is, at the speed at which the magnetic field created by the field coils rotates. The speed of this type of machine is given by the equation:

$$\mathrm{Ns} = \frac{120\mathrm{f}}{\mathrm{P}} \qquad (4)$$

Where 'f' is the frequency in Hertz and 'P' is the number of poles of the machine." [8]. The principle of operation of a synchronous machine is based on Faraday's law of induction: to create an induced voltage in the stator, a magnetic field must be created in the rotor by inducing a voltage in the armature winding. When using the machine as a generator, an external mechanical entity must be in charge of moving the rotor of the machine (hydraulic turbine, combustion engine, etc). It is not enough to simply move the shaft to convert mechanical energy into electrical energy in an efficient way, it is also necessary to induce DC voltage to the field winding that is directly connected to the generator rotor so that, when rotating, the magnetic field generated by the rotor poles has a relative movement to the conductors of the stator windings. This movement between the induced magnetic field and the generated magnetic field varying in time will make Faraday's law effective in generating alternating current on the stator side. This type of generator is the most commonly used in large-scale electrical systems (thermoelectric, hydraulic).

The problem of alternating current generators for the project lies in the speed required to ensure generation in addition to the external source of excitation of the field winding. The exercise of connecting a synchronous generator to the elliptical machine was performed and voltage measurements were made at various speeds considered typical. As expected, no more than a few hundred millivolts were obtained, which is not appropriate for our objective. With this conditional fact, we proceed to analyze the DC generators.

2.3 Direct current generators

DC generators are much less widely used than AC generators because systems worldwide run on AC power. However, in some specific situations, it is better to use these types of machines. "There are five main types of DC generators which are classified according to how their field flux is produced:

1. Separate excitation generation: The field flux is derived from a separate power source independent of the generator itself.

2. Shunt generator: Field flow is derived from the field circuit connection directly across the generator terminals.

3. Generator in series: The field flux is produced by the field connection in series with the armature of the generator.

4. Cumulative compound generator: In this one both the shunt field and the series field are present and its effects are addictive.

5. Differential compound generator: In this one both the shunt field and the series field are present, but their effects are subtracted.

These types of direct current generators differ in their terminal (voltage-current) characteristics, and therefore in the applications for which they are suitable." [9]. As with AC generators, they must be driven by a mechanical element (turbine, combustion engine), and depending on the speed they provide at the generator output we will have a DC voltage to arrange and use.

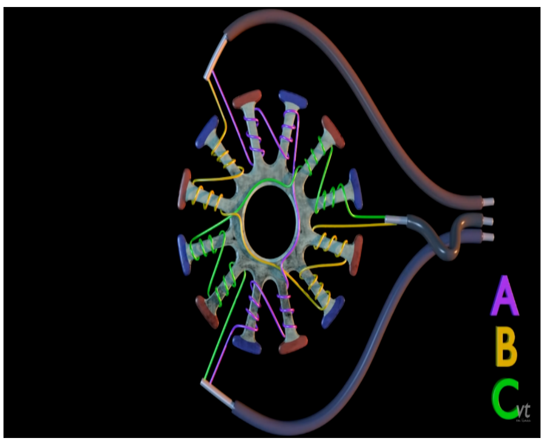
However, up to now, all the generators mentioned above, regardless of whether they are AC or DC, need an external source as a generation tool, and since in most cases a variable source is not available, a type of machine that does not require this element for its operation was sought.

“A brushless DC motor is one whose poles are made of permanent magnets. Since they do not require an external field circuit this type of motor has no copper losses. Because they do not require compensation windings, they can be smaller than those connected in DC shunt.” [10].

“Its operation is mainly given by energizing two of its three coils at the same time and exchanging them thanks to a hall sensor inside.” [11]. This voltage in turn induces a magnetic field that allows the rotor to move. A constant variation between at least two of the three coils will guarantee an output of up to 10hp (common motors) on the motor shaft.

A brushless machine was used as the generator for the project because of its benefits and ease of operation.

