Modelling of adaptive power management circuit with feedback for self-powered IoT

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Abstract. In general, self-powered sensor networks/Internet of Things (IoT) are equipped with a power management system and use a timer as a reference for the device's active time, both using an internal timer and an external timer. The system is less efficient because it requires that there are parts that continue to function when the device is in sleep mode. In addition, the amount of harvested energy also influenced by many factors with an uncertain amount. An IoT self-powered system that uses a timer as an active interval reference will encounter problems when the amount of system energy demand is greater than the harvested energy. This paper presents an adaptive power management system equipped with feedback for self-powered IoT for room temperature and humidity monitoring applications. The power management system can provide adaptive active intervals based on the harvested energy capacity. Microcontrollers send feedback to the power management circuit at the end of each cycle. The power management circuit immediately disconnects the controller circuit from the energy storage’s component (supercapacitor) so that energy used efficiently. Several methods of minimizing the energy consumption of the device are also applied to provide optimal results. The research method begins with system modelling, including an energy harvester circuit, power management, and controller. The research scenarios include energy harvester performance tests, calculating the energy requirements of the power management and controller circuit, and validating research results. Overall, the system can work well, the active interval/data transmission of 14.41 seconds to 22.34 seconds in a room with a light intensity of 800 lux to 1000 lux.

1. Introduction
Experts project that by 2020 nearly 26 billion embedded devices will be connected to the internet and become a huge business opportunity [1]. The embedded device can be in the form of smart meters, wearable devices, and WSN. WSN is a modern information technology that integrates sensors, low-power embedded components, wireless communication, and distributed data processing [2]. Because of
its rapid development, WSN used in a large number of applications, including environmental monitoring [3], object detection [4], body area network [5], fire detection [6,7] and so on.

Conventional WSN systems powered by batteries [8], but there are many problems with the battery as an energy source. First, the leakage current that makes the energy in the battery continues to decrease even if not used. Second, extreme weather conditions can result in leakage of the battery chemicals and cause environmental damage [9]. In addition, WSN also has the main obstacle with energy availability that makes a lifetime limited [10–12]. WSN's lifetime refers to the time all nodes in the network are work until one node does not work [13].

WSN systems require higher maintenance costs due to battery replacement, especially networks that consist of thousands of nodes [14] and located where they are difficult to reach. To overcome this problem, many researchers have combined WSN with energy harvester technology to create self-powered WSNs that are maintenance-free. Energy harvester allows the device to capture and convert wasted energy in the environment into electrical energy that can be used directly or stored for later use [15].

In general, self-powered sensor networks/ IoT are equipped with a power management system and use a timer as a reference for the device's actives time, both using an internal timer and an external timer. The system is less efficient because it requires that there are parts that continue to function when the device is in sleep mode. In addition, the amount of harvested energy influenced by many factors with an uncertain amount. The self-powered IoT system that uses a timer as an active interval reference will face problems when the amount of system energy demand is greater than the harvested energy.

Therefore, this paper proposes an adaptive power management system equipped with feedback for self-powered IoT for room temperature and humidity monitoring applications. The power management system can provide adaptive active intervals based on the harvested energy capacity. Microcontrollers send feedback to the power management circuit at the end of each cycle. The power management circuit immediately disconnects the controller circuit from the energy storage component (supercapacitor) so that the energy used efficiently. One cycle is defined as the actives time of the controller circuit until the power management circuit decides the controller circuit from the supercapacitor.

Overall, the system composed of components intended for low power applications. The system uses the ATmega238P microprocessor, the HDC1000 sensor, and the Bluetooth Low Energy (BLE) HC-42 communication module. Several methods of minimizing the energy consumption of devices are applied to provide optimal results. The results of temperature and humidity monitoring are sent to a cloud database and displayed via a smartphone application.

The self-powered device sue required energy is lower than the harvested energy [16]. Figure 1 shows an illustration of the comparison of the system energy requirements with the harvested energy. These needs make the development of solar panels specifically for self-powered devices to appear. Authors [17] develop ultra-thin flexible solar panels based on metamaterial characterization. The solar panels intended for self-powered wireless system applications. Focusing on self-powered wearable devices, Authors [18] developed flexible organic solar panels.

