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SIMULATION MODEL FOR A LOW-POWER PIEZOELECTRIC ENERGY HARVESTING APPLICATION

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Abstract. In the field of self-powered microelectronics with low power consumption, piezoelectric materials that convert mechanical energy into electrical energy are a widely used energy source. In the previous studies, only a few analyses have been carried out in the scope of optimal energy management of the entire electronic system. In this paper, a simplified energy simulation model of the real-time behavior of a whole energy-autonomous system is proposed. Different operating modes such as sleep, normal and standby, by using the newest ultra-low power Bluetooth communication technology (Bluetooth 5.2) for wireless transmission of measurement data, are analysed. This model was implemented in Simulink using the Pulse-width modulation (PWM) circuit as the power management unit. Based on the simulation data, the value of the output power was predicted, as well as the operation process was designed accordingly to ensure that the system can operate at the lowest power consumption normally. The simulation results demonstrate that the combination of multilayer Lead zirconate titanate (PZT) plates after the rectifier can provide the energy requirements for the normal operation of a microchip. When the energy source is not active, the energy stored in the capacitor can guarantee the processing of at least one measurement cycle. The simulation of the model is then discussed by comparing it with the experimental data.

Key words: low-power microelectronics, simulation model, self-sufficient, Simulink.

1 INTRODUCTION

On the premise of realizing the same function, some renewable energy presents more advantages due to the use of more and more low-power or even ultra-low-power devices, which also conforms to the general trend of recent technological development. In terms of power generation efficiency, there is a large difference between various energy sources. Among them are the widely used solar cells with energy densities in the range of 100 $\mu W/cm^2$ to 100 mW/cm^2 [1]. The thermal energy conversion method based on the Seebeck- or Peltier-principle has a relatively low efficiency [1][2]. There is also energy source from ocean [3], wind energy, bioenergy and usable noise energy [4].

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Mechanical energy tends to be an easily available energy form and is used frequently in microelectronics technology. This paper mainly simulated a complete sensor system using piezoceramic material as the energy source. The complete system structure is shown in Figure 1.

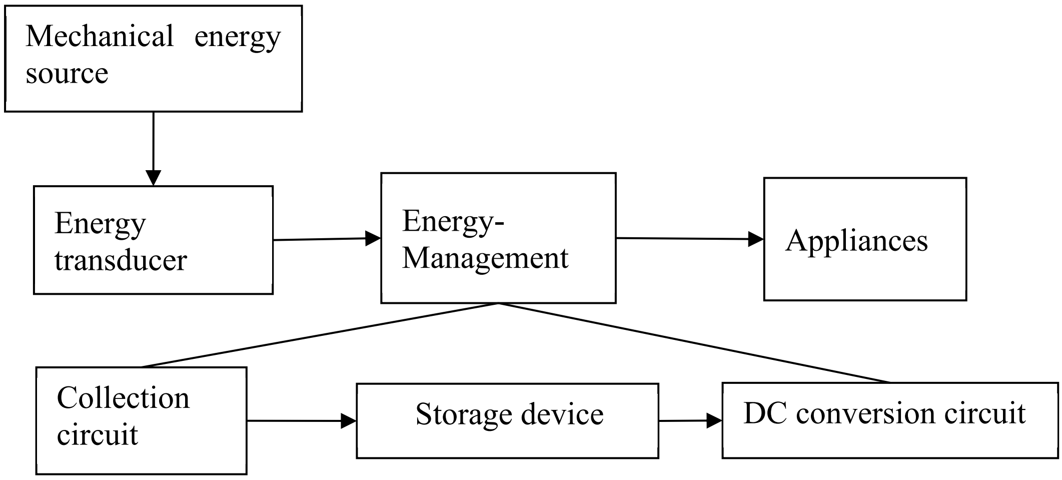


Figure 1: Components of a complete energy harvesting sensor system

Mechanical vibrations are converted into electrical energy with the help of piezo transducer, which is thereafter stored in energy storage units after being rectified, such as a supercapacitor or battery. Finally, the Direct current (DC) voltage waveform, which meets the requirements of the electrical appliance, is given through the DC conversion circuit.

