

Optimized Power Harvesting Module for an Autonomous Sensor System Implanted in a Total Knee Prosthesis

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Abstract— Harvesting modules are a viable solution for powering measurement device avoiding the use of batteries or cabled solutions. This feature became important in biomedical devices and implantable biosensors for measuring vital body parameters. In this paper previously designed power harvesting module of autonomous sensor for implantable knee joint has been optimized. This device allows performing a force distribution measurement, a minimal data processing and a wireless transmission of measured value to the external unit. In addition, the designed module does not require any battery or external power source to power supply the system. The required energy is harvested by knee simulator movement which corresponds to human walking with frequency of 1Hz (step/s). Depending on calculated energy of capacitors, the design has been optimized along with the reduction in initial charging time of the power harvesting circuit, which has been improved from 14.6 s to 9.6 s. Moreover, the optimized circuit has also been tested on different walking frequencies in order to observe the threshold frequency on which the energy can be harvested and accurate data transmission can occur.

Keywords—*optimization; implantable biomedical device; villard circuit; wireless transmission; energy harvesting; autonomous sensor; total knee prosthesis; power management circuit*

I. INTRODUCTION

Nowadays energy harvesting (EH) technique is progressively investigated as substitute to batteries, mainly in low power sensing applications [1-3]. Its use within biosensor implants is rapidly getting in higher demands where the use of battery or external power source is not preferred and cannot be prosecuted due to risk of personal safety [4] and other specific reasons, which include inaccessibility to implant site, limited lifetime and battery's large size [5]. Thus, researchers have designed and developed several energy harvesting methods for implantable devices and it has been found that the human body is a great energy reservoir and it could be one of best source of harvesting energy [6]. For instance, it is possible to harvest electrical energy from kinetic energy of human body motion via electrostatic transduction, piezoelectric and electromagnetic generator methods [7-9]. In our work, the electromagnetic generator method has been used to transduce the knee movement into electrical energy, which is further used to power up the main circuit within implantable knee prosthesis and no external power is required. Therefore ideally, once it is implemented in human body then no maintenance would be needed from an energy point of view. In the literature, wireless power transfer is proposed [10] for power supplying

implantable device in prosthesis inside the human body. However, this method requires a coil around the leg for inductive coupling with an implanted inductor. Therefore, if adopted for continuous monitoring during daily life, this solution can be perceived invasive and it can constrain physiological movements during walking. Contrary, in the proposed solution, no device is necessary around the leg.

The need of optimized energy harvesting module for human knee implant arises as current research has manifested that by 2016 there will be increase in 50% of patients (under 65) that will require total knee replacement (TKR) [11]. Hence, in future the chances of revision TKR (second surgery) are highly possible event [12-13]. Therefore, a sensor based prosthesis system that will be capable of computing in vivo parameters like prosthesis force; stress etc. could be a feasible solution to this problem. This system will help to identify the total knee prosthesis (TKP) current conditions. Furthermore, physicians could continuously monitor and gather patient's information to improve its rehabilitation and therapy [14].

Hence, the present work aims at optimizing the performance of previously designed energy harvesting module [15]. The optimized module, which is capable of harvesting mechanical energy from knee joint movement and converts it into electrical energy, has been implemented in a force measurement device in human knee implants. As one of the problems that energy harvesting techniques suffer is low output voltage, so one of the solutions is to amplify the voltage via using Villard voltage multiplier circuit that has been used in the presented paper. An optimization method based on measurement procedure has been performed on the Villard circuit aiming at powering the measurement circuit every step. New Villard configurations have been analyzed experimentally to find out the optimized combination that fulfills the energy and voltage requirement of energy management circuit and will also transmit the data externally so that continuous monitoring of implant would be possible.

The complete structure of the paper has been organized in several sections. First section overviews the system description whereas, second section encompasses design of power harvesting module and its hardware implementation. Experimental results and analysis have been discussed in third section and finally last section highlights the conclusion and future work of our research work.