Research on power management systems has also emerged to improve energy efficiency. Authors [19] developed a solar panel power management system for self-powered IoT nodes. The system architecture uses on-chip capacitor based power converters to achieve higher efficiency. Researchers [20] also proposed a solar panel power management scheme for solar-powered BLE beacons. The system uses two logic blocks consisting of four comparators, three logic gates, and 3 MOSFETs. This power management system has three conditions follows:

- Mode 1. The energy generated by the solar panel is above the threshold so it can charge the battery and activate the sensor node.
- Mode 2. The energy generated by the solar panels is not large enough to charge the battery, so the energy used to activate the sensor node without reducing battery power.
- Mode 3. The power generated by the solar panel is not enough to activate the sensor node, so the system uses the battery to power the sensor node.
Figure 1. Energy comparison

Turning to implementation, Authors [21] developed a self-powered wearable body sensor for security applications. The system uses getting electrical energy from solar panels with a 3 cm diameter. The solar panel capable of achieving a maximum output of 0.27 mW at a light intensity of 600 lux. The harvested energy stored in a 12.5 F capacitor. The system uses an ATmega328P microcontroller and a LoRa RFM95 communication module to send data over a Wi-Fi network. The sensor node equipped with temperature, humidity, and UV sensors. The RFM95 LoRa module consumes 10.3 mA current and consumes only 0.2 µA when sleep mode. The system uses a star network topology. The sensor node sent the environment data to the gateway node.

Authors [22] combines the solar energy harvester and the BLE RFD77101 module to monitor health parameters. The BLE consumes 8 mA of current when transmitting data. Authors [23] applies the concept of solar energy harvesting to reduce system maintenance costs (battery replacement). The system uses a 3.75-inch × 2.5-inch monocrystalline solar panel and Crowbow MICAz mote as a router.

Research [24] and [25] developed a self-powered sensor network using solar panels measuring 165 mm × 165 mm and OPM15 as the controller that sends data over Wi-Fi networks. Authors [24] developed a sensor node with carbon dioxide and temperature sensors. This research uses lithium polymer batteries (LiPo) as energy storage. The author [25] equips the device with a temperature-humidity sensor (DHT11) and soil moisture. The device uses a 3.7 V 6600 mAh lithium-ion battery as energy storage.

Authors [26] developed the Batteryless System on Chip (SoC) for biomedical applications. The system equipped with an integrated energy harvester that gets input from solar panels or thermoelectric generators (TEG). This system uses an MSP430 as the controller and equipped with an integrated radio transmitter that consumes power 6.45 µW when transmitting data at 187.5 kbps. The author claimed that the power management circuit used was able to achieve 75% efficiency.

Research [27] presents the design and implementation of long-range self-powered IoT prototypes using nRF52840. The device obtains energy from 0.36 W monocrystalline solar panels measuring 63 mm × 63 mm. Device's battery averaged charged with 941.94 µW in the indoor test environment. This device uses IC BQ25570 as a power management circuit that has a starting voltage of 330 mV and 900 nA quiescent current. This device can work for 12 months using a 120 mAh fully charged coin battery with a data transmission interval of 55 seconds.

**Comparison and contrast.** Comparison and contrast of this research with existing research as follows:

- Research [21,23–27] uses Wi-Fi networks as a data delivery medium. Our system uses Bluetooth as a data transmission medium.
- In contrast to the power management system in research [19,20,23], our study uses an adaptive power management system that can provide active intervals of devices that are more flexible according to the harvested energy capacity. The system is also equipped with feedback to increase energy efficiency.
In contrast to researchers [21,23–25,27], the system that we propose uses super capacitors as energy storage.

In contrast to research [22] that also uses Bluetooth technology, our system can forward data to the cloud database. Other users can access environmental data.

