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# Modeling and Analysis of the Self-powered Device for Wireless Heart Rate Measurement

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**Abstract.** A new circuit model of the self-powered device for heart rate measurement is presented in this paper. This device consists of piezoelectric energy harvester (PEH), power management circuit (PMC) with energy storage, microcontroller, Photoplethysmography (PPG) sensor, and Wi-Fi module. The PEH is placed under the insole to harvest the pressure energy from human foot-step to generate ac power. In our model, a PEH is represented by a sine voltage source, where its parameters were taken from experiments with 20 volunteers. The PMC is simplified by a switch with gain δ placed in series with the main circuit. The model of the main circuit is RC elements in parallel, where C is the capacitance of the storage device, and R is the equivalent parallel resistance of the microcontroller, PPG sensor, and Wi-Fi modules, respectively. The value of R depends on the power and current absorbed by those modules during sleep, deep sleep, sense, and transmit modes which collected from the datasheet. Finally, the proposed circuit model of the self-powered device was built and simulated in SPICE. The simulation results were compared with the laboratory experiment using commercial devices. Based on the results, the proposed model had small gaps compared to the real self-powered devices in terms of average current, voltage, power and efficiency.

**Keywords:** ambient human energy, piezoelectric energy harvester, RC circuit model, self-powered device, wireless PPG sensor

## 1. Introduction

Self-powered devices are broadly used in structure [1, 2] and medical or health monitoring application [3]. The term self-powered means that the device is battery-less which powered itself by scavenging the ambient energy from the environment. The tool that is used for scavenging the ambient energy is called energy harvester. The main advantage of these devices is maintenance-free and pollution-free since they are replacing battery [4].

A piezoelectric is commonly used for energy harvesters (EH) in biomechanical application because it can give higher power density [1]. Piezoelectric converts vibration into electrical energy or in reverse. Human locomotion produces sustainable energy, for example, a walking human gives force to the shoe insole which high enough to supply the

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self-powered device. Base on the review in [5] mentions that the harvested energy from a 68 kg walking man using piezoelectric is about 20 mW to 80 mW depending on the structure of piezoelectric. Meanwhile, the average power generated by a 1 $cm^3$ piezoelectric is about 100 μW [1, 6] deep sleep mode in the microcontroller which reduced the power consumption from mA to μA. Moreover, the development of PMC such as LTC3588 brings the PEH to become more efficient [7].

Some researchers [4, 8-10] has been focused on developed PEH model for wearable devices which is embedded in the shoe. Most of them derived a circuit model and tested their model through simulation and/or experiment. Only a few authors derived the mathematical model for computation and optimization with high complexity [11, 12]. For the best of our knowledge, none of the previous works were formulated the PEH circuit as the simple RC charging-discharging circuit. Thus, in this paper, we proposed a simple RC equivalent circuit for performance analysis of the self-powered devices for heart rate measurement. Finally, we conducted an experiment to validate our model.

In a medical application, the self-powered devices use for physiological measurements including but not limited to heart rate. Since the traditional measurement, the heart rate is commonly measured on the wrist. As the rapid development of the PPG sensor, the heart rate could be measured from the neck, ear or fingertip [13]. Our contribution in this paper is extended to the heart rate measurement, where the heart rate data are collected from dorsalis pedis located on feet. This proposal is aimed to make a compact wearable device which integrated with a shoe. Besides, it reduces the number of microcontrollers and wireless module carried by the human body. Until this far, there is none of the self-powered embedded shoes was considered the heart rate measurement from the feet artery.

The rest of this paper is organized as follow. The next section is related works which continued by Method. Then, the results and analysis are presented. Finally, the summary of this research is described in the last section.

## 2. Related Works

The self-powered devices which used piezoelectric energy harvester (PEH) are broadly used in many applications, such as bridge vibration monitoring [1], applied forced to floor in building interior [2], telemedical care [3], and wearable applications, e.g. integrated shoe [4,8-10,14]. In this section, we describe the related works more specific to PEH circuit modeling and optimization for wearable devices.

