Power Harvesting Integrated in a Knee Implant for Autonomous Sensors Implanted in Human Body

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***Abstract*— This paper describes an energy harvesting system (EHS) composed of an electromechanical generator (EMG) and a dedicated energy management circuit integrable in a human total knee prosthesis, in which the mechanical energy from the knee joint is converted into electrical energy. Since the energy supplied by the proposed EMG is discontinuous in time, a tailored energy management circuit is necessary to adapt the harvested energy to the load energy requirements. The electromechanical generator is composed by two series of NdFeB magnets positioned into each condyle and a coil, placed in the pin of the tibial insert, which collects the magnetic flux variations, generated by the knee movements. A total knee replacement (TKR) prototype has been developed and realized in order to reproduce the knee mechanics. Therefore, electrical performances have been evaluated, at the first, measuring the EMG open circuit voltage by means of a high impedance buffer amplifier, and, subsequently, connecting the EMG to the energy management circuit able to manage the produced energy and to power an implanted circuit for force measurement inside the human knee. The tests showed that the EHS is able to supply the measuring circuit guaranteeing a tension between 2.45 V and 2.15 V for 25 ms almost every 1.5 s with a walking velocity of 1 Hz. The tests successfully demonstrate the possibility to power a measurement circuit transmitting the measurement data outside the prosthesis every about one-step and half.**

Keywords— electromechanical generator; human energy harvesting; biomedical devices; autonomous systems inside human body.

I. INTRODUCTION

A total knee replacement (TKR) is divided into three distinct parts, the femoral component (made up of the condyles), the tibial plate inserted in the tibia and the plastic insert on which the condyles slide. The tibial component and the femoral component are made of a titanium alloy or cobalt-chromium, while the plastic insert is made of polyethylene. The first cause of knee implant revisions is the wear of the articular insert and the infections following the wear of TKR (osteolysis) [1-3]. For reducing the wear of the Ultra High Molecular Weight Polyethylene (UHMWPE), the material constituting the tibial insert, two possible solutions are: the use of new materials for the contact surfaces and a more correct design of the prosthetic geometries. In fact, recent studies strengthen the hypothesis that, in the general case, for increasing the life of a TKP implant, a more appropriate design of the inserts is an aspect of primary importance, more than the wear performances of the material [4]. These considerations justify the effort to better understand the articular dynamic of the knee, due to its strict relation with the surface shear stresses (responsible for the UHMWPE wear).

The aim of the research is the realization of a measurement system energetically autonomous and implantable in the human body, more precisely within the knee prosthesis, able to measure the forces arising in the polyethylene insert in-vivo. Generally, these devices require a battery to function and this represents a major limitation, in fact, it must be replaced often due to the exhaustion of the battery and the battery is then to define the duration of the entire device. For this reason, alternative techniques are being studied to feed this kind of devices. One of these techniques is represented by power harvesting, which consists in recovering energy from the environment in which the device is located, in this case the human body.

In this paper, a specific system of power harvesting was considered. It is an energy harvesting system (EHS) composed of an electromechanical generator (EMG) and a dedicated energy management circuit implantable in total knee prosthesis capable of converting the mechanical energy, relative to the movement of the knee, into electrical energy. This EHS has been conceived in order to power an autonomous sensor system, integrated inside the prosthesis, able to measure in-vivo the loads on the articular surfaces and to transmit those outside. Since the energy supplied by the proposed EMG is discontinuous in time, a tailored energy management circuit is necessary to adapt the harvested energy to the load energy requirements. The EHS is fully integrated inside the knee prosthesis; in the thickness of each condyle, a series of prismatic magnets is placed, whereas one cylindrical coil is inserted in a cavity between the two condyles. The energy management circuit can be placed in the polyethylene insert. In this way, the relative motion between femur and tibia induces on the coil a voltage, according to Faraday-Newmann-Lenz's law. A CAD model was designed, and a finite element electromagnetic simulation has been conducted considering a flexion of approximately sixty degrees during the swing phase of the gait cycle with the aim to simulate a motion, as more as possible, corresponding to the real one. An experimental performance evaluation of the electromechanical generator (EMG) was done by developing an apparatus that simulates the human gait.

