Bike-Powered Electricity Generator

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***Abstract** – Finding new energy sources is an important challenge of our times. A lot of research focuses on identifying such sources that can also be exploited with relatively simple and efficient systems. These sources can be either new materials that can be used to generate energy, or solutions to scavenge already existing forms of energy. Part of the latter class of solutions, the system presented in this paper converts the energy consumed by many people in gyms (or even at home, during exercise) into electric energy. This energy exists anyway, because people want to be healthier or to look better. Currently, this significant (in our opinion) amount of energy is actually wasted and transformed into heat. Instead, in this study, a prototype scavenging system (dedicated to fitness/stationary bikes) to collect and (re)use this energy is presented. Specifically, we depict the design of a low-budget system that uses existing, discrete components and is able to scavenge some of the energy spent by the biker. The experimental results show that the system is functional, but its efficiency is limited by (mechanical) losses before the collection.*

***Keywords** – bicycle, electrical brake, energy conversion, scavenged energy.*

INTRODUCTION

Picture this: a gym with a lot of cardio devices and equipment, including many stationary bikes, and people training hard to improve their physical condition. This picture shows a great amount of energy *being consumed*. All these cardio devices have different levels of difficulty that allow users to adjust their effort using mechanical or electro-magnetic brakes. By increasing the brake power, more energy must be generated by the users and further transformed into heat - in case of mechanical brakes. In other words, it is simply wasted. What if we can design a system that can play the role of an electro-magnetic brake which would convert the physical energy of the user into electric energy instead of just dissipating it ?Define abbreviations and acronyms the first time they are used in the text, even after they have already been defined in the abstract.

Stationary bikes seem to be the most convenient devices to be transformed in electric generators due to the compatibility of the rotation movement needed for engaging the generator. Therefore the design of a system that replaces bike's mechanical brakes with electric ones is aimed. First, we have to investigate how much energy a user consumes, in order to determine the amount of energy available for conversion. This energy has two components: one for *low work level* used to rotate the wheel in a normal way, and one for *high work level*, for more difficult exercises, such as virtual hill climbing. Because the first category is expected to give little benefits (Glaskin, 2013) we focus on estimating the energy available for collection in the high-work regime.

Data for 24 people, aged from 16 to 61 years old, riding a bicycle for 17 km (10 miles) were recorded and analyzed. During data logging procedure the average power of a biker varied between 215W to 375W. The graph in Fig. 1 shows the maximum duration of human effort for different levels of power. From this graph one can observe that "healthy humans" can sustain approximately 75W (0.1hp) for a full 8-hour period, while "first class athletes" can sustain approximately 300W (0.4hp). And that is for a single (stationary) bike; they are 20 times larger for a medium-sized gym with 20 bikes. We believe these numbers are promising and justify an attempt to harvest (part of) this energy efficiently.

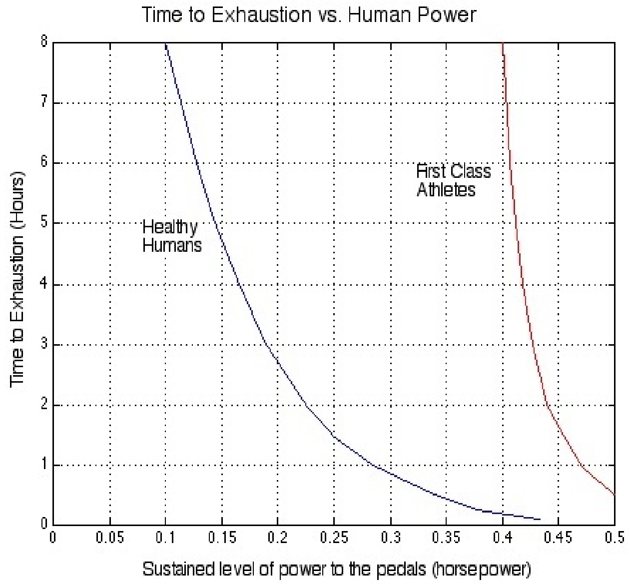

Figure 1. Human effort time vs Sustained power; the maximum duration of human effort for different levels of power (Glaskin, 2013)

Various scenarios for using the scavenged energy can be imagined. For example, at home or in fitness centers, the harvested electric energy can flow into the local power network or can be stored locally for future consumption.