A PEH consists of the piezoelectric, rectifier, storage capacitor and power management circuit [4]. Piezoelectric is a device to convert the mechanical energy to electrical energy or vice versa. Fig. 1 shows the commonly used piezoelectric for PEH application. The circular type of commercial piezoelectric is depicted in Fig. 1, which mostly ceramics. Fig. 1.b. shows the rectangular shape piezoelectrics (so-called cantilever beam) is available in many types of materials. In [1], cantilever beam which made from Micro Fiber Composite (MFC) material to accommodate the bridge structure, where MFC was represented by an

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equivalent voltage source with series capacitance. They were not considered the power management circuit in a simulation, but they used LTC3588 to developed their prototype for evaluating the feasibility of MFC for powering a vibration monitoring device.

(a) (b)

Fig. 1. Piezoelectric shapes, (a) circular shapes piezoelectric, (b) Rectangular shapes piezoelectric.

Oh, *et.al* [3] considered a complete mechanical-electrical equivalent circuit for replacing piezoelectric in the simulation. They developed a Complementary Metal–Oxide–Semiconductor (CMOS) controlled full-wave rectifier for averaging the AC voltage generated by piezoelectric. The rectifier was loaded by 45 kΩ and the generated output voltage is 703 mV.

The Heel Strike System that can generate power about 0.5 W, was developed by researchers in [4]. PZT-5H ceramic [8] with a steel frame for embedded shoe and experience to generated 1.43 mW of electrical power. A nonlinear PEH under resonance and nonresonance conditions had been reported in [9]. The numerical simulations [10] and experiments of eight and six stacks of PEH embedded shoe was generated the average power outputs reached 20 mW/shoe on a given walking speed about 5.6 km/h.

MFC material for replacing piezoelectric membrane due to high flexibility in large deformation have studied in [15], where two piezoelectric materials (PZT-5H and PZT-8) were placed into the sole to form a sandwich PEH structure. Moreover, computer software was used to observe the parameters of the sandwich-type of PEH and derived Lagrange approach to formulating a general electromechanical model of a sandwich PEH. The sandwich PEH could generate electrical power until 1.42 mW by using 0.4% of the applied force from 90 kg mass.

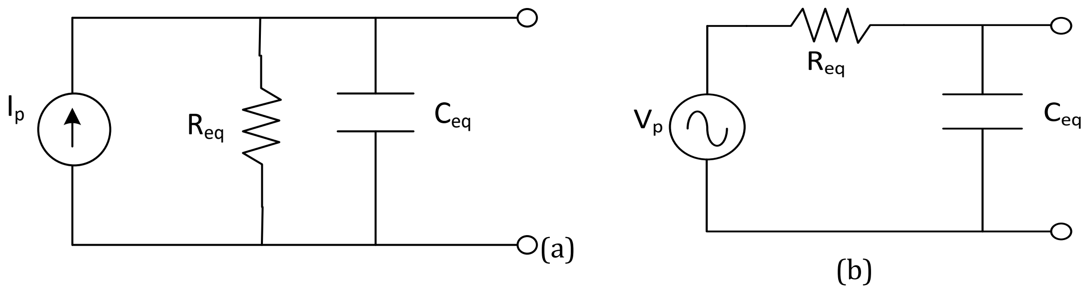


Fig. 2. PEH equivalent circuits as a current source (a) and as a voltage source (b).

PEH is commonly represented by a voltage or current source as depicted in Fig. 2. The equivalent circuits for representing piezoelectric in PEH are current source model and voltage source model, which are shown in Fig. 2.a. and Fig. 2.b., respectively. The works of

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[1,2] in literature used voltage source model, and some of them used a current source [3,5]. The voltage and current sources in Fig. 2 are sinusoidal voltage, where the maximum RMS values of $I_p$ and $V_p$ occur at the resonant frequency of piezoelectric. Since the piezoelectric generated ac voltage; therefore, a bridge rectifier circuit used to convert the PEH output into a dc voltage. Moreover, some works have studied this model using an external resistor for tested PEH.

The works in the modeling of the power management circuit had been reported in the literature [11-12, 17-21]. Most of them used DC to DC converter to manage the generated voltage by the piezo generator. Moreover, the PEH circuit was optimized by Ottman, G. K., *et. al.* [11]. The structure of PEH and the axial deformation of PEH was introduced in the literature [20].

**Comparison and contrast**. The following are the comparisons and contrasts of our works with the previous state of the arts.