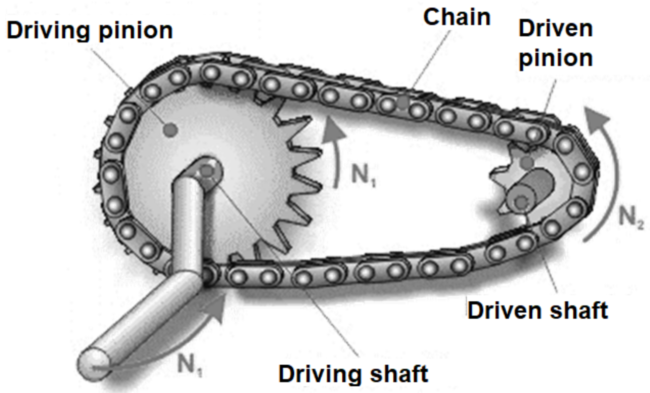
Figure 3. Internal model of the generator).



Source: own.

The generator is anchored to a base with the help of two ‘L’ shaped supports and bolted to each side of the machine; along with this, stability is provided with the help of extra wooden supports from our manufacturer to reduce, as much as possible, unwanted movements of the generator when it is driven by the elliptical bike. Two sprockets and a conventional chain will be used for the transfer of motion from the bicycle shaft to the generator shaft.

Figure 4. Sprockets will be used for the transfer of motion.



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As can be seen in Figure 4, two sprockets will be used for the transfer of motion. The driving sprocket is anchored to the axis of the elliptical bicycle, being the larger one, and the smaller one (driven sprocket) is anchored to the generator using a toothed steel chain. The size difference in the sprockets is given to take advantage of this difference to gain speed. This fact is known as the transformation ratio and is explained as follows: “the transformation ratio is a difference between (in this case) speeds which can be expressed mathematically as a gain. The higher the gain in the system, the higher the speed will be increased, but the torque will be lost and inversely, since as is well known, energy does not disappear, it is only transformed. This gain is controlled by the number of sprockets in the arrangements, which in turn depend on the radius of the plate where they are arranged” (12).

Where ‘a’ be the gain, ‘V’ the velocities, and ‘N’ the number of teeth, the following relationship can be made.

$$a = \frac{N1}{N2} = \frac{V1}{V2} \quad (6)$$

As can be seen in Figure 3, the type of generator used contains three coils in series which are energized in the sequence of coil A, coil B, and coil C periodically and consecutively.

When storing or transferring energy, either alternating or direct current, we have, in a single-phase nomenclature, a positive terminal and a negative terminal, so, having three different coils, we need a three-phase rectifier which is responsible for joining the three signals from the coils at the input and output to provide a positive and a negative terminal.

Figure 5. Three-phase bidirectional rectifier. [13]

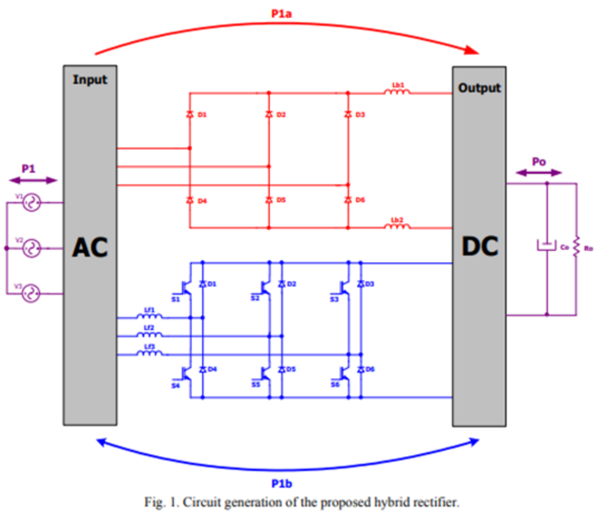


Figure 5 represents the three-phase bidirectional rectifier: "This type of element is used as a technology for power systems to perform a flow and efficiency analysis more simply. In other words, rectifiers are employed to simplify systems at a low cost." [13]. In this specific case, a unidirectional rectifier was needed 'only' to simplify our system, so, it is of interest only the P1a section of the graph. This arrangement is composed of 6 diodes in a parallel configuration with 2 diodes for each line of the circuit. As shown in the figure each of the generator coils (in this case represented as synchronous machines) is connected in the intermediate of each pair of diodes so that at the end of the configuration the part denoted as load in the circuit is connected to a battery capable of storing the voltage generated.