Thinking bigger, the scavenging system can be part of a generating system delivering the energy in the regional power network. Integration of small, local energy suppliers into local or regional powers systems is discussed in (Dumitrache *et al.*, 2008) and other authors.

The rest of this paper is organized as follows: Section 2 presents the architecture and Section 3 presents the functionality of a system that harvests the energy spent on stationary bikes. Section 4 presents the possible integration into an energy system. Section 5 presents experimental results and Section 6 and 7 present related work, conclusions and future plans to improve the current solution.

SYSTEM ARCHITECTURE

The main goal was to develop a simple and modular system that can be used both in gyms and at home without special mechanical or electrical skills. The basic idea is to connect a bicycle to a static system capable of transforming the rotation of the pedals into electric energy.

The system that converts mechanical energy into electric energy consists of two blocks:

A. Mechanical Block – has the role to transfer the rotation movement of the pedals and adapt it to the generator requirements.

B. Electric Block – has the role to convert the energy provided by the mechanical block into electric energy.

2.1. Mechanical block

The mechanical block was designed starting from the following assumptions:

1. Use available components that should not change their functionality. In other words, every part of the mechanical block is an independent device, that can be further replaced with better or cheaper versions.
2. Use recycled and refurbished components. The "age" of the components does not matter as long as their initial functionality is not altered or damaged.
3. Use low-budget equipment. Assuming that the system will be replicated for many fitness devices, its cost should be as low as possible.
4. Individual components must allow fast and safe connectivity and operation

In Fig. 2 the physical system is presented. The mechanical block consists of:

1. *Fitness bicycle*: a regular road bicycle with d_r = 71 cm (28 inch) wheels and equipped with front and rear derailleurs was used for the experiments. The front derailleur moves the chain across two chain rings having c_1 = 47 and c_2 = 52 teeth respectively. The rear derailleur moves the chain across six sprockets which have s_1 = 14, s_2 = 17, s_3 = 20, s_4 = 22, s_5 = 24 and s_6 = 26 teeth respectively.
2. *Home trainer*: supports the weight of the bicycle and the user and also plays the role of a multiplicative system. The rear wheel of the bicycle connects to the cylinder of the trainer, which has a diameter d_c = 3 cm, multiplying the cylinder speed with a factor of 23. This multiplication is needed due to the generator requirements. Movement (rotation) is transferred between the wheel and the cylinder only based on the friction between them. The home trainer can be used with virtually any type of bicycle extending the latter's functionality (from road bicycle to indoor fitness bicycle) so the user will no longer need two different equipments this way saving both money and depositing space.
3. *Transmission module*: a pulley was installed on the cylinder of the trainer, which is connected with the pulley of the generator through a transmission belt. The diameters of the pulleys are the same and the transmission ratio is 1.

Figure 2. Bike-powered electricity generator; scavenging system – mechanical block and electric block

2.2. Electric block

The electric block is presented in Figure. 3.

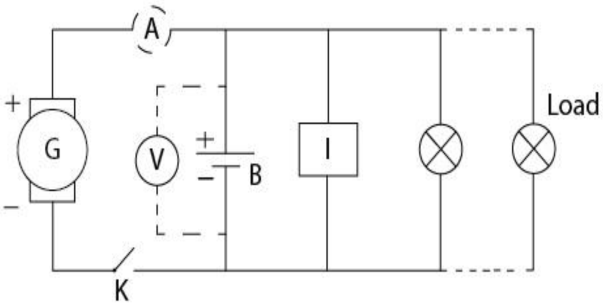

Figure. 3. Electric block diagram

where:

G – generator
B – group of lead–acid rechargeable batteries
I – inverter
A – ammeter
V – voltmeter
K – switch

There were three options for choosing the generator: car alternator with an integrated voltage regulator, car alternator with an external voltage regulator and a permanent magnet alternator.

The three criteria used in choosing the generator were:

1. The generator output voltage should comply with the battery charging conditions. For this reason, the output voltage should be between 14.2V and 14.8V.
2. The connections between the components should be very simple.
3. Embedded regulator into alternator chassis would be preferred since it may help save space, reduce wiring demands and the system would be less susceptible to mechanical damages due to error in handling or even during regular use.