- Contrasting with the previous works in literature that exploited a cantilever beam which rectangular in shape [1-4, 9-12,15-22], we used the circular shape of piezoelectric.
- We used a voltage source equivalent circuit without considering $R_{eq}$ and $C_{eq}$ as introduced by Whitaker [7].
- Our self-powered device operates under a deep sleep mode [23, 24] to decrease power consumptions. Meanwhile, the works in [1, 14,18] had reported that the sleep mode was applied to all nodes.
- We used SPICE for simulation. But, we derived the simulation parameter from datasheets and experiments with 20 volunteers.
- We validated the obtained results with NodeMCU [21] powered by the popular PEH chip (LTC3588) [1].

**Novelties**. The ultimate novelties of our works are as follow. The first is to simplify the model of self-powered devices, especially for load model which represented by resistors. We derived the resistances of each resistor for replacing microcontroller, sensor and transceiver modules. The second is the heart rate collection method. We collected the heart rate using the PPG sensor through dorsalis pedis artery located on feet. The third is a new model for a power management circuit which formed by a switch with gain $\delta$. The details of this model will explain in the next section.

## 3. Method

### 3.1 System Description.

Fig. 3 shows the self-powered devices for wireless heart rate measurement. This device consists of PEH, power management and control circuits (PMC), storage device, microcontroller, PPG sensor, and Wi-Fi transceiver which placed together on the insole. PEH composes by a piezoelectric and bridge rectifier. The walking forces generate AC voltage to the piezoelectric terminals. A rectifier converts ac power generated by piezoelectric to DC power for charging a supercapacitor 3300 uF/10 V. A PMC manages the power delivered to the load. The load consists of a microcontroller, PPG sensor, and Wi-Fi transceiver. The power ratings of those parts are listed in Table 1, where these data were collected from datasheet [1, 23-24].

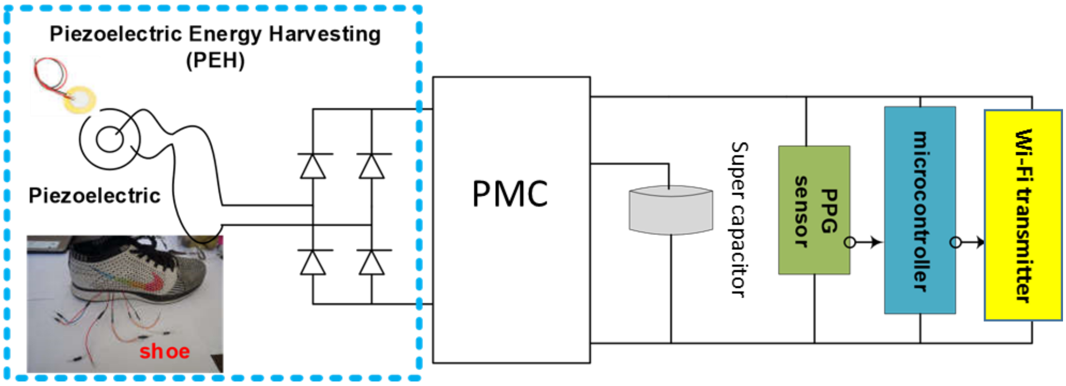

Fig. 3. A self-powered device for wireless heart rate measurement.

Table 1 Operating mode of the self-powered devices

| Task | Active Mode | Time duration | Current Consumption |
|---|---|---|---|
| Sleep mode | microcontroller | 1000 [ms] | 100 [μA] |
| Wake up | microcontroller, Wi-Fi transmitter | 2 [ms] | 7 [mA] |
| Read heart rate data using PPG sensor | microcontroller, PPG sensor | 3000 [ms] | 20 [mA] |
| Transmitting heart rate | microcontroller, Wi-Fi transmitter | 30 [ms] | 18 [mA] |
| Deep sleep | RTC | 3600 [ms] | 15 [μA] |

### 3.2 Dorsalis pedis heart rate measurement.

We proposed a new heart rate measurement through the dorsalis pedis artery which is located on feet (Fig. 4.a.). The PPG sensor is placed on the top of feet as shown in Fig. 4.a. The measured heart rate data send to the cloud data-storage through a microcontroller and Wi-Fi module. The user can monitor the heart rate from a smartphone as depicted in Fig. 4.b.