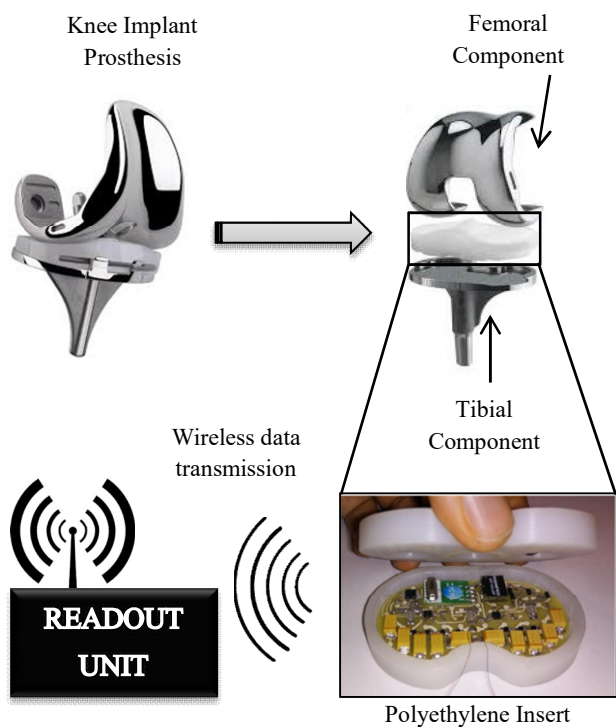


Fig.1. Schematic Representation of Knee Implant with Implantable Biosensor

II. SYSTEM DESCRIPTION

The overall system's schematic diagram has been shown in fig.1 which displays the human knee implant constructed by Ultra High Molecular Weight Polyethylene (UHMWPE) insert, a tibial component and a femoral component along with an implantable circuit within a knee implant. The entire measuring system is enclosed in the polyethylene insert, hence avoiding the biocompatibility complications and modifications of traditional implant shape as needed by other related applications [16–18]. This section has been further divided into 2 sub-sections of “Electromagnetic Generator (EMG)” and “Autonomous Sensor System” which are explicated in detail in further segment of the paper.

A. Electromagnetic Generator (EMG)- Total Knee Prosthesis (TKP) Simulator

Here previously built EMG [19] has been used as input for polyethylene insert which has capability to simulate the actual knee movement and depending on the walking frequency generates a voltage required to power the electronic circuit implanted within the knee prosthesis.

The proposed EMG is composed of six magnets that are inserted in each condyle of the knee prosthesis along with one coil situated among the two condyles as shown in fig.2. The extension and flexion of femoral component causes the relative movement of all 12 magnets with respect to the coil inductor which in turn causes a variation in the magnetic field flux induced within the inductor, and as a result induced electromotive force is generated to the heads of the coil themselves which acts as an input for polyethylene insert circuit.

B. The Autonomous Sensor System

Since in medical field substituting batteries with the energy harvesting system is advantageous and avoids medical problems, therefore it is need of an hour to switch towards autonomous sensor based energy harvesting systems for human implanted systems. Hence, in this work energy harvesting module of an autonomous sensor system for force measurement in knee implants has been discussed. This module mainly consist of two parts, first comprises of “implanted circuit” that will be inserted into the polyethylene of TKP and other part consist of the external receiver unit that will wirelessly receive the data from implanted circuit and display the transmitted data on output device (fig.3). However, in this paper only implanted circuit of the system has been discussed.

The implanted circuit consist of power harvesting module, force sensors, low power microcontroller, transmitter and antenna. The power harvesting module includes Villard circuit, startup capacitors and switching circuit. This module is used to harvest energy from the main electromagnetic generator (EMG) which then undergoes amplitude amplification via Villard circuit. Afterwards, switching circuit will store the harvested energy in the startup capacitors and will make it available for the rest of circuit depending on the requirement.

The force sensors used in this design comprises of magnetoresistive force transducers [10]. They are meant for generating a voltage proportional to the force applied from femur on the polyethylene insert.

The microcontroller is adopted in order to acquire, process, encode and transmit the data, a microcontroller has been used which also controls the activation of sensor system for data transmission only when required, thereby avoiding unnecessary transmission and reducing overall power consumption of the system. Here low energy consumption microcontroller MC9S08B4 produced by Freescale has been selected (TSSOP 16-pin package) that works on a supply voltage between 1.8 and 3.6 V.