In a previous paper [5], a first prototype of an electromechanical generator (EMG) was built and tested. The tests showed that the first prototype of EHS was able to supply a load of 2.2 kΩ guaranteeing a tension between 2 V and 1.8

978-1-4799-6477-2/15/$31.00 ©2015 IEEE

V for 16 ms every 7.6 s. The experimental energy efficiency was about 10%. Then, that first prototype was redesigned and improved considerably respect to the output power. Furthermore, the power management circuit was redesigned with the aim to use more efficiently the scavenged energy. In this paper, the improved prototype is described and the new designed considerations described and commented. The new prototype was built and tested, and the experimental results reported.

II. DESCRIPTION OF THE PROPOSED POWER HARVESTER

Generally, the amount of energy produced by the human body is theoretically more than sufficient to power an implantable device [6]. The energy of the human body can be divided into three types: chemical energy, thermal energy and kinetic energy. The kinetic energy is, among the three listed above, the most abundant and more easily convertible into electrical energy. For example, during a normal walk, the different involved joints produce a significant amount of energy [7]; to get an idea of the values of energy and power involved, Table 1 shows the values of work and power calculated for different joints.

TABLE 1, WORK AND POWER CALCULATED DURING A WALK WITH A STEP OF 1 Hz [7].

Joint/Motion	Work [J/Step]	Power [W]
Ankle	34.9	69.8
Knee	24.7	49.5
Hip	19.6	39.2
Elbow	1.07	2.1
Shoulder	1.1	2.2

The power harvesting systems, which exploit the kinetic energy, can in turn be classified according to the physical principle exploited for the mechanical - electrical conversion; more precisely, these systems are divided into electromagnetic generators, electrostatic generators and piezoelectric generators. For example, the physical principle of an electromagnetic generator is based on the Faraday- Neumann –Lenz; a magnetic flux variable in time chained to a coil generates an induced electromotive force at the ends of the coil itself; the induced voltage is proportional to the speed of change of flux. Electrostatic generators, however, take advantage of a change in capacity to produce energy, whereas the piezoelectric generators exploit the properties of piezoelectric materials and produce an electric field when they are suitably deformed.

The proposed electromagnetic generator is fully integrated into a total knee replacement able to transduce the mechanical energy generated by the knee movement into useful electrical energy to power a circuit within the implantable prosthesis.

The proposed electromechanical generator is a non-resonant generator inserted in knee prosthesis. As shown in Figure 1, it is composed of six magnets in the shape of prism inserted in each condyle of the prosthesis and one coil positioned between the two condyles, in a protuberance of the tibial plateau. The relative movement of the magnets with respect to the inductor due to the movement of flexion-extension of the knee generates a variation of the magnetic field flux concatenated with the inductor, which in turn generates an induced electromotive force to the heads of the inductor themselves.

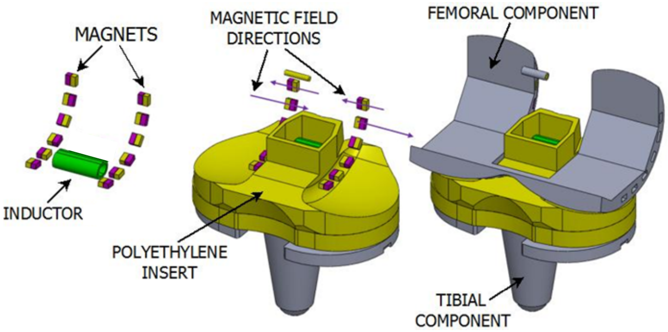

Fig. 1. Structure of the electromagnetic generator.

The proposed device is based on a direct conversion of the relative movement of tibia and femur, without the motion or the deformation of any other object, as commonly happens in the inertial (electromagnetic or electrostatic), fluidic and piezoelectric Energy Harvesting Systems (EHS).

Furthermore, in the proposed prototype, with respect to the existing EHS, the absence of moving or buckling components reduces the risk of failures of the materials (electromechanical components are not in contact and fixed in a dedicated housing) and consequently allows for a longer operating life.