The generator (G) that meets all the above requirements is the automotive alternator with integrated voltage regulator. The availability on the market, the variety of shapes, sizes and outputs have been other advantages that have been taken into consideration when choosing this unit for prototype implementation. Furthermore, the working principle was validated, over many years, by the automotive industry, where more severe challenges (extreme temperatures, humidity, high revs) are met.

To temporarily store the harvested energy a group of 12V lead – acid batteries (B) was used. In order to deliver the stored energy into the (local or regional) power network we also use a 300W, $12V_{cc}/220V_{ca}$ inverter (I).

The voltmeter (V) and the ammeter (A) have a double significance: they are used during the experimental stage but they are replaced with transducers for the batteries management in the final solution.

SYSTEM FUNCTIONALITY

The equation that calculates the generator pulley speed, as a result of pedals rotation movement is:

$$N(t) = N_{ped}(t) \cdot m_1 \cdot m_2 \cdot m_3 \qquad (1)$$

with:

$$m_1 = c_i / s_j;\ m_2 = d_r / d_c;\ m_3 = d_{pt} / d_g \qquad (2)$$

where:

N – generator pulley speed [RPM]
N_{ped} – pedals speed [RPM]
c_i – chain ring dimension [teeth]
s_j – sprocket dimension [teeth]
d_r – rear wheel diameter [cm]
d_c – home trainer cylinder diameter [cm]
d_{pt} – pulley home trainer diameter [cm]
d_g – pulley generator diameter [cm]

Table I presents the "theoretical" values of the generator speed and the values of the output current, considering the output voltage rather constant and the mechanical block power much bigger than the generator power. The output current values I_g were taken from the alternator characteristic $I_g = f(N)$ (Delco Remy, 2008).

Table 1. Theoretical values of the generator speed and the values of the output current

m_1	m_2	N_{ped}	N	I_g
c_1 / s_6 = 46 / 26	23	60	2441	50
c_1 / s_5 = 46 / 24			2645	54
c_1 / s_4 = 46 / 22			2885	60
c_1 / s_3 = 46 / 20			3174	64
c_1 / s_2 = 46 / 17			3734	71
c_1 / s_1 = 46 / 14			4534	76
c_2 / s_6 = 52 / 26			2760	56
c_2 / s_5 = 52 / 24			2990	61
c_2 / s_4 = 52 / 22			3261	65
c_2 / s_3 = 52 / 20			3588	70
c_2 / s_2 = 52 / 17			4221	74
c_2 / s_1 = 52 / 14			5125	77

The energy produced by the user while using the bike is harvested and transformed into electric energy using the generator described in the previous section and then stored into batteries.

This solution may sound simple and somehow intuitive but its' implementation posed quite some design and engineering challenges for interconnecting the blocks and for actually harvesting the energy for future re-use.

In the electric block, the generator transforms the mechanical energy, produced by the user, into electric energy. The equation used to model the dynamic parameters of the alternator (Danciu, 1999) is:

$$I_g(t) = [\omega(t)\cdot k \cdot I_{ex}(t) - U_G - U_D\,] / Z_G(t) \quad (3)$$

with $\omega(t) = [2 \cdot \pi \cdot N(t)] / 60$.
where:

U_G – alternator output voltage [V]
$\omega(t)$ – alternator pulley speed [rad/s]
$I_{ex}(t)$ – excitation current [A]
$Z_G(t)$ – alternator impedance [ohm]
$I_g(t)$ – generated current [A]
U_D – diode rectifier voltage [V]
N(t) – generator pulley speed [RPM]
k - constant

The connection of the two blocks reveals *the first problem* we have encountered. The generator requires a minimum (threshold) speed (see Fig. 9). To solve this problem we have introduced the switch K in the electric block. The switch remains in the state „open" until N(t) exceeds the threshold speed of the generator. The period of time with K in the state „open" means a small effort for the user and can represent a „warming up" stage.