As the measured data has to be transmitted wirelessly to the external reader unit therefore a suitable transmitter and antenna was required. Hence, to establish a wireless communication it

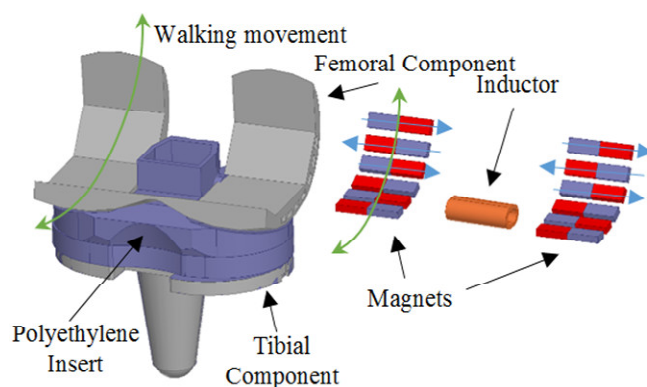


Fig.2. Structure of Electromagnetic Generator

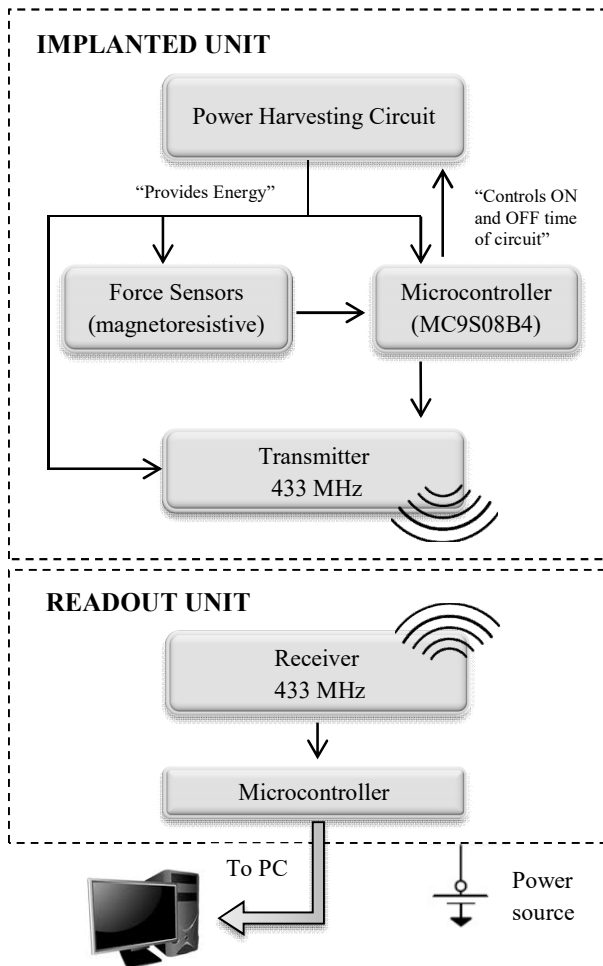


Fig.3. Overview of Autonomous Sensor System

is therefore necessary to choose a frequency of the carrier according to requirement. Thus, a frequency 433MHz that is not licensed and is free, well-known and tested has been chosen and finally 433MHz compatible transmitter unit “QAM-TX1” produced by QUASAR and antenna module “ANT-433- μ SP” produced by the Antenna Factor by Linx has been used.

III. DESIGN OF POWER HARVESTING MODULE

The designed power harvesting unit mainly comprises of Villard circuit which is connected to two startup capacitors which are further linked to switch circuit performing function of supplying input voltage to the electronic circuit containing microcontroller and other components used to transmit data wirelessly to the external unit. The block diagram of overall implemented power harvesting module has been shown in fig. 4. In this section the concept of Villard circuit and its implementation will be discussed in detail.