The dimensions and the characteristics of the magnets and the electric characterization of the coil are reported in Table 2.

TABLE 2, CHARACTERISTICS OF THE COMPONENTS.

Comp.	Parameter [unit]	Value
Coil Copper	Diam. Int.; Diam. Ext. [mm]	4.5; 8.5
	length [mm]	16.5
	widings	2500
	equivalent series resistance [Ω]	204
	equivalent series inductance [mH]	36.5 mH
Magnet NdFeB	width, height, length [mm]	4; 4; 16
	residual induction [mT]	814
	coercive force [kAm^{-1}]	989
	intrinsic coercive force [kAm^{-1}]	1040
	energy product BH max [kJm^{-3}]	399
	max operating temperature [°C]	60

III. EXPERIMENTAL SETUP

The experimental setup used for the characterization of the electromagnetic generator and developed by the research group is shown in Figure 2. The motion control system, used for activating the prototype is in open loop. It consists of the programmable drive RTA PLUS K5 with dedicated PC based motion controller and of the stepper motor Sanyo Denki, model 103–H7823–1740 with basic step angle 1.8°±0.09° and theoretical acceleration 35700 rad·s^{-2}.

The EMG, tested through the experimental setup to simulate the movement of the knee, produces a voltage signal that depends on the walk frequency.

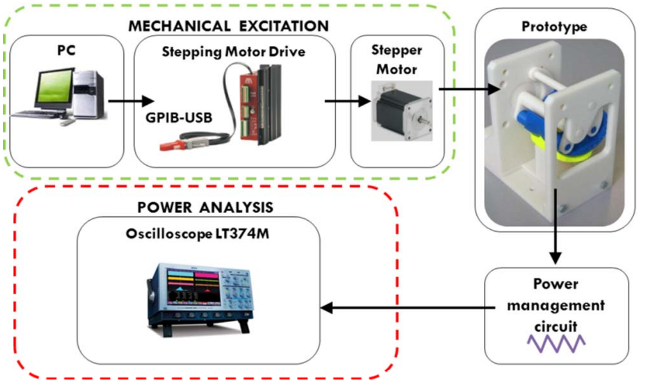

Fig. 2. Schematic of the experimental setup for the use and characterization of the electromagnetic generator.

More precisely, as shown in Figure 3 (a), the generator is able to produce a nearly sinusoidal waveform with a peak voltage at open circuit equal to about 2 V with a walking frequency of 1 Hz.

As shown in Figure 3 (a), each step can be divided in two parts, swing and stance. Only during half cycle, the EMG generates a waveform output, since, for simplicity, during the tests, only the swing phase of the cycle path was considered significant for the power harvesting. During this phase, the knee has in fact the variation of angle more significant and it is, therefore, reasonable to neglect the stance phase. In Figure 3 (b), (c) and (d), the generated output voltages with a frequency of 1 Hz and different resistive loads connected to the EMG are reported. The decrease in the amplitude of the voltage due to the effect of the load is evident. Further tests are underway to evaluate the power curve of the generator varying the load resistance and the walking speed.

In all the figures, the signal amplitudes are not equal; this is because the relative movement of some magnets with respect to the coil is not perfectly axial. However, the positions of these magnets can not be improved because of geometric construction constraints.