**Novelties.** First, the model can adapt the active time interval of the device based on the harvested energy capacity. The threshold voltage of the model can be adjusted according to the energy requirements of the load (controller) through changes in the resistor value in the power management circuit. Second, the controller can send feedback to the power management circuit when the cycle is complete. The power management circuit immediately disconnects the controller circuit from the supercapacitor when receiving a feedback signal. Third, the network architecture applied can minimize the cost of making the system because it uses a smartphone as a gateway.

2. Methods

2.1. **System modelling**

The system divided into three main parts, namely the energy harvester circuit, power management, and controller. The energy harvester circuit serves to provide a maximum impedance to produce the maximum input component performance. Energy harvester input components can be solar cells, piezoelectric, and TEG. This study focused on the solar panel as an input component of the energy harvester circuit. Figure 2 shows the energy harvester circuit used in this study.

![Energy harvester circuit](image)

**Figure 2.** Energy harvester circuit

The configuration of the energy harvester circuit based on previous research [14] that uses a transformer with a ratio of 50:50 turns. Transformers made using 0.01 mm thick wire and circular ferrite cores. Ferrite cores used have an inner diameter of 6 mm, an outer diameter of 10 mm with a thickness of 4 mm. Component D1 used as a solar panel protector to prevent backflow current from the transformer, while D2 used to prevent backflow from supercapacitors (energy storage) in the power management circuit. Figure 3 shows the power management circuit used in the study.
In general, the power management circuit uses two MOSFETs as a switch. In this study, the power management circuit uses TPS22860 as a substitute for MOSFET. Based on reference [28], TPS22860 has a low leakage current of 2 nA at pin $V_{IN} = 3$ V and 10 nA at $V_{BIAS} = 5.5$ V makes it suitable for use in low-power applications. TPS22860 controlled by TLV3691(U3). TLV3691(U3) as an inverting buffer that gets input from TLV3691(U2). The TLV3691(U2) output influenced by the voltage at the supercapacitor ($C_1$). This circuit uses the comparative hysteresis theory to produce a flexible active cycle based on the harvested energy capacity. In the power management circuit, the MCP1700 low dropout regulator (LDO) used to provide input to TLV3691(U2) and TPS22860 $V_{IN}$.

The system uses a supercapacitor ($C_1$) 0.47 F 5.5 V as energy storage. The resistor values in Figure 2 selected based on market availability and the current requirements of each component. The component used works on nano-power, so the resistor value on the MΩ scale used to minimize the current passing through the resistor [28,29]. The highest resistor value available on the market is 9.1 MΩ [30,31]. The MCP1700 output value is set to 3.3 V to adjust the voltage of the microprocessor and sensor used. Based on reference [32], LDO MCP1700 can produce an output voltage ($V_R$) of 3.3 Volts with the following conditions:

- The lowest $V_{IN}$ must meet the conditions: $V_{IN} \geq 2.3$ V and $V_{IN} \geq (V_R + 3\%) + V_{dropout}$.
- $V_{dropout}$ is defined as the difference between input and output when the output voltage falls 2% below the measured value by applying the difference $V_R + 1$ V.

Both of these conditions make the pin $V_{IN}$ must get a minimum voltage of 3.577 V to produce a 3.3 V output voltage. If it determined that the output changes TLV3691(U2) to low when $V_{C_1} = 3.8$ V with $R_5 = 9.1$ MΩ and $R_6 = 4.7$ MΩ, it is necessary to know the voltage at the inverting input pin TLV3691(U2) or $V_{R_2}$ using Equation (1).

$$V_{R_5} = \frac{R_5}{R_5 + R_6} \times V_{C_1} \tag{1}$$

After finding the $V_{R_5}$ value, determined the $R_4$ value based on $V_R = 3.3$ V, $R_2 = 9.1$ MΩ and $V_{R_2} \approx V_{R_5}$ using Equation (2).

$$V_{R_2} = \frac{R_2}{R_2 + R_4} \times V_R \tag{2}$$
$R_4$ value is set to 3 MΩ to adjust to the availability of resistor values on the market. Adding the value $R_4$ makes the $V_{R_2}$ value a little higher than $V_{R_5}$, but can be tolerated. When TLV3691(U2) output produces low logic (GND), TLV3691(U3) as an inverting buffer produces high logic output ($V_{C_1}$). These conditions make TPS22860(U4), and TPS22860(U5) become Normally Closed (NC) so that the controller circuit gets power from the supercapacitor. The charge in the capacitor continues to decrease because it is used by the controller circuit to work. The controller circuit power consumption reduces the $V_{C_1}$ value, so the hysteresis concept is used by adding $R_3$ to hold the TLV3691(U2) output to a low logic (GND) condition until the controller circuit has finished working.