A. Villard Circuit as a Voltage Multiplier

Voltage multiplier that has been used is “Villard voltage multiplier”, which comprises of capacitor and diode in its circuit. Villard circuit has been selected as it provides more amplified output voltage when cascaded in series, hence acting

as cascaded batteries. Thus, the more stages we add in a circuit, the more output voltage would be obtained.

B. Four Stage Villard Circuit and its Implementation

In the presented power management circuit, Schottky diodes have been used in four stages Villard voltage multiplier which is coupled with startup capacitors and a switch circuit (fig.5). As the input to Villard circuit via EMG is sinusoidal wave therefore in order to utilize both the input cycles we have divided four stages multiplier into two Villard circuits (each of two stages voltage multiplier). The connection is made in such a way that one Villard circuit will work on positive cycle of sinusoidal input whereas, other Villard circuit will work on negative cycle and hence both will collectively amplify the output voltage. Besides, the four stages multiplier is selected because an operating voltage of around 2.2 V was required by the electronic circuit in order to perform its function and experimental test shows that required voltage could be obtained with minimum four stages Villard circuit with the given input. In the Villard circuit, the Schottky diodes (RB551V-30) having a threshold voltage of around 150 mV with a current value of 1 mA has been used. In fig.6 the hardware execution of harvesting unit has been shown which will harvest and supply energy accordingly, when connected to the rest of the circuit. This is one of the most important modules as the time duration of data transfer via power management circuit is controlled by charging and discharging time of Villard circuit capacitors. Hence, the Villard circuit has been optimized which results reduction in initial charging time of the capacitor and results in quick transfer of data to the output device.