Once the speed exceeds the threshold and the user decides to increase the difficulty of the exercise, the switch is manually closed and the generator becomes an electric brake (the breaking intensity depending on the load connected to the generator). From this moment, the physical exercise intensity is directly related to the generator load (the bigger the load, the more difficult the exercise becomes). At the same time, the user should be able to choose the level of effort he wants to be subject to. Implementing an electric brake for different levels of effort means, by default, choosing between different levels of load. These different levels of effort (brake power) can be created using either more consumers (bulbs, radio, laptop etc.) or some storage capacities (batteries). Because, for now, we couldn't connect our system to a smart grid, or other local or regional power system, the energy had to be consumed or stored into batteries.

The amount of harvested energy is time variable depending on a lot of factors: the number of users, the time of the day, the intensity of the exercises and so on. This means that the amount of energy is almost always different (bigger or smaller) than the amount of energy required by the consumers. Therefore, an energy buffer that can be able to "moderate" between the energy produced by the generator and the energy required by the consumers must be introduced. The batteries play the role of this buffer but they are also mandatory for the alternator excitation (Danciu, 1999).

If the batteries are the only load of the generator, the charging current (and by this the user's effort) is linearly dependent on the storage capacity and on the state of charge of the battery (Kiehne, 2003). Fig. 4 presents the three-stage charging profile of lead–acid batteries.

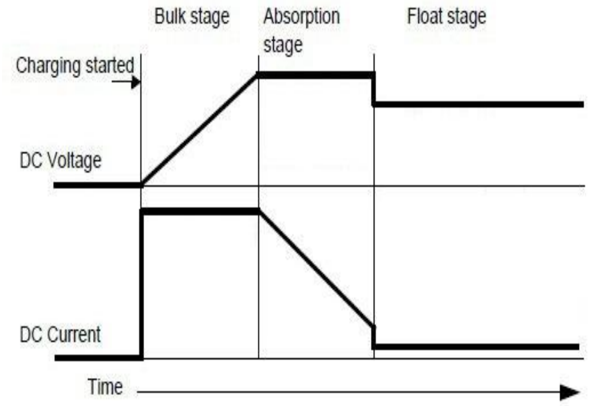

Figure 4. Three-stage charging profile of a lead-acid battery.

An important characteristic of the charging process is the initial charging current of the battery. *The second problem* that was encountered is the trade-off between initial charging current and effort. At the beginning of the process, the internal resistance of the battery has a small value. Because of this, the charging current has an overshoot (about 30% from the maximum current that specifies the battery capacity) for a short period of time (Kiehne, 2003; Pang *et al*, 2001). This phenomenon and the low inertia of the mechanical block will lead to a sudden increase in user effort in the time interval immediately after the switch is closed. Another drawback is represented by the possible loss of friction between the bicycle wheel and the metallic cylinder of the home trainer on one hand and the pulleys and the rubber belt, on the other. Because we have to provide a seamless transition between levels of effort, we have to reduce the initial charging current and to use batteries with low storage capacities. This way, the user will feel a smoother operational shock when activating the switch.

The harvested energy is stored, for this prototype, in two batteries with the same capacity. Using such a structure, it was possible to implement an electric brake through dynamic switching. The criterion used for transition between different levels of effort is the battery charging current I_{ch}.

ENERGY MANAGEMENT

The batteries of the scavenging system have to meet the following conditions:

1. The voltage measured at the battery terminals has to be always greater than the minimum allowed value. Otherwise, excitation for the alternator will not ensure it's functionality.
2. After the users' training, the stored energy should be converted (from 12V to 220V with the aid of the inverter) and injected into the power network.

Because the storing capacity of the batteries is small and it takes a lot of time until the scavenged energy is going to be delivered into the power network, we decided to add a third battery (named *secondary battery*) with a storage capacity at least twice bigger than the primary batteries capacity. This battery has to insure the interface with the network.

Figure. 5 presents the algorithm of energy transfer during training while Figure 6 presents the energy transfer flowchart at the end of the training.