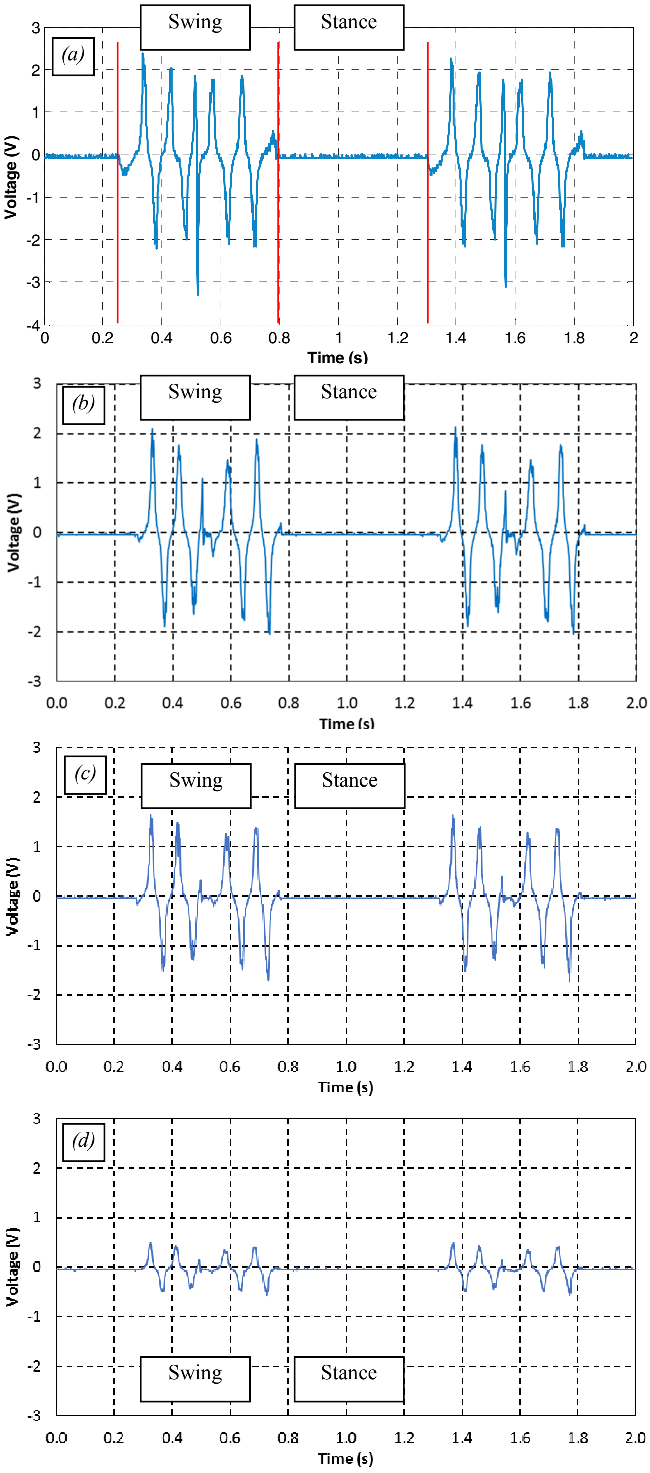

Fig. 3. Output voltage generated by the electromagnetic generator with a frequency of 1 Hz walk, (a) open circuit; (b) resistance of 100 kΩ; (c) resistance of 10 kΩ; (d) resistance of 1 kΩ.

IV. PRELIMINARY EXPERIMENTAL RESULTS

In Figure 4, the overall system tested experimentally is shown. The proposed power management circuit is composed by two multiplier circuits (Villard configuration) in two stages to which is connected a switch circuit. In the Villard circuits, the diodes are Schottky diodes (RB551V-30) and they have a threshold voltage of about 150 mV with a current of about 1 mA. The Villard circuits performs an AC / DC conversion of the signal. The Villard circuits, if not connected to the switch circuit, allow obtaining an output voltage multiplied per two, in steady-state conditions.