The stability of $V_R$ maintained so that the controller circuit still works well, so that hysteresis is set to the value of $V_{C_1} = 3.577$ V. Before setting the $R_3$ value for hysteresis, the $V_{R_3}$ value when $V_{C_1} = 3.577$ V needs to be known using Equation (3).

$$V_{R_3} = \frac{R_3}{R_5+R_6} \times V_{C_1} \quad (3)$$

If the value of $V_{R_3} = 2.36$ V, then it takes $V_{R_2}/R_5 \approx 2.36$ V and $V_{R_2}/R_3 \geq 2.36$ V. The value of $R_2/R_3$ that meets the condition $V_{R_2}/R_3 \approx 2.36$ V can be obtained using Equation (4).

$$V_{R_2}/R_3 = \frac{R_2/R_3}{R_2/R_3 + R_4} \times V_R \quad (4)$$

If the value of $R_2 = 9.1$ MΩ and $R_2/R_3 = 7.5$ MΩ, then the $R_3$ value can be known using Equation (5).

$$\frac{1}{R_2/R_3} = \frac{1}{R_2} + \frac{1}{R_3} \quad (5)$$

The required $R_3$ value is 41.67 MΩ (very high) and not available on the market, so $R_3$ uses several resistors arranged in series. Based on the calculations, the final configuration of the power management circuit shown in Figure 4.

![Figure 4. Power management circuit](image)

TPS22860 output connected to the controller circuit. Figure 5 shows the controller circuit used in this study. The controller circuit consists of the ATMEG328P microprocessor, the BLE HC-42 module, and the HDC1000 temperature-humidity sensor. At the end of each cycle, the microprocessor sends high logic signal feedback via the PD2 pin to the non-inverting TLV3691(U2) input pin. These conditions make the value $V_{R_2} \approx V_{C_1}$ so that the hysteresis process ends because of $V_{R_2} > V_{R_5}$. 
The device sends beacons so that data received by all nearby Bluetooth devices. Figure 6 shows the communication system architecture. In this study, a smartphone used as a beacon receiver. The smartphone used has an installed application to forward data to the cloud database. The application runs as a smartphone background process so that it does not interfere with smartphone usage activities.

The Bluetooth icon represents the proposed device. The beacon concept makes data sent to the nearest Bluetooth device so that one smartphone can receive data from several sensors. The smartphone forwards the data to the cloud database via a Wi-Fi router or Base Transceiver Station (BTS). Cloud database storage allows data to be accessed by other users far from the sensor or outside the location of the sensor placement.

2.2. Research scenario
The research scenario begins with testing the amount of energy that can be harvested by an energy harvester. The energy harvester tested with several variations of light intensity. The next step measures the current consumption required by the power management circuit. The current consumption used by each component is calculated based on [28,29,32].

The research continued by measuring the energy consumption of the controller circuit. Several methods of minimizing energy consumption [33–35] applied to microprocessors and BLE modules. At this stage, the controller circuit's active time for one cycle needs to be known. The study continued with the validation of the results obtained. At this stage, a comparison of the provided energy for one cycle is made based on the power management circuit configuration and the system energy requirements. Overall, the sequence of research scenarios is detailed as follows:
3. Results and Discussion

3.1. Energy harvester performance test
The energy harvester performance test adjusted to the previous research [14]. Energy harvester gets input from solar panel arranged in series and parallel (PV array) measuring 125 mm × 125 mm. Figure 7 shows the PV array used in the study. The previous research show that at a 1000 lux light intensity, the harvested energy \( E_{EH} \) is 5,712 mW. When working at 800 lux light intensity, the energy harvester can harvest 3,696 mW of power [14].