Since in such a low-power system, the absolute value of the effectively utilized energy is extremely limited, and the same as harvested energy, which scales up the energy loss effect of the circuit. In this case, the more typical examples are the voltage drop of bridge rectifier and the energy loss through the switch in a DC conversion unit [5]. The commonly used diode full-bridge rectifier circuit has a high energy loss due to the factors such as the turn-on voltage. Some alternative examples to reduce this energy loss such as the diode-less bridge circuit [6] or using field effect transistors (MOSFET) instead of diodes [7] are provided in recent studies. The advantages and disadvantages are explained by the author. Since this paper focuses a completely energy self-supply system, all energy consumption except main electrical appliances should be excluded. In [5], a dual-stage H-Bridge rectifier circuit is provided, which does not require additional power supply to turn on the switches and the MOSFETs. For the DC conversion circuit in the second stage, the author only gives the chosen component, without explaining the reason for not using external energy supply. In the simulation environment, all parameters can be set to ideal conditions, such as the turn-on voltage and internal resistance of the diode. In addition, the PWM signal to control the DC switching circuit can be directly generated by using the functional module in Simulink. As a result, the simulation of generated energy and the power consumption of the sensor system is more accurate.

The detailed modeling process of the complete system showed in Figure 1 is described in the following sections, which based on the working principle of the real component. For power users, a real sensor system operation sequence is designed, and the power consumption curve simulated. At the end of study, the simulation results are compared with the experimental data.

2 ENERGY SOURCE MODELING

A simplified electromechanical model can be used to describe the piezoelectric energy transduce device, which is shown in Figure 2. This model has been widely used with its general vibration equation expressed as:

$$m\ddot{u} + d_0\dot{u} + Ku + F_E = F \tag{1}$$

where d_0 is the damping coefficient, K is the elastic constant, F_E is the force generated by the internal electric displacement of piezo material, and u is the displacement. Further on, this can be integrated into an energy balance expression:

$$\frac{1}{2}m\dot{u}^2 + \int d_0\dot{u}^2\,dt + \frac{1}{2}Ku^2 + \int F_E\dot{u}\,dt = \int F\dot{u}\,dt \tag{2}$$

Considering the piezoelectric equation mentioned in [8] and the expression of the piezo material constants [9], there are two elastic coefficients with the same dimension in this system, one is the elastic deformation coefficient K , and the other generates the mechanical force F_E through the inverse piezoelectric effect.

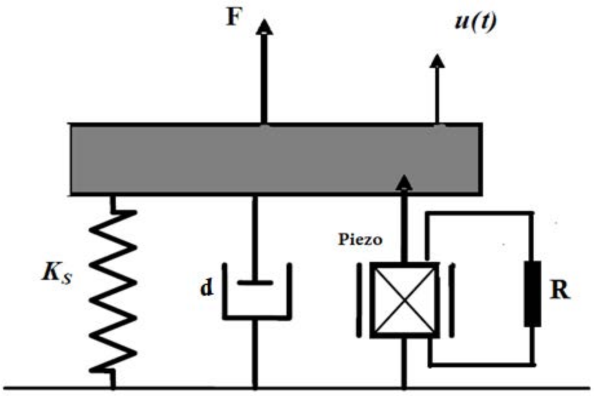


Figure 2: Electromechanical model

Note that capacitive effects inside the piezoelectric material must be considered. The electrical energy output generated by the positive piezoelectric effect can be expressed as two parts:

$$\int F_E\dot{u}\,dt = \frac{1}{2}C_0V^2 + \int VI\,dt \tag{3}$$

Where C_0 is the internal equivalent capacitance of the piezoelectric transducer, V and I represent the output voltage and current, respectively. Thus, in addition to the output power of the circuit, the method to use the first part of energy, which is stored in the internal capacitor, is one of the key factors to improve the energy conversion efficiency of piezo materials. In the next section, several solutions to this problem will be mentioned.

This electromechanical model as an energy source can be built intuitively in Simulink combined with the Simscape plugin. Figure 3 and Figure 4 show the schematic diagrams of the vibration source and the attached piezoelectric stack in Simulink, respectively. The basic principle of this simulation model is the same as the simplified model above. The mechanical energy generated by the vibration mass system is used as the input of piezoelectric stack, which brings the displacement of piezo sheets, due to the positive piezoelectric effect, it can output a voltage. The material coefficients of piezo stack can be modified directly in this module.