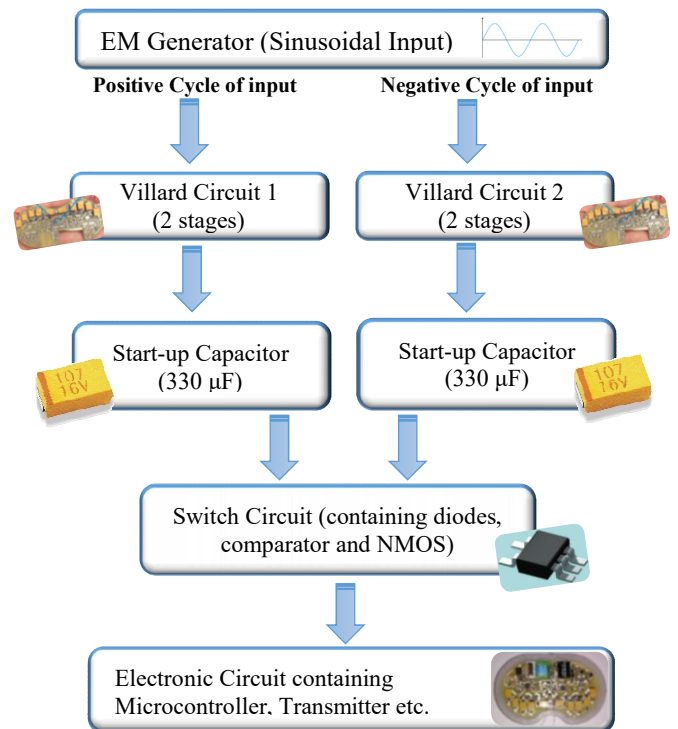


Fig.4. Block Diagram of Power Harvesting Unit

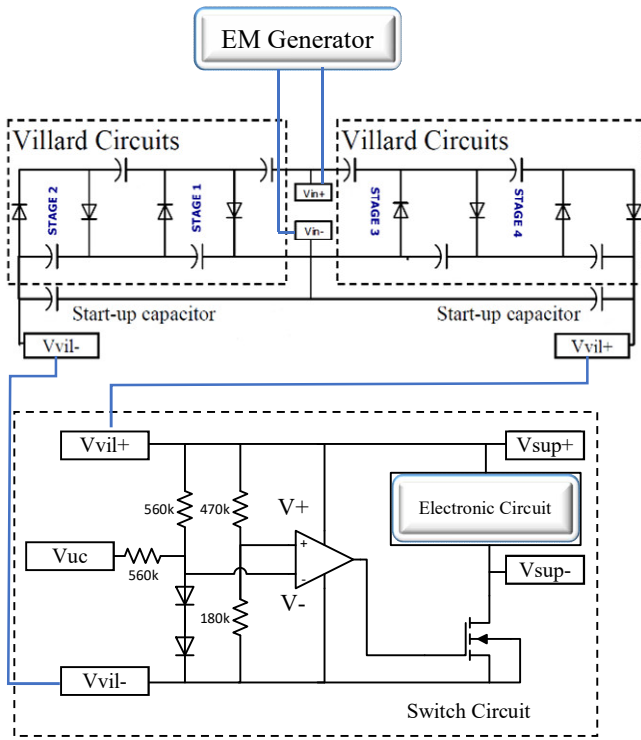


Fig.5. Design of Implemented Villard Circuit and Switch Circuit

IV. EXPERIMENTAL RESULTS AND ANALYSIS

After designing a circuit, various tests have been performed in order to analyze its performance. The performance was examined based on the following two main factors:

- Firstly, the correct data transmission to the external unit.
- Secondly, the charging time of capacitors that is required to achieve desired voltage needed to power supply the circuit

As the power harvesting module contains the microcontroller, therefore useful information have been extracted from its datasheet which shows that circuit needs approximately average voltage of 2.25 V with current consumption of 5 mA along with required operating time of about 23 ms. Consequently from these provided information, total energy required by the circuit to perform its task is calculated via equation (1).

$$E = V \cdot I \cdot t \quad (1)$$

Where “E” is energy, “V” is voltage, “I” is current and “t” is operating time. As a result, total energy required by the circuit is around 260 μJ . Hence keeping in consideration this energy value, different values capacitor for Villard circuit has been tested. The energy provided by the Villard circuit can be calculated using formula of energy stored in a capacitor which has been represented in equation (2).

$$E = (1/2) \cdot C \cdot V^2 \quad (2)$$

Here “C” is the capacitance and “V” is the peak voltage obtained by the capacitors during their charging phase.

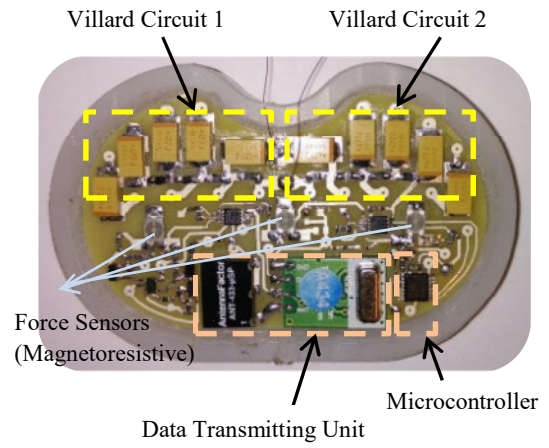


Fig.6. Hardware Implementation of Power Harvesting Unit

However, before calculating the energy we should know what would be the minimum capacitance combinations that we can use in our circuitry in order to obtain desired results. Thus, from equation (3) and (4) we can determine what should be the minimum capacitance value for the startup capacitors that can provide the required energy of minimum 260 μJ .

$$C_{\min} = (2 \cdot E) / V^2 \quad (3)$$

$$C_{\text{single_min}} = 2 \cdot C_{\min} \quad (4)$$

In above shown equation “E” is minimum energy required by the main circuit to perform data transmission activity, “V” (2.25 V) is the required voltage and “ C_{\min} ” is the minimum capacitance value needed. As there are two startup capacitors in series that’s why “ $C_{\text{single_min}}$ ” is the minimum capacitance value for a single capacitor. Thus by using equation (3) and (4), “ C_{\min} ” value obtained is about 215 μF which means that startup capacitor value should be more than 215 μF . This statement has been supported by table I which shows that at 100 μF required energy cannot be obtained.

The table I shows that except 100 μF , all the other capacitors are capable of providing desired energy but we have selected 330 μF as our startup capacitors, because in this case high energy is not required and in order to keep power level low and near to required energy 330 μF would be the best option.