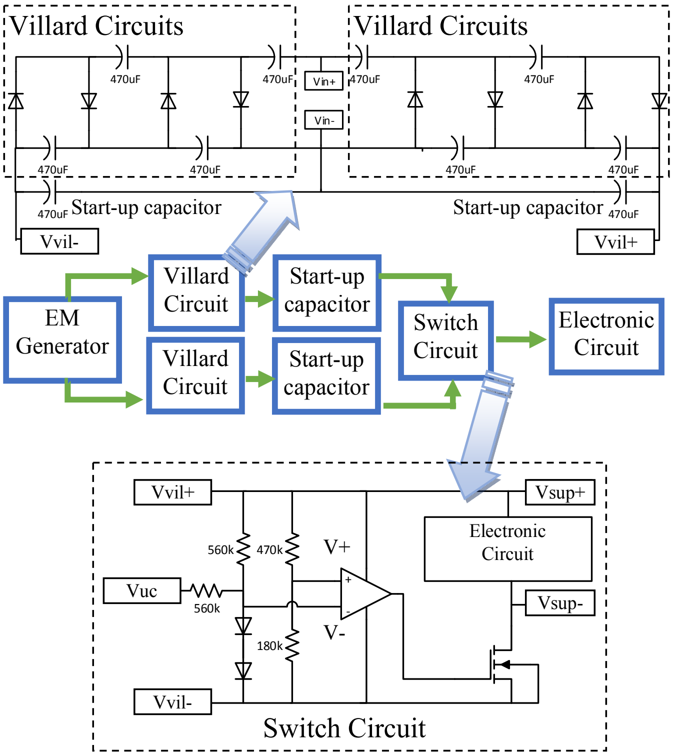

Fig.4. Overall system tested experimentally, overall block diagram and circuit diagrams.

The switch circuit permits to store the energy generated by the Villard circuits in the start-up capacitors and it releases this energy when it exceeds a specific value. The two diodes in the switch circuit are small signal fast switching diodes (1N4148). The amplifier used as comparator is the LT6003 marketed by Linear Technology.

As shown in Figure 4, the operation of the switch circuit can be schematized by a switch and two start-up capacitors. In particular, while the energy is accumulated, the start-up capacitors are not connected to the electronic circuit, because the voltage V+ is less than V- and, therefore, the NMOS (Si2342DS marketed by Vishay) is turned off.

When the voltage across these capacitors exceeds a certain value, the comparator turns on the transistor connecting the capacitors to the electronic circuit. During this phase, the start-up capacitors discharge through the electronic circuit shown in Figure 4, which is, in the present configuration, an implantable electronic circuit such as in [8]. The electronic circuit, which is under development, has a mean current consumption of about 5 mA with a mean power supply voltage of about 2.25 V. The required operation time is about 23 ms. Consequently, a total energy E_L of about 260 μJ is necessary for its functioning.

In the present configuration, a low-power microcontroller is used in the electronic circuit. This microcontroller allows adjusting the charging and discharging phases going to act on the voltage *Vuc*. When the transistor is turned on, the microcontroller is turned on as well, then the microcontroller imposes *Vuc* = *Vvil-* allowing to keep turned on the transistor and then the electronic circuit for the time necessary to perform the operations of measurement and transmission of the data. When the measuring cycle and the transmission is completed, the microcontroller can automatically disconnect the power supply by placing *Vuc* = *Vvil+*, this operation restarts the charging phase of the star-up capacitors.

Figure 5 shows the experimental results obtained with a gait cycle frequency of 1 Hz and 0.7 Hz. The time of the first start-up, the first charging of the capacitors, is equal to 14.6 s and 21.2 s respectively for 1 Hz and 0.7 Hz. When the voltage across the capacitors exceeds the value of 2.45 V the capacitors discharge through the output electronic circuit. After the first charge and discharge (about 14.6 s or 21,2 s, in the two analyzed cases), the following next charging times are always under 2 s and 4 s respectively for 1 Hz and 0.7 Hz. The time, during which the energy flows to the electronic circuit, corresponds to the discharge time of the capacitors and it is equal to approximately 25 ms (Figure 6).