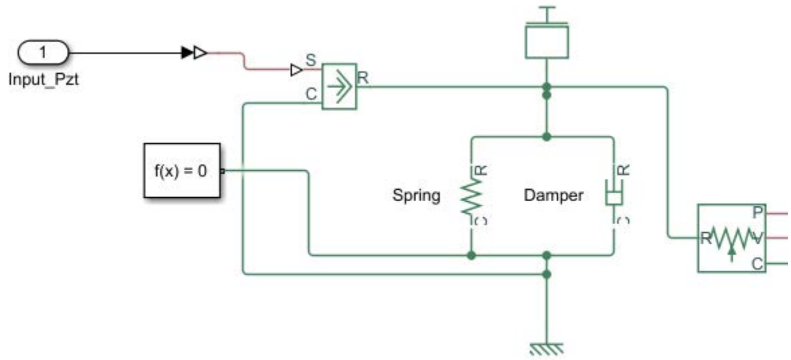


Figure 3. Vibrator-model in Simulink

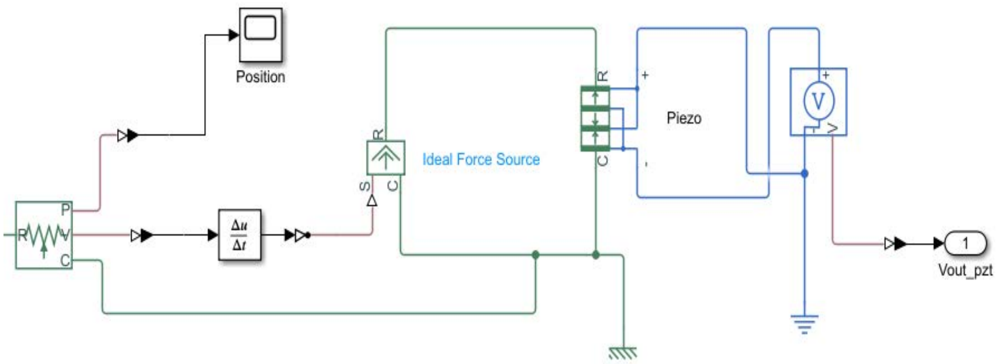


Figure 4: Piezo-Stack attached to the vibrator as the voltage generator

3 HARVESTING CIRCUIT

In [6][7], the energy harvesting circuit is divided into two parts, which are the rectification circuit and the optimization circuit. A basic full-bridge rectifier circuit and its implementation in Simulink are shown in Figure 5. In [7], the author discussed detailly the great influence of the load resistance on the output power. In the simulation environment, the load resistance can be changed arbitrarily, despite, the current consumption of the Microcontroller Unit (MCU) and the wireless funk unit in different modes is uncontrollable in real situations, it is difficult to match the resistance that gives the maximum output power.