TABLE I. ENERGY PRODUCED VIA STARTUP CAPACITORS

START UP CAPACITANCE ($C_{\text{single_min}} - \mu\text{F}$)	EQUIVALENT CAPACITANCE (2 in Series - μF)	ENERGY PRODUCED (μJ)
100	50	156
330	165	516
470	235	734
680	340	1063

Now the next step is to select appropriate capacitance value for four stages of Villard circuit. The combination that has the least initial charging time of the capacitor and the least time interval between two consecutive transmissions along with accurate data transmission has been considered as optimum option. Thus, for this regard different experimental tests have been conducted with different capacitor combination. During tests, TKP simulator has been used to simulate actual walking speed of 1 Hz (1 step/second). Experimental results for different capacitor combinations have been shown in table II. As discussed before that 100 μF combination is not able to provide enough energy so the test results also confirm this hypothesis. As no data transmission has been carried out with this combination therefore its initial charging time is not recorded as without data transmission it is of no use.

It can be observed from the experimental results that as the capacitance values increase from 330 μF to 680 μF then charging time also increase and this response is due to the fact that capacitor charging time has direct relationship with capacitance value. Furthermore, it is also observed that individually 100 μF was unable to provide enough energy but when alternate stages of 100 μF and 330 μF were used then collectively they were able to provide enough energy for transmitting data as well as with least initial charging time. Hence the best optimized combination was of alternate stage with 330 μF and 100 μF which reduces the initial charging time of previous work [15] from 14.6 s to 9.6 s which shows that optimization of system by around 35% has been achieved. The graphical representation of results obtained in table II has been presented in fig.7(a-d) which shows that after initial charging of the capacitor it reached the voltage of around 2.5 V and then undergo discharging phase. This phenomena occurs because

when the system reaches to specific voltage then switch circuit initiate the discharging of capacitors to powered up the microcontroller and at that time microcontroller performs its activity of transmitting the values measured by the sensor to the external device.

TABLE II. COMPARISON OF INITIAL CHARGING TIME AND DATA TRANSMISSION AT DIFFERENT CAPACITANCE VALUES

	CASE 1	CASE 2	CASE 3	CASE 4	CASE 5
STAGE 1 CAPACITANCE (μF)	680	470	330	330	100
STAGE 2 CAPACITANCE (μF)	680	470	330	100	100
STAGE 3 CAPACITANCE (μF)	680	470	330	330	100
STAGE 4 CAPACITANCE (μF)	680	470	330	100	100
START UP CAPACITANCE (μF)	330	330	330	330	330
INITIAL CHARGING TIME (s)	40.0	14.6	13.2	9.6	-
DATA TRANSMISSION STATUS	Ok	Ok	Ok	Ok	No