For diode sizing, the following was performed:

$$\text{In} = \frac{\text{Pn}}{\text{Vn}} \qquad (7)$$

$$\text{In} = \frac{250\text{W}}{36\text{V}} = 6.944[\text{A}]$$

As it is a 6-node configuration, the current is divided over 6 nodes to know the current value that each node needs to support:

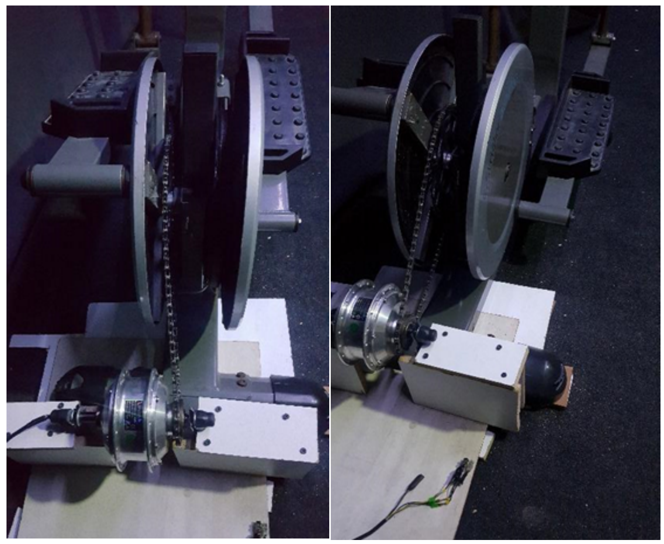
$$\text{Idiode} = \frac{\text{In}}{6} \qquad (8)$$

$$\text{Idiode} = \frac{6.94\text{A}}{6} = 1.157\text{A}$$

Each diode must withstand at least 1.16A. Based on this data, the motor voltage, and the purpose of the circuit, the 1N5404 rectifier diode is selected, which has a nominal voltage of 3A and a maximum operating voltage of 30V.

With this type of diode, we make the rectifier circuit and with this configuration and the above-mentioned, a series of tests were performed to determine the generation capacity of the machine:

Figure 6. Tests were performed to determine the generation capacity.



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As mentioned above, to support the generator and attach it to the elliptical bicycle, a wooden base was made with the help of angles, which are responsible for holding the generator in the position required for the coupling.

On the elliptical shaft, the disc with the largest diameter was attached and on the generator shaft, the pinion with the smallest diameter. This configuration was explained above. These two disks are joined using a chain that was adjusted specifically for this configuration and distance to take advantage of the movement in the best possible way.

With this configuration, tests were performed at low, medium, and high speeds and the results obtained were as follows:

Table 1. Tests were performed at low, medium, and high speeds.

Intensity	Generated voltage (VDC)
Low (18 rpm)	Between 5 V and 12 V
Average (27 rpm)	Between 12 V and 19 V
High (55 rpm)	Between 19 V and 30 V

Source: own.

A multimeter with NENG with an accuracy of 0.01% in DC voltage measurement on a 200DVC scale was used for data acquisition.

Photographic evidence is attached below:

Figure 7. A multimeter with NENG.

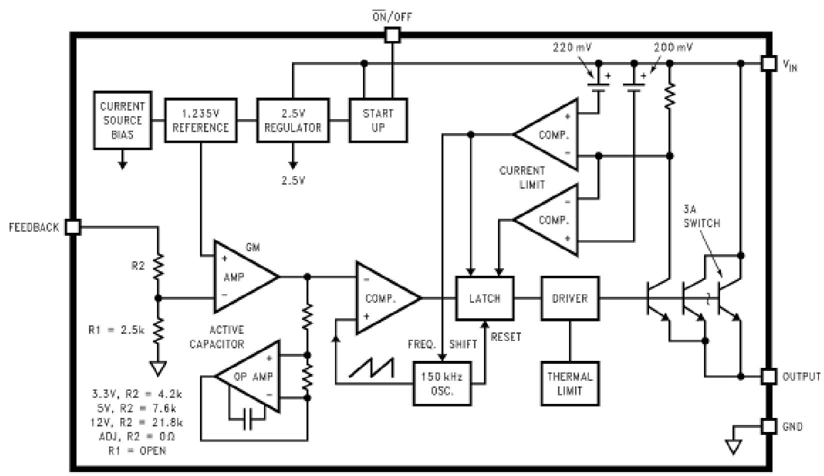
Source: own.

Considering that we will store the electrical energy generated in a DC battery, we must implement a DC converter circuit and DC reducer which is responsible for regulating the output voltage to a constant voltage of 12 V-24 V-36 V (depending on the battery to be connected) which will be transferred to the battery to be stored.

Figure 8. LM2596.

Source: own.