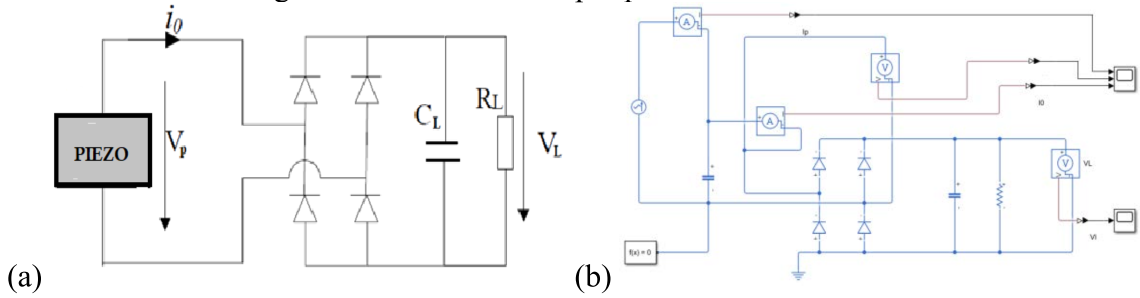


Figure 5: (a) Full bridge rectifier circuit (b) Implementation in Simulink

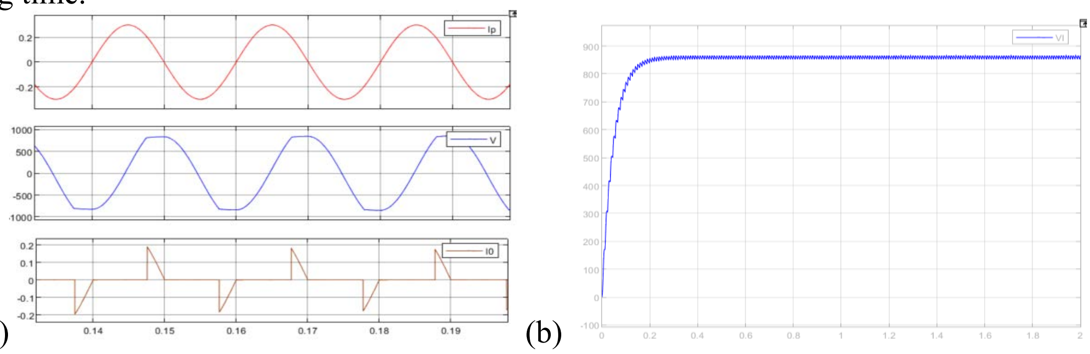
In order to ensure the feasibility of each part of the model, a current source with a parallelly connected capacitor is temporarily used as an equivalent piezo generator. Note that this bridge rectifier will involve the energy loss problem which has been mentioned above, it only works when the voltage generated by the piezo transducer V_P is higher than the sum of the turn-on voltage of the rectifier circuit V_{on} and the Load voltage V_L. Regardless of other factors, the relationship between the output voltage and the input voltage is represented by (4).

$$V_P > V_{on} + V_L \tag{4}$$

In order to match the output power requirements, this basic circuit must be improved. When the input voltage is too low, a boost circuit is required to amplify the output. As an example, a voltage doubling circuit is introduced in [10], which is used to harvest radio frequency (RF) energy. For the problem of how to effectively utilize the electric energy stored in the internal capacitance of piezoelectric harvester mentioned in the first section, several approaches have been analyzed in [11], such as Parallel-SSHI and Series-SSHI circuits. The most implemented is the voltage regulator circuit using switching principle, which contains boost- and buck-mode respectively. In the following study, these optimized circuits were built in Simulink, since the focus of this study is to establish a simulation model that based on the principle of the LTC3588-1 module, the optimized circuits were only modeled in Simulink for backup use, which is in other way for later combined implementation according to the practical situation.

3.1 Standard circuit

A typical advantage in Simulink is that the turn-on voltage and resistance of the diode can be adjusted freely, they can be set to the ideal state ($V_{on} \approx 0, R_{on} \approx 0$). Figure 6 (a) shows the simulation result of current and voltage inside the piezoelectric material as a current source. The internal resistance of the piezo transducer is not considered here. The simulated results are in good agreement with the waveforms in the literature. Note that the voltage drop of the diode is not set to zero here, instead a very small value, which needs the generated voltage V_P to meet the conditions in (4) to ensure the energy harvesting process. In addition, Figure 6 (b) is the output voltage curve of this standard circuit. The output voltage tends to be stable after a period, but there is still small vibration, which strongly depends on the load capacitance. Choosing a larger load capacitor is beneficial to stabilize the output voltage, which brings however longer charging time.

(a) 

(b)

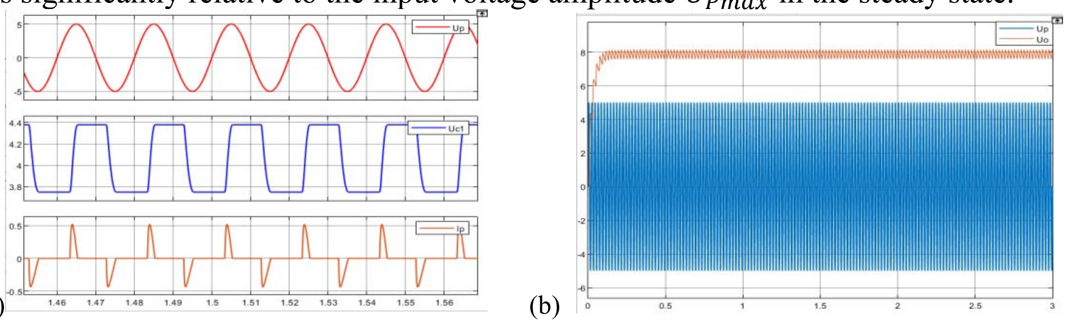
Figure 6: (a) Input waveform from Piezo (b) Output voltage