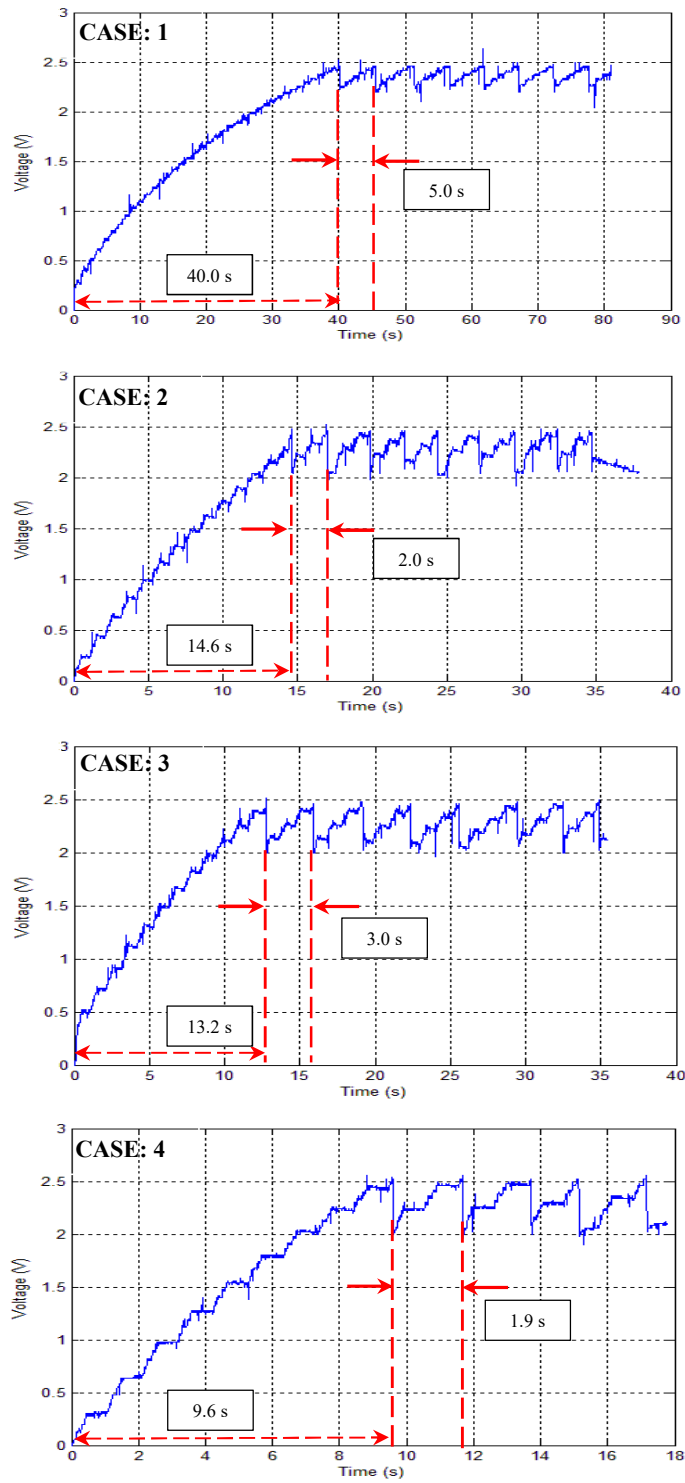


Fig.7. Experimental results: Voltage across the start-up capacitor at 1 Hz (a) Case: 1 (b) Case: 2 (c) Case: 3 (d) Case: 4

TABLE III. SYSTEM RESPONSE AT DIFFERENT WALKING FREQUENCIES

FREQUENCIES (Hz)	INITIAL CHARGING TIME (s)	AVERAGE TIME FOR EACH NEXT TRANSMISSION (s)	DATA TRANSMISSION STATUS
1.0	9.6	1.78	Ok
0.9	10.8	2.1	Ok
0.8	13.2	2.4	Ok
0.7	17.0	3.4	Ok
0.6	20.4	5.4	Ok
0.5	34	9.6	Ok
0.4	-	-	No

Furthermore, more experimental tests have been performed in order to check the minimum threshold walking frequency on which this device can function properly and transmit data correctly. Lower frequencies below 1 Hz have been tested because higher frequencies are not practically used as the patients with total knee replacement patient are suggested to avoid fast walking speed. Therefore, system's response at walking speed of 1 Hz and below have been measured and recorded which can be seen in table III. From experimental results it has been inferred that the designed system has minimum threshold frequency value of 0.5 Hz, as below 0.5 Hz it is unable to transfer data to the external unit. Additionally, it has also been observed that optimum response of the system is at walking frequency of 1 Hz and as the frequency decreases the initial capacitor charging time increases and as well as average time taken by the system to make every next transmission of measured data also rises.

V. CONCLUSION AND FUTURE WORK

In the presented paper, design of power harvesting module has been presented and optimized with measuring the initial charging time for different configurations. Moreover, the minimum threshold frequency has also been determined on which this device can function properly and transmit data correctly. The complete system has been tested through experimental setup which allows the efficient use of harvested energy via controlling the switching of charging and discharging time of capacitors as per requirement. Besides, the acquired results indicated that developed energy harvesting system (EHS) is capable of supplying the voltage between 2.15 V and 2.45 V along with walking speed of 1 Hz for almost 25 ms which is sufficient to switch ON the microcontroller used to transmit data to external peripheral device. Further experimental tests are in progress to evaluate the functioning of the overall system including sensors sensitivity, data transmission range, transmission accuracy etc.

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