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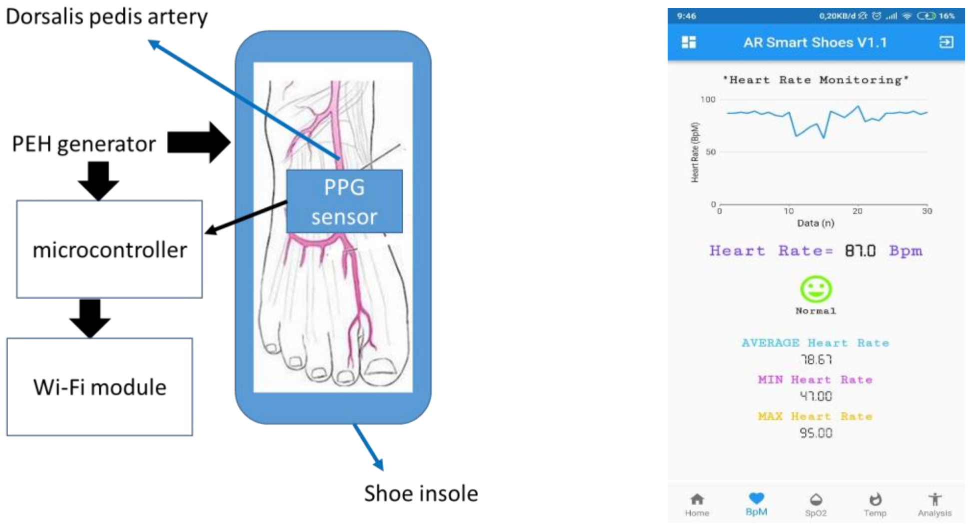


(a) (b)

Fig. 4. Wireless heart rate measurement, (a) PPG sensor placement, (b) Heart rate measurement displayed on Smartphone.

### 3.3 Modeling

The following steps are the development process of our self-powered model. The first step is simplifying the PEH model, which a piezoelectric and bridge rectifier as PEH (Fig. 3), to a voltage source with $V_{PEH} = 0.367.V_{PZ}$. The value of 0.367 determined the ratio of rectification by the bridge diode. The second step is modeling the PMC. A single-pole, double-throw (SPDT) switch replaces PMC. This switch has gain denoted by $\delta$, where $\delta$ is a real number between 0 and 1.

The last step is derived from the equivalent resistors for the microcontroller, PPG sensor, and Wi-Fi transmitter modules while running a specific task, where $R_{Sleep}$, $R_{Wakeup}$, $R_{Read}$, $t_{ransmit}$, $R_{Deepsleep}$ respectively is their resistances. $S_1$, $S_2$, $S_3$, $S_4$, $S_5$ and $T_1$, $T_2$, $T_3$, $T_4$, $T_5$ are representing the switches and timers for activating each task, respectively. The length of the timers is equal to the time duration of tasks in Table 1. The proposed RC equivalent circuit for our self-powered devices is depicted in Fig. 5.

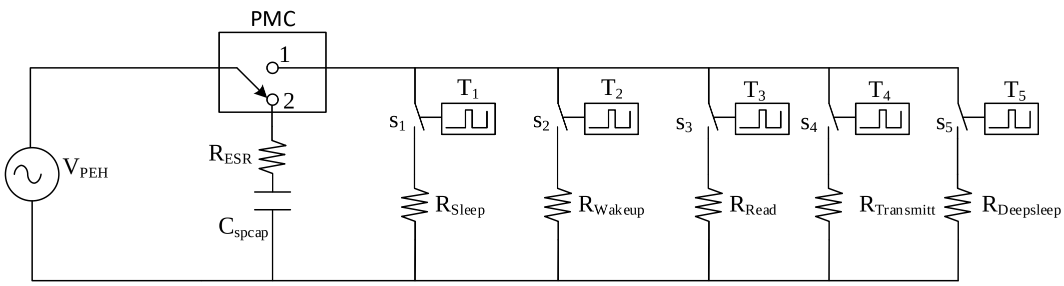


Fig. 5. RC equivalent model of our self-powered device.

### 3.4 Simulation

The proposed model of our self-powered device (Fig. 5) is simulated in the Simulator Program with Integrated Circuit Emphasis (SPICE) for 10 s. The parameters used for the

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simulation are shown in Table 2. We measured the open voltage on the rectifier, $V_{PZ}$ which is given from the average of 20 samples. This approach gives more accuracy since the voltage dropped in rectifier are involved in measurement rather than calculated.