3.2 Optimizing circuit

In this section the implementation of two optimizing circuits in Simulink will be introduced, which are voltage doubling circuit and Parallel Synchronized Switch Harvesting on Inductor (P-SSHI) circuit respectively.

1) Voltage Doubler

According to the circuit proposed in [10], the simulation model can be directly built up after being simplified and connected to an Alternating current (AC) voltage source, the detailed explanation of the Voltage Doubler is stated in [10]. In this study only the simulation results of this model in Simulink are given (Figure 7). It can also be seen from Figure 7(a) that, due to the voltage drop from diode, the input voltage will not charge the capacitor until it overcomes the diode turn-on voltage, the time interval in which the current I_P is not 0 shows how long the charging period lasts. From the results in Figure 7(b), it is clearly that the of the output voltage increases significantly relative to the input voltage amplitude U_{Pmax} in the steady state.

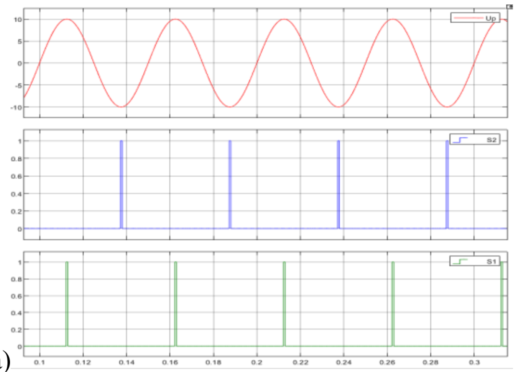
(a) 

(b)

Figure 7: Simulation result of voltage doubler

2) P-SSHI-Circuit

As mentioned, a proposed Parallel-SSHI-Circuit in [11] can extract the electric charge retained in the internal capacitance of the piezoelectric material, which can improve the energy utilization efficiency. A more detailed study of this circuit can be found in [12], based on which the simulated results in Simulink can be seen in Figure 8. In addition to the simulated waveform information shown in Figure 8(b), the signals for the two switches are also given in Figure 8(a).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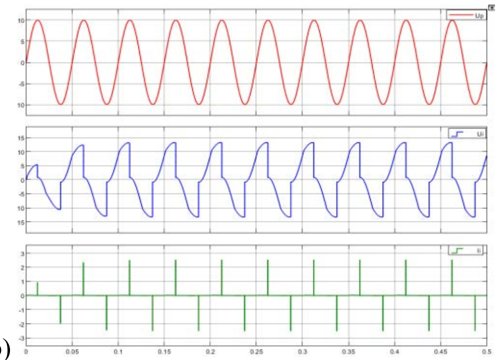
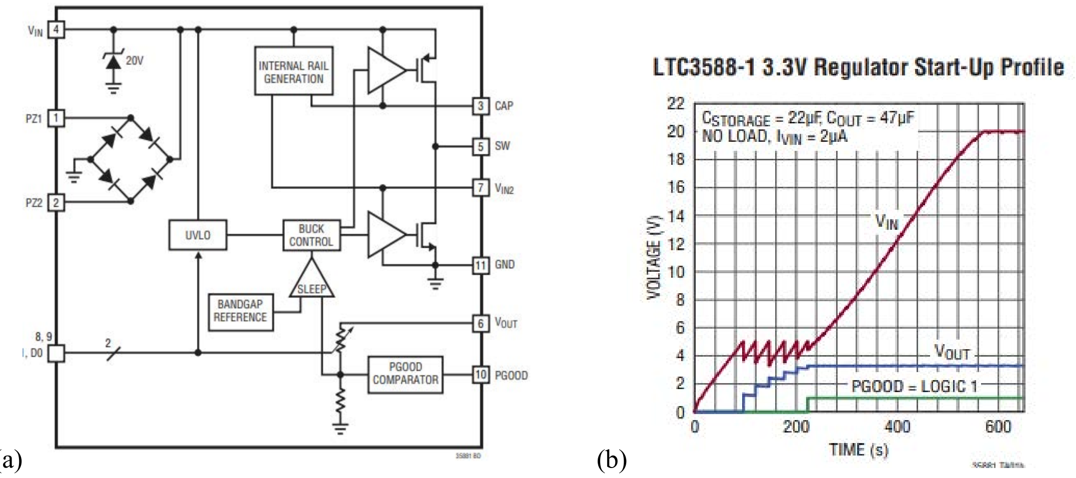