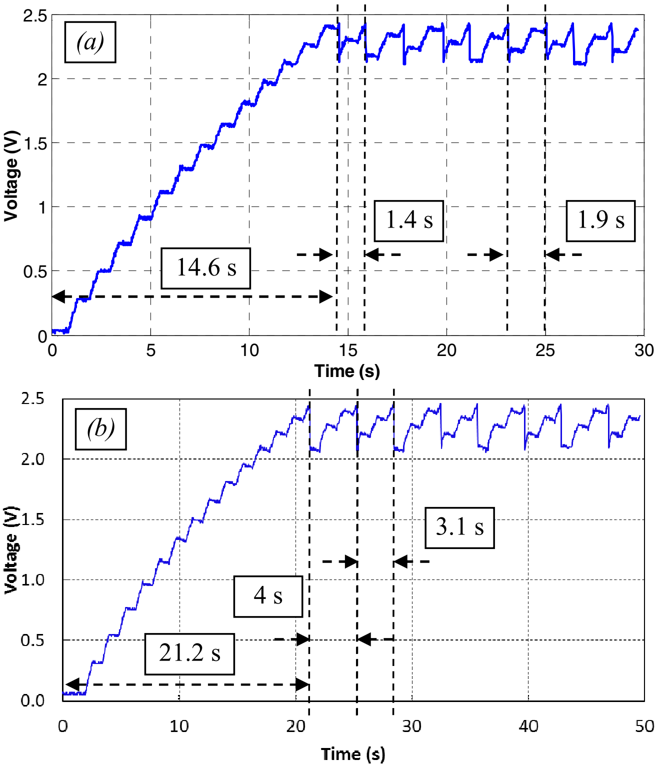

Fig. 5. Experimental results: Voltage across the start-up capacitor. (a) walking speed 1 Hz; (b) walking speed 0.7 Hz.

In other words, before being able to feed the electronic circuit in the prosthesis, it is necessary to wait for a time of about

14.6 s with the capacitors completely discharged and a less than 2 s with the capacitors partially discharged if a walking speed of 1 Hz is kept.

The difference between the time intervals (1.4 s, 1.9 s, etc.), in which the capacitors are recharged, is given by the fact that the energy from the generator due to the knee movement (Figure 3) is not continuous. This signal is characterized by a swing phase in which active energy flows in the capacitors, and a stance phase in which there is no energy generation. Therefore, the difference between the intervals depends on the moment in which the system occurs a phase or another (the stance phase or swing).

Figure 6 shows the output voltage ($\Delta Vsup = Vsup+ - Vsup-$) during the discharge phase and the voltage across the start-up capacitors ($\Delta Vvil = Vvil+ - Vvil-$). The output voltage decreases from a maximum of 2.45 V to a minimum of 2.15 V during an interval of about 25 ms, which is sufficient to perform all the operations required by the new measurement circuit under development, which is estimated in 23 ms.

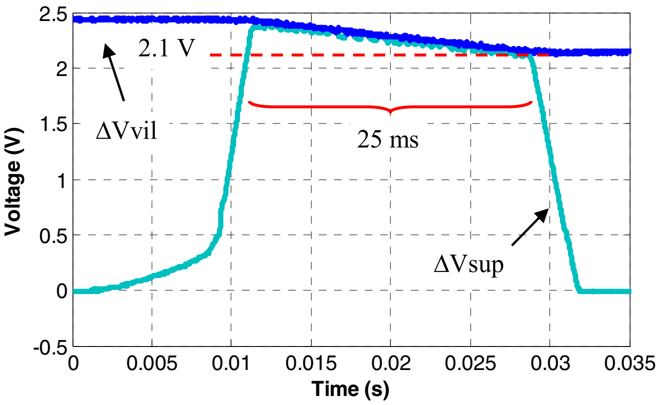

Fig. 6. Experimental results: output voltage (ΔVsup) during the discharge of the start-up capacitors (ΔVvil).

V. CONCLUSIONS

In this paper, respect to the state of the art, an improved power harvesting system is presented, based on an electromagnetic converter for the power supply of devices implantable within the human body. The proposed solution is designed in order to power supply a measuring circuit implantable inside total knee replacements. The generator consists of two rows of magnets, one coil and a circuit for energy management. A new power management circuit was designed, built and tested. This circuit permits to use more efficiently the scavenged energy controlling the switching thresholds. The overall system has been tested experimentally through a setup built ad-hoc. The tests proved the possibility of power supplying an implantable measuring circuit every 1.5 s via a walk with a step frequency of about 1 Hz. The experimental results were obtained using a measurement circuit under development and, therefore, not optimized in the power consumption and in the operation time. An optimization of the circuit in terms of reduced power and reduced operation time could lead to a further improvement of the performance. Further tests are underway to evaluate the performance of the system with different walking speeds and different resistive loads.

VI. ACKNOWLEDGMENTS

The Authors would like to thank Eng. Marco Bonfaini for his precious help in the implementation of the system.

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