Table 2 Simulation Parameters

| Parameters | Values | Description |
|---|---|---|
| $V_{PZ}$ | 11 [V] | The maximum output voltage measured at the piezoelectric terminal |
| $V_{PEH}$ | $0.637.V_{PZ}$ | PEH output voltage measured from the output terminal of the bridge rectifier (Fig. 3). $V_{PEH} = (2/\pi). V_{PZ}$, where the rectification ratio is $2/\pi$ or equal to 0.637. |
| $R_{Sleep}$ | 33 kΩ | The resistance of self-power device during sleep mode |
| $R_{Wakeup}$ | 471 Ω | The resistance of self-power device during wake up mode |
| $R_{Read}$ | 33 Ω | The resistance of self-power device during reading heart rate |
| $R_{Transmit}$ | 33 Ω | The resistance of self-power device during data transmission |
| $R_{Deepsleep}$ | 330 kΩ | The resistance of self-power device during deep sleep |
| δ | 0.9 | PMC gain. This value was selected to guarantee the minimum voltage required by the microcontroller and another module. |

The volunteers are divided into 3 groups based on their weight. Volunteers in Group A had an average weight of 50 kg with a deviation of 3.2 kg. Group B is volunteers with an average weight of 60 kg with a deviation of 5.6 kg. The average volunteer's weight in Group C is 70 kg and the deviation is 2.5 kg. The last stage is to analyze the influence of the difference in mass on the current and voltage produced by PEH. In addition, we also display PEH characteristics and calculate efficiency. The rest of the parameters used in our simulation are listed in Table 2. The values of $R_{Sleep}$, $R_{Wakeup}$, $R_{Read}$, $R_{Transmit}$, $R_{Deepsleep}$ were collected from direct measurement to the device.

## 4. Results and Analysis

The proposed self-powered device was developed and tested in several times using SPICE. Each simulation has done for 10 s. The results of the simulations and performance analysis of the self-powered devices are presented in this section. Fig. 6 shows the averages of PEH output voltage, $V_{PEH}$ generated by the walking samples for each group. As the applied forces to the PEH is increased the output voltage is also increased; thus, Group C or the walking 70 ± 2.5 kg mass gives the highest open voltage at the piezo terminal. The smallest average voltage measured on PEH output is given by the forces from 50 ± 3.2 kg mass (Group A).

The short circuit current of PEH, $I_{SC}$ is depicted in Fig. 7. The highest short circuit current ($I_{SC}$) is drawn by the highest mass which belongs to Group C, and the lowest $I_{SC}$ produced by the lowest pressure caused by the lowest mass (Group A). The characteristic

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of our PEH which is taken from the experiment is shown in Fig. 8. The short circuit current ($I_{SC}$) of single circular piezoelectric is more than 10 µA with the open-circuit voltage is 2 V. When $I_{SC}$ decreases to 4.5 µA and the voltage was 20 V, the generated power was 90 µW. This condition achieved by hard force on shoe insole by 70 ± 2.5 kg (Group C) walking mass. We add two more pieces of piezoelectric which connected in parallel to increase the power. Since the sufficient voltage for the charging capacitor is 11 V; therefore, the given power is 280.5 µW, enough for wireless heart rate transmission. A supercapacitor will back up the power while our device read data from PPG sensor, wake up mode and transmitting data through Wi-Fi.