Figure 7. PV array

3.2. Energy harvester performance test
The energy requirements of the power management circuit are calculated based on [28,29,32]. LDO MCP1700 has a typical quiescent current of 1.6 µA, and TLV3691 has 75 nA per channel. TPS22860 has a \( V_{BLAS} \) leakage current of 10 nA at 5.5 V. The component also has a \( V_{IL} \) leakage current of 2 nA and an \( I_{Q} \) max leakage current on 100 nA. By calculating the value of the current that passes through resistors \( R_5, R_6 \) and \( R_2, R_4 \) when \( 3.577 \, \text{V} < V_{C_1} < 3.8 \, \text{V} \) uses Equation (6) and (7), the estimated currents needed for power management circuit calculated using Equation (8).

\[
I_{R_3R_6} = \frac{V_{up} + V_{down}}{R_5 + R_6} \tag{6}
\]

\[
I_{R_2R_4} = \frac{V_{up} + V_{down}}{R_2 + R_4} \tag{7}
\]

\[
I_{PMC} = I_{MCP1700} + 2 \times (I_{TLV3691} + I_{TPS22860}) + I_{R_5R_6} + I_{R_3R_4} \tag{8}
\]

Where,

- \( V_{up} \) = \( V_{C_1} \) upper limit (3.8 V)
- \( V_{down} \) = \( V_{C_1} \) lower limit (3.577 V)
- \( I_{PMC} \) = Power management circuit current (nA)
- \( I_{MCP1700} \) = MCP1700 current (nA)
- \( I_{TLV3691} \) = TLV3691 current (nA)
- \( I_{TPS22860} \) = TPS22860 current (nA)
3.3. Energy harvester performance test

The controller circuit uses the ATmega328P microprocessor with minimized energy consumption based on research [34]. In general, ATmega328P mounted on an Arduino board has a current consumption of 49 mA when using a 5V power supply. Table 1 shows the total minimized current consumption.

Table 1. ATmega328P current’s savings

| No | Method                                      | Current (µA) |
|----|---------------------------------------------|--------------|
| 1  | Using minimal board Arduino compatible      | 30500        |
| 2  | Using internal clock 8 MHz                 | 5100         |
| 3  | Using Power Reduction Register (PRR)       | 2100         |
| 4  | Disable ADC converter                       | 334          |
| 5  | Disable brown-out detection                | 25           |
|    | **Total**                                   | **38059**    |

The applied method can save the microcontroller currents consumption up to 38,059 mA. The current of the HDC1000 sensor and the HC-42 Bluetooth communication module based on [36,37]. Overall, the current consumption of the controller circuit is 13371 µA calculated using Equation (9).

\[ I_{CC} = (I_{MC} - I_{MC5}) + I_{HDC} + I_{HC} \]  

(9)

Where,

- \( I_{CC} \) = Controller circuit current (µA)
- \( I_{MC} \) = ATmega328P current before optimization (µA)
- \( I_{MC5} \) = ATmega328P current after optimization (µA)
- \( I_{HDC} \) = HDC1000 sensor current (µA)
- \( I_{HC} \) = HC-42 module current (µA)

After knowing the current consumption, the controller circuit energy consumption determined through the active time needed for one cycle. One cycle counted starting from the controller circuit active until it sends feedback to stop hysteresis. Figure 8 shows the active time for the controller circuit from several test results.

![Figure 8. The controller circuit active time](image-url)
The controller circuit requires an average active time for one cycle of 1.67 seconds. Based on the current consumption of 13.371 mA and the active controller circuit when $3.577 \, V < V_{C1} < 3.8 \, V$, the controller circuit’s energy requirements calculated using Equation (10).

$$E_{CC} = \frac{V_{up} + V_{down}}{2} \times I_{CC} \times t_c$$

(10)

Where,

$E_{CC}$ = Controller circuit energy (Wh)

$t_c$ = The controller circuit active time (h)