Figure 9. Internal diagram.

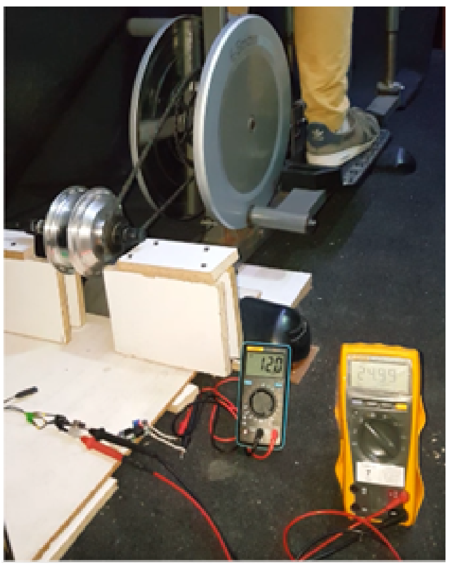


Source: own.

The LM2596 converter circuit in Figure 9 is operated with a variable input voltage between 4.5 VDC and 40 VDC with a current up to 3 Amp and a variable output voltage from 1.5 VD to 35 VDC. With the potentiometer shown in the upper part of the figure the output voltage is regulated, tests were performed again and the voltage level was set to the required level (12 V was used as the test voltage). Figure 10 represents the internal diagram of the integrated used in the converter circuit which works by employing a comparator that adjusts a PWM that adjusts the SW output of the circuit. [14].

Another test was performed again where a multimeter was placed at the output of the rectifier circuit and another one at the output of the converter circuit to set the output voltage with the help of the potentiometer and show the change in the voltage difference:

Figure 10. Load through the generator with two multimeters.



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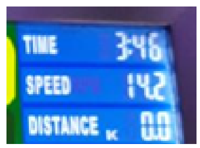
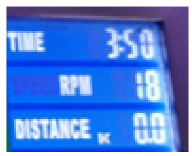
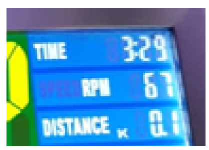
The circuit is in Figure 11.

Once the voltage level for the energy input to the battery has been set, it is ready to show the load through the generator.

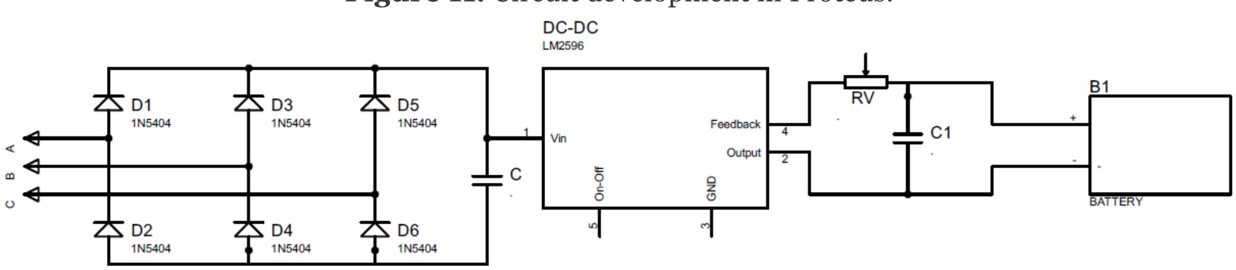
When coupling the elliptical bicycle generation system to the battery it is necessary to use a semiconductor diode which will be responsible for allowing only the passage of current in one direction (generator-battery), since, otherwise, the battery will feed the motor with a voltage that will not be used and therefore would be a loss of energy. The diode for this case is selected according to the maximum current that can dissipate the gear circuit which is 3A. For this reason, a semiconductor diode of the following commercially available value was selected. The diode selected was the MIC 6-A-8.

Table 2. Data collection evidence table.

Speed (RPM)	Generated Voltage
	
	
	
Connection to the LM2596	

Source: own.

Figure 11. Circuit development in Proteus.



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3. Conclusions

It is possible to implement additional alternatives to conventional ones to generate electricity. Implementing an elliptical bike, in addition to taking advantage of the movement to the maximum possible for the generation, allows better physical conditioning for the user. Although there is no constant output voltage, it can be regulated with a DC-DC converter.

The energy collected will depend on the characteristics of the battery used and the time it is used, taking into account that the maximum current is 3Amp and the voltage is variable for a battery of up to 36V.

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