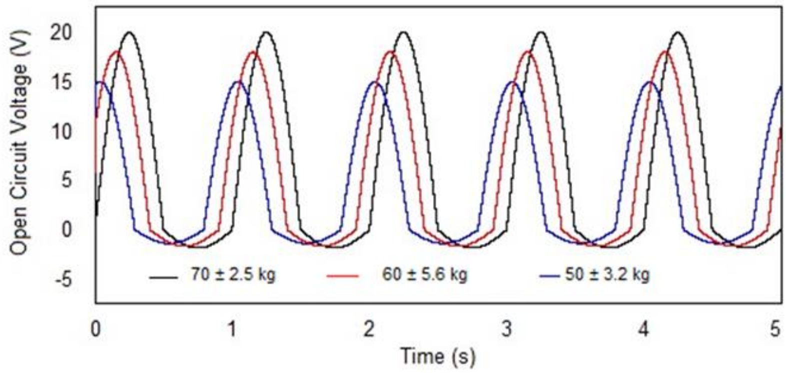


Fig. 6. PEH output voltage

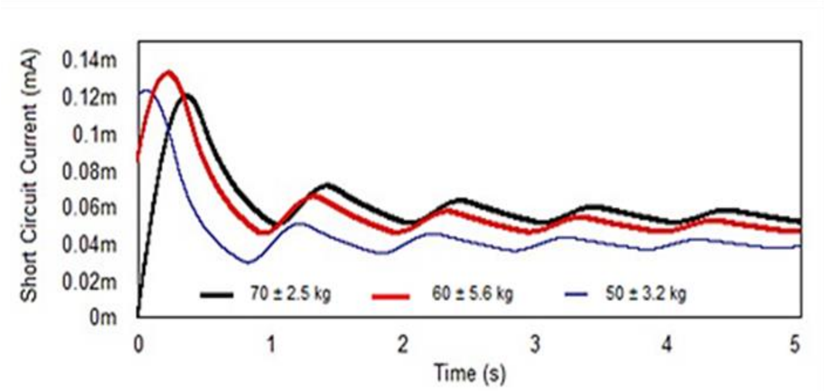


Fig. 7. Short circuit current of PEH.

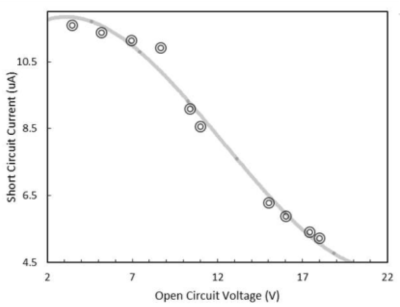


Fig. 8. PEH Characteristic.

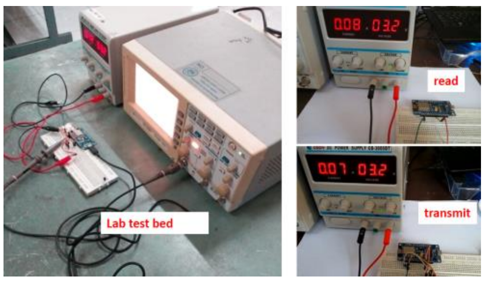


Fig. 9. A lab testbed with the standard device (NodeMCU).

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The test bed (Fig. 9) results of the current consumption of a standard device commercially available in the market, such as NodeMCU [23-24]. The minimum current and voltage required for operating NodeMCU are shown in Fig. 9. The average current required for running NodeMCU and our model are listed in Table 3. During sleep mode, the proposed model consumed 100 mA for reading the PPG sensor which is lower 10mA than the current consumed by NodeMCU. The current needed for the operation of writing and data transmission task is equal to the datasheet of NodeMCU. These results show that our proposal can reduce power consumption under sleep mode. Moreover, the simulation results of our model for deep sleep mode are depicted in Fig. 10. The red line represents the current drawn by NodeMCU under deep sleep mode, while the blue line is our model. From this figure, we can conclude that our model is better 5 µA than the NodeMCU.

Table 3 Current consumption comparison

| Item | Read (A) | Write (A) | Transmit (A) |
|---|---|---|---|
| Node MCU test | 0.11 | 0.11 | 0.12 |
| NodeMCU (datasheet) | 0.14 | 0.08 | 0.08 |
| Our model | 0.1 | 0.08 | 0.08 |

Table 4 Power consumption

| Mode | Power [mW] | | Error (%) |
|---|---|---|---|
| | Simulation | Testbed | |
| Normal Mode [14] | 100 | 110 | 10 |
| Sleep mode only [1] | 40.3 | 50 | 24.06 |
| Deep Sleep Mode [our model] | 40 | 42 | 5 |

Table 4 shows the power consumed by the devices for running sensing and transmitting task in 3 modes of operation (normal, sleep, and deep sleep) in both simulation and experiment. In the normal mode, the power absorbs by the device under simulation test is 100 mW. The experiment for the same operating mode gives 110 mW, so the error is 10%. The smallest error or the difference between simulation and testbed is achieved by our model is 5%.

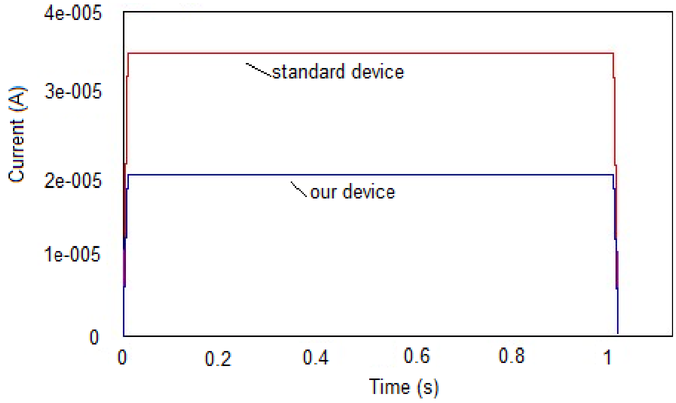


Fig. 10. Current consumption comparison chart.