(b)

Figure 8: Simulated results (a) Gate switch signals (b) Waveform of P-SSHI-Circuit

3.3 Modeling based on LTC3588-1

Using the LTC3588-1 [13] is one of the main purposes of this paper. This module is a complete energy management unit that integrates a full-bridge rectifier and voltage regulation circuit. The block diagram is shown in Figure 9 (a), for the buck regulator in regulation unit, it uses a hysteretic voltage algorithm to control the output to reach the reference, which needs no extern energy resource. The input and output waveform in the start period is in Figure 9 (b) expressed. In addition to the basic circuits mentioned above, A unique feature of the system is that there is a UVLO gate between the rectifier and the voltage regulator, which controls whether the regulator works based on the rectified input voltage. The PGOOD signal switches to 1 when the regularization process is completed. For the modeling of BUCK converter, this paper used the voltage control with a PI feedback unit because of the simpler control loop and faster response time. The closed loop principle from [14], which also provided a detail method for the system stability test, this can be implemented in MATLAB using Control System Design Toolbox for more optimized results.

The complete simulation model using the harvesting energy source from Figure 4 and the harvesting circuit LTC 3588-1 in Simulink is represented in Figure 11 (a), and the simulation results are shown in Figure 11(b). The pink line represents the UVLO gate signal, from which can be seen that the voltage regulator started to work within a short time after the circuit is turned on. According to the simplified structure in Figure 10, this is related to the size of the input capacitor C_{IN}, when this storage capacitor is large, it will need a longer time to charge until reaching the threshold voltage of UVLO, which allows the regulator to start to work. During the simulation, the vibration source is interrupted in the middle so that there is no energy input within a short period, during which the system is powered by the storage capacitor, which appears as a drop down in the capacitor voltage value (red line). When the output voltage starts to decrease, the PGOOD signal (brown line) will output a low level. After the energy source continues to collect energy, the input capacitor will charge, and the system will start up again.



(a) (b)

Figure 9: (a) LTC3588-1 block diagram (b) Start-Up-Voltage-Waveform [13]

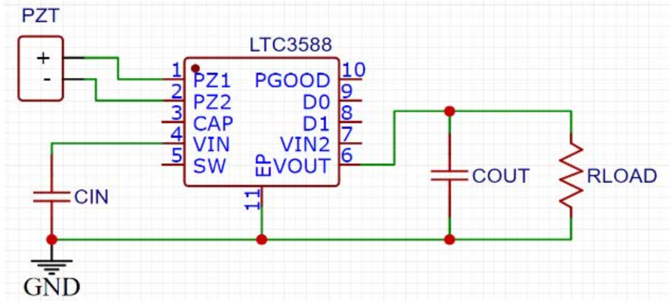


Figure 10: Basic principle for LTC3588-1

(a)

(b)