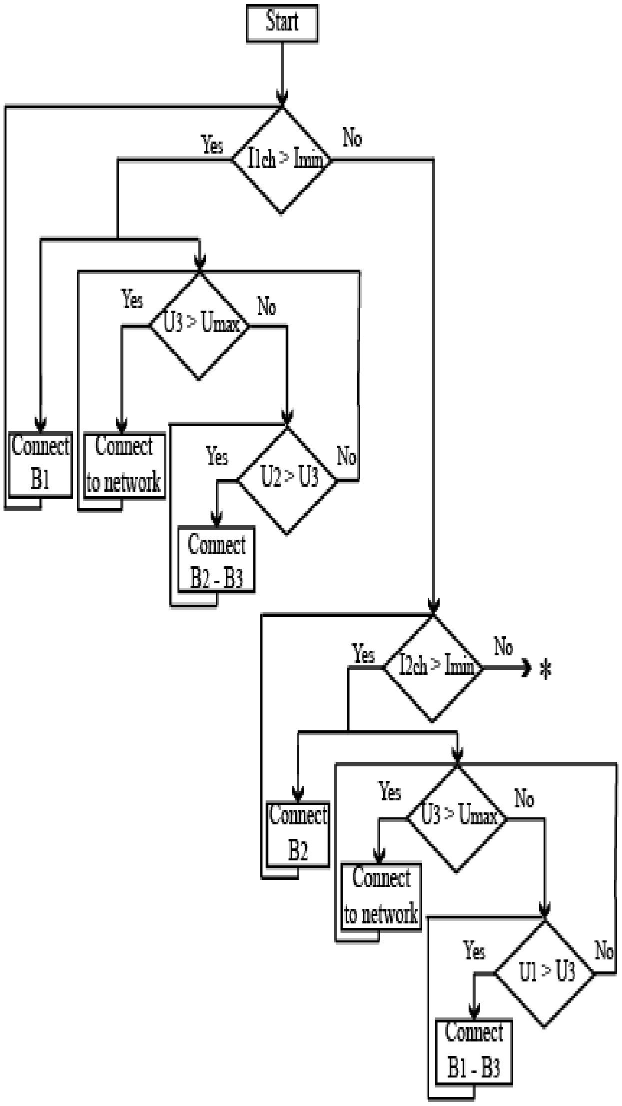

Figure. 5. Energy transfer flowchart during training, showing how the primary (B1,B2) and secondary (B3) batteries connect.

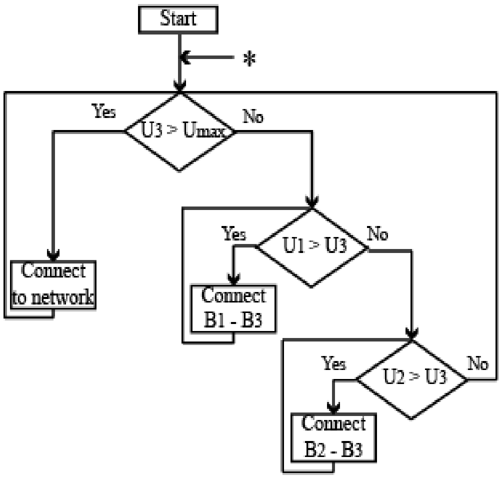

Figure 6. Energy transfer flowchart at the end of the training, showing how the primary (B1-B2) and secondary (B3) batteries connect.

where:

$B_{1,2}$ – primary batteries
B_3 – secondary battery
$U_{1,2,3}$ – primary and secondary batteries measured voltage
I_{min} – charging current during the float stage (see Fig. 4)
U_{max} – 12.6V, the voltage of the 90% charged battery

For the moment this algorithm is implemented using a programmable logic controller.

The secondary battery works as follows:

1. The energy from the primary batteries will be delivered into the secondary battery using an active balancing method.
2. The energy accumulated in the secondary battery should be delivered into the network at the end of the training session. As we discussed in Section I, there are two possible destinations: the local power network or the regional power network.

4.1 Using the local power network

In most countries country, the power installation in buildings is usually split in two: lighting installation and power socket installation. Since our system, at least at this moment, can produce up to 150Wh, the only eligible component is the lighting installation (because the power needed for a fridge or a washing machine is much larger). Due to latest technologies and innovations involved in reducing lightning energy consumption ("green" bulbs, LED based bulbs or "economic" bulbs), the harvested energy can be enough to power up to ore even more than10 bulbs for one hour. Since 2 bulbs are more than enough for having a regular room (15-24 m^2) illuminated, thins means the scavenged energy is enough for about 4-5 hours.