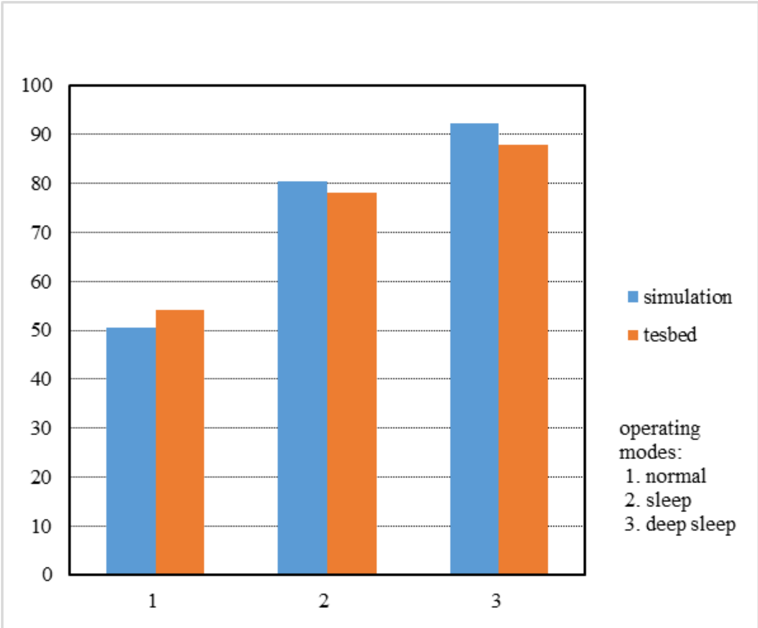


Fig. 11. Efficiency comparison of our model simulation) and standard device (testbed).

Fig. 11 shows the efficiency comparison of our model with a standard self-powered device (NodeMCU). The efficiency was calculated from the ratio of power absorbed by the device to the input power from PEH, where those data were collected from several tests. In the test, the source voltage kept constant and both devices are performed in three modes, namely normal, sleep and deep sleep. Since the output power is proportional to the square of the current flow to the resistance; therefore, the smallest current dissipated the lowest power and gives the highest efficiency. Based on the above rationale, the highest efficiency is reached by our model under a deep sleep, because our device consumed lower current compared to the standard device, see Fig. 10.

The lowest efficiency given by our model is 50.2% which occurs in normal mode. In normal mode, our model absorbed more power for warming up, while the standard devices could run under very low power. Thus, our device has lower efficiency compare to

NodeMCU. In sleep mode, the proposed self-power device gives higher efficiency equal to 80.5%, which higher than the standard device. After warming up, our device could absorb lower current compared to NodeMCU, thus our model has lower power dissipation and higher efficiency. Our model gives higher efficiency for about 4.3% compared to the commercial device while it operates in deep sleep mode. As we can see from Fig. 10, the proposed devices have drawn lower current compared to the NodeMCU; therefore, our device could have higher efficiency.

## Conclusion

The self-powered device for wireless heart rate measurement was modeled into a simple RC circuit. The simulation was built and ran under SPICE. The proposed model performs better than the commercial MCU with Wi-Fi module in both sleep and deep sleep modes. Furthermore, our RC equivalent model reduces the deep sleep current to 5 μA. The proposed system could generate power more than 200 μW which is surpassed the previous work in [1]. The proposed model is better to compare to the previous works and standard commercial device (NodeMCU).

This model can perform better than the standard model in term of current consumption. In the future, we will improve our proposal and derive the mathematical model by using an ordinary differential equation and solve by numerical computation. In addition, we will involve our Queen honey-bee migration (QHBM) [25] for optimization.

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**Authors Statement**

Aripriharta (idea, project leader, and funding support, draft paper), Muladi (co-funding, data analysis), Nandang Mufti (draft paper), Ilham Ari Elbaith Zaeni (method), I Made Wirawan (test manager, Gwo Jiun Horng (final manuscript)

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**Conflict of Interest**

The authors declare there is no compete interest.

## Ethic Clearance

The data shown in this paper is clear through standard protocol of using human data for publication.