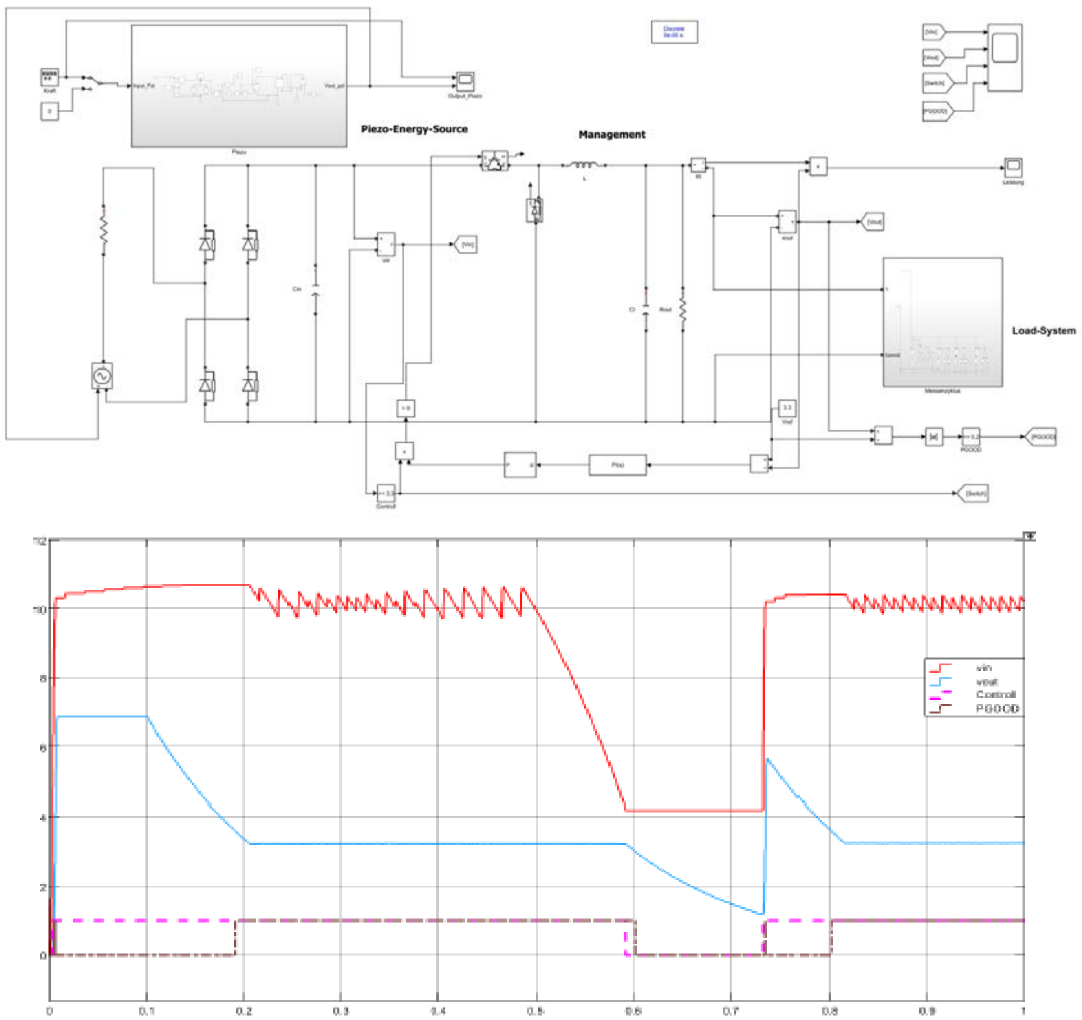


Figure 11: (a) Simulation Model of total system (b) Simulation results based on the principle of LTC3588-1

Note that the power of electrical appliance is in practical situation changes in real time. The equivalent resistance in simulation model from Figure 11 should be changed with time. Thus, a simplified sequential model of system operation process is presented in the next section.

3.4 Energy Consumption Simulation

The scenarios simulated in this section are the maximum current consumption in each working state. According to the working sequence shown in Figure 12, it is assumed that the vibration source operates continuously and a DC voltage after being processed by the LTC 3588-1 is provided. The current consumption in the standby state is almost 0, and the general CPU current consumption does not include the Bluetooth data transmission, the sending and receiving of data is represented by TX and RX. The current consumption to calculate the equivalent load resistance with 3.3 V is obtained from the data sheet. The corresponding implementation method is shown in Figure 13. The approximate simulation results are shown in Figure 14. In the case when only MCU is working (CPU), the current is about 0.1 mA, after adding the Bluetooth module (TX), the current consumption increases to 0.12 mA. The data transmission duration is here determined arbitrarily. In the subsequent research, in order to use the collected energy more effectively, it should be chosen according to the size of the data packet and the transmission speed.