The block diagram in Figure 7 presents a method to connect the system into the local power network. The switch has the role to connect the scavenging system, so that the energy, stored in the secondary battery, can be delivered into the lighting network.

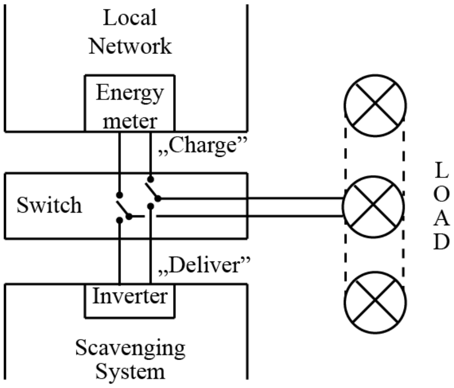

Figure 7. Local power connection block diagram. The scavenging system is connected into the lighting network, in parallel with the Local Network

The switch has to choose between the two sources like this:

1. If the secondary battery voltage will be greater than a maximum threshold (U_{max}), the scavenged energy will be delivered to the load.
2. If the secondary battery voltage is lower than a minimum threshold (U_{min}), the battery is going to be charged with the stored energy from the primary batteries and the energy will be delivered by the local network. Fig. 8 presents the switching process.

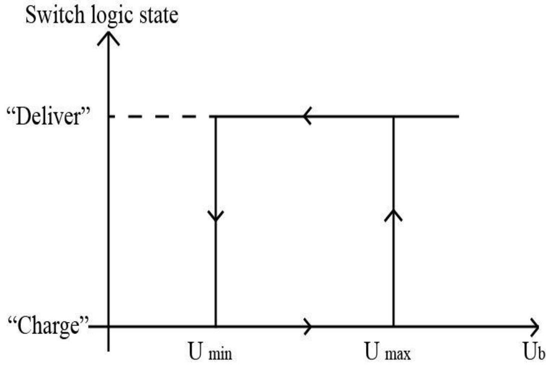

Figure 8. The switching process: the secondary battery behavior depending on the switch logic state (on/off)

4.2 Using the regional power network

In this case, we talk about the concept of a *smart grid* (Hamid & Reza, 2011). In this scenario, the end user can play to roles: consumer and producer. Every consumer that has the capability to produce electric energy using solar panels, wind turbines, or other modern technologies, can become a producer. The electric energy produced by the scavenging system can be delivered into the power grid using special equipment and safety devices to protect the grid components in case of faults. Another very important issue is represented by the control of electrical power systems, this problem is presented in (Dumitrache *et al.*, 2008).

V. EXPERIMENTAL RESULTS

The main goal of this study is to demonstrate that the energy from stationary bikes is worth scavenging by showing that the energy produced is not negligible. Therefore, we aim to determine the characteristic of the generated energy versus the generator speed (determined by the pedals speed) as a functional characteristic of the system.

Due to the linear dependence of energy with I_g (considering the voltage U_G rather constant), the generated current (I_g) can be used as a measure of the energy produced by the system. The measuring process consists of two indirect procedures: calculus of the generator speed and evaluation of the produced energy. We calculate the generator speed using equation (1), starting from the speed of the rear wheel measured with a bike computer.

The produced energy is evaluated using a set of bulbs (having different powers - 8W, 15W, 25W, 40W, 75W) as the generator load. We have used an increasing load, determining the values of speed corresponding to each load value: we increase the speed until *p* bulbs (totalizing *P* watts) light up, and we log the data point as the speed necessary to generate *P* watt.

During the experiments, the following conditions were enforced:

1. The batteries were fully charged to minimize the charging current and to deliver the whole amount of harvested energy to the consumers.
2. The user's heart rate was normal for this kind of exercise because the system is dedicated to „healthy humans".

For measurements, we used a 4-digit multimeter to measure the charging current and primary batteries voltage, a bike computer to measure the rear wheel speed, and a heart-rate monitor chest strap to measure the user's heart rate during exercise.