3.4. Validation

In this section, the overall system performance validated using comparing the power management system model and system energy requirements. Based on [38–40], the energy stored in a supercapacitor calculated using Equation (11). Based on the used power management circuit model, the usable energy in supercapacitor from 3.393 J to 3.007 J, so the energy that can be used by the system is 0.386 J calculated using Equation (12).

$$E_{SC} = \frac{CV^2}{2}$$

(11)

$$E_{SCU} = E_{SC1} - E_{SC2}$$

(12)

where,

$E_{SC1}$ = The upper limit of the usable supercapacitor’s energy (J)

$E_{SC2}$ = The lower limit of the usable supercapacitor’s energy (J)

$E_{SCU}$ = Usable supercapacitor’s energy (J)

![Figure 9. $E_{H}$ graph](image-url)

Provided $E_{SCU}$ by the power management circuit is $107.22 \times 10^{-6}$ Wh. This value is higher than the energy requirement of the controller circuit for one cycle of $22.88 \times 10^{-6}$ Wh so the system can work properly. Next, we validate the time it takes for the energy harvester to charge the supercapacitor energy based on a predetermined value limit. After that, we also calculate the time needed for the energy harvester to meet the energy requirements of the controller circuit. Assuming the power management circuit is always active, the energy that can be harvested energy harvester ($E_{H}$) is the harvested energy and burdened with the energy requirements of the power management circuit. First, we calculate the energy used by the power management circuit ($E_{PMC}$) using Equation (13).
\[ E_{PMC} = I_{PMC} \times \frac{V_{up} + V_{down}}{2} \times t \]  

Then \( E_H \) calculated using Equation (14). Calculations also performed on each variation of the applied light intensity. Figure 9 shows the overall calculation results.

\[ E_H = E_{EH} - E_{PMC} \]  

The system set to work in the range of \( E_{SC2} \) to \( E_{SC1} \), so the time needed for the energy harvester to charge supercapacitor's energy \( t_{ESC} \) calculated using Equation (15). Figure 10 shows the calculation results for each variation of light intensity. Furthermore, the time needed by the energy harvester to meet the energy requirements of the controller \( t_{EC} \) calculated using Equation (16). Figure 11 shows the calculation results for each variation of light intensity.

\[ t_{ESC} = \frac{E_{SC1} - E_{SC2}}{E_H} \times 3600 \]  

\[ t_{EC} = \frac{E_{CC} - E_{EC}}{E_H} \times 3600 \]

**Figure 10.** \( t_{ESC} \) graph  

**Figure 11.** \( t_{EC} \) graph  

Based on Figure 10, when the device is in a room with a light intensity of 1000 lux, it takes 67.68 seconds to charge the supercapacitor's energy from \( E_{SC2} \) to \( E_{SC1} \). If the light intensity of the room is 800 lux, then the time needed is 104.71 seconds. Figure 11 shows the energy harvester takes 14.41 seconds to harvest the energy according to the needs of the controller circuit at a light intensity of 1000 lux. If you are in a room with a light intensity of 800 lux, then it takes 22.34 seconds. Overall the system can work well, the active interval/data transmission of 14.41 seconds to 22.34 seconds in a room with a light intensity of 800 lux to 1000 lux.

4. **Conclusion**

In the concept of self-powered devices, the energy requirements of the system must be lower than the harvested energy. Therefore, self-powered sensor nodes must be prepared using components with low energy consumption levels and apply energy consumption minimization methods. The proposed system has a higher power efficiency scheme compared to self-powered sensor nodes in general because it does not use a timer to activate the cycle. The system activates each cycle based on threshold voltages that set in the power management circuit. The scheme makes the system able to provide adaptive cycle intervals according to the harvested energy capacity. The validation results show the configuration of the power management circuit can provide enough energy for one active cycle. When receiving feedback from the controller, the power management circuit immediately disconnects the controller circuit from the supercapacitor so that energy used efficiently. Our next research will apply this system to sensor nodes that use Wi-Fi communication and data logger devices.
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Acknowledgement
This work was supported by Hibah Penelitian PNBP 2020, Universitas Negeri Malang, Indonesia.