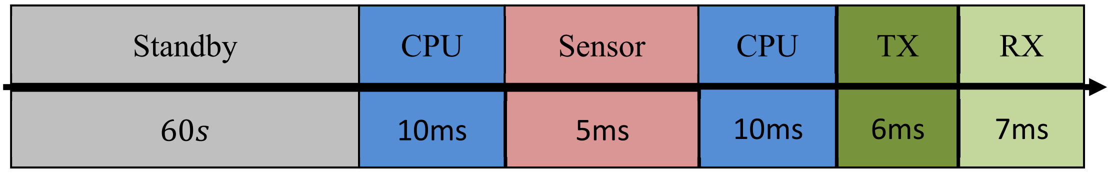


Figure 12: System operation sequence case

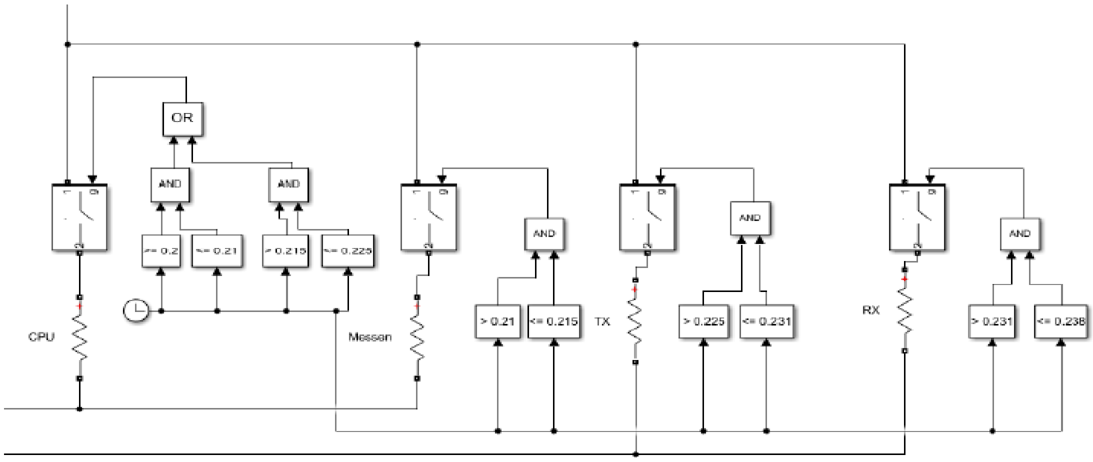


Figure 13: Realization of load system in Simulink

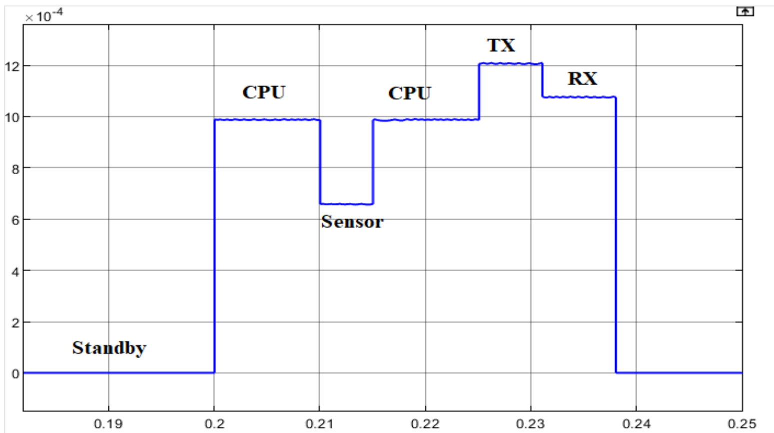


Figure 14: Current consumption simulation result [A]

3.5 Experimental Comparison

The purpose of this experiment is to measure the power consumption of this system, which can be measured as current at the rated voltage (3.3 V). The test setup is given in Figure 15 (a), in order to meet the experimental requirements more flexibly, a function generator and a power amplifier (MX-200) were used to represent the piezoelectric material as the power supply. It can be seen that in Figure 15 (b), the oscilloscope shows that a DC-Voltage of 3.3V is given across the entire energy harvesting circuit, which powers the MCU and the Bluetooth module.