The steps of the experiment were:

- The bike's pedals are rotated with the highest speed possible (for a biker); theoretically we have a value of speed N close to the maximum;
- A number of bulbs connected as load to the inverter terminals turn on;
- N_{ped} is decreased until the bulbs turn off, the values I_g and rear wheel speed are logged and N is calculated;
- We increase the load and repeat the above steps.

Figure 9 presents the resulting experimental characteristic (the dotted line) and the alternator theoretical characteristic (Delco Remy, 2008) (the solid line). The two characteristics should be similar, meaning that similar values of the alternator pulley speed should determine the same output current values.

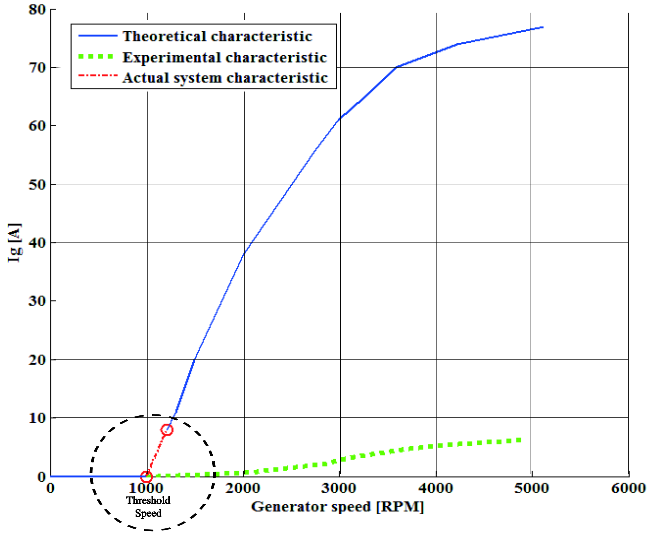

Figure 9. Experimental vs. theoretical characteristic

In Figure 9, however, there is a big difference between the theoretical characteristic and the determined one: the experimental characteristic associates current values with speed values much bigger than the expected ones according to the theoretical characteristics. This indicates that the pulley speed differs from the calculated one since the current "is generated" by the pulley speed and the pulley's speed is determined indirectly from the wheel's speed. The difference represents a loss of speed that can reach 75% of the calculated speed: we have expected a speed of 5000 RPM, and we have only about 1220 RPM at the generator pulley. This means that the calculated generator speed is much bigger than the actual one - i.e., we have been optimistic in Equation (1), where we did not account for any loss transfer of the speed from the wheel to the generator, and we had therefore overestimated the expected energy output.

The generator's pulley speed difference can be explained if we carefully analyze the mechanical block of the scavenging system presented in Fig.1. First problem is generated by the "connection" between the rear wheel of the bicycle and metallic cylinder of the home trainer. Low friction coefficient leads to a gliding connection which could not be compensated by varying the pressure of the tire. Despite initial expectations, by overinflating the tire the situation did not improve. Instead, severe damages were observed at the tire's exterior walls. A possible solution for this problem may be represented by a ribbed metallic cylinder (of the home trainer).

The second problem is generated by the transmission module, also presented in Fig. 1. Although the solution is widely and successfully used in automotive industry, the length and the rigidity of the rubber transmission belt have a serious impact over the system's functionality. If the belt is too tight, it generates a high mechanical resistance due to low material deformation at small distances and angles. If the belt is too lose, the friction between itself and the pulleys decreases and which means the generator gets even lower than the one we estimated and calculated based on the bike's rear wheel speed. A possible solution for this problem may be represented by the use of a synchronous belt (or toothed belt) and timing pulleys (teeth pulleys). The timing chain may be an alternative solution by this will lead to an increase of weight and inertia. At his point, this does not seem a valid approach.

Further analyzing the data, we could still determine the system functional characteristic starting from the generated current values, knowing that theoretical characteristic of the generator is unique. Therefore, we built the pairs (I_g, $N_{alternator}$) presented in Table 2; the resulting characteristic is presented in Fig. 10.

One can observe that the measured characteristic is in fact the first part (marked with a circle in Fig. 9), of the „theoretical" characteristic.

Overall, our results show that the designed system is capable to scavenge (some of) the energy produced by the biker on a stationary bike but the collected energy heavily depends on the losses in the system *before* reaching the collection point. Some of these losses do not appear in professional gym equipment but need to be addressed for home-use systems like the one proposed in this paper. Minor improvements at the mechanical block (as indicated above) should increase the generator's speed and, consequently, the output current.

Table 2. Experimental values

N	**$N_{alternator}$**	**I_g**
2111	1084	0.65
2322	1097	1.25
2856	1122	2.08
2980	1129	2.75
3187	1386	3.35
3676	1146	4.58
4160	1180	5.41
4901	1213	6.25

where:
$N_{alternator}$ – actual generator pulley speed [RPM]
N – calculated generator pulley speed [RPM]
I_g – generated current [A]

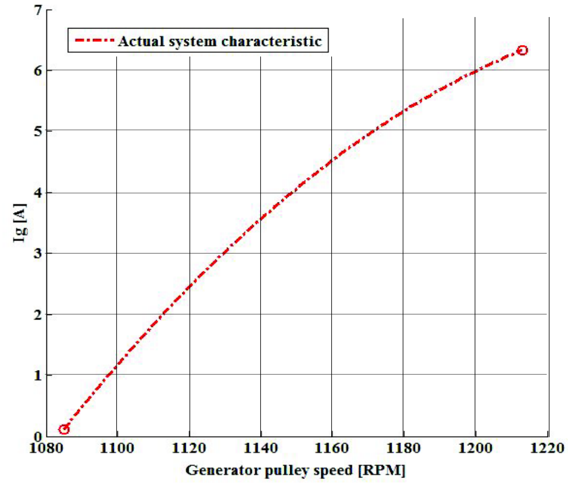

Figure 10. Actual system characteristic

EXPERIMENTAL RESULTS

There have been previous attempts to estimate the potential to generate electric energy using a stationary/fitness bicycle. For example, Michael Bluejay has proposed in (Bluejay, 2013) an estimate of the efficiency of generated electric energy by humans using a bicycle. His conclusions are that humans consume more energy than they produce when using bicycles, and therefore such a system is not efficient. However, while we agree with his calculations, we focus on a case where his premises are wrong: we scavenge energy *already spent* by people exercising, and not building a sustainable man-bike-powered electric generator.

Similarly, a calculation of the loss of energy in a pedal powered generator is presented in (De Decker and Joubert, 2011). The generator and the batteries we have chosen increase this efficiency up to 48%. At the same time, because the system described in (De Decker and Joubert, 2011) is being viewed as a sustainable generator, the calculated costs are wrong. When we are talking about return of investment, the energy delivered should not cover the price of the whole system. Because it is a scavenging system, the only components that should be taken into account are the generator and the batteries, the rest being independent and ordinary components or existing (general purpose) equipment, which is the case of the bicycle.

Ohio University presents in (Ohio University, 2014) the performance of human powered vehicles. It presents a steady-state power equation that takes into account the losses through air drag, surface wind, rolling resistance and ground slope. With this equation, we can determine the amount of high work level, correlate it with the slope ground and develop different energy profiles.

Contrary to these previous attempts, our approach does not aim to provide a solution for a sustainable generator system. Instead, we focus on transforming the effort spent by humans during exercise, nowadays lost, in useful electric energy.

CONCLUSIONS

In this paper an energy scavenging system built with *recycled* and *independent* components and targeted at the energy consumed while exercising was presented. The amount of harvested energy is more than sufficient to motivate us not to let it be wasted into heat or other forms of un-useful energy. While building the scavenging system we have encountered a couple of problems related to both the interconnections between the mechanical and electrical systems, as well as the interconnection between the scavenging system and the electrical network. Solutions for these problems were presented and a functional prototype of the system was created and tested in real working conditions. From an economical perspective, due to the recycled components, the system is affordable, costing about 400$. All the components can still be used separately.

The results obtained so far show that the prototype is functional. Its efficiency is, however, limited by various losses in the system, which needs to be addressed in its future generations.

In the next steps of this research, we plan to enhance and refine the design and test new solutions (e.g., use other types of batteries, such as lithium–ion, or a different type of generator such as an alternator with permanent magnets) and we are going to create a new strategy for the problems discussed so far. As soon as all the above mentioned options will be explored and the efficiency of the system will be satisfactory we aim to start working on a prototype to be built at industrial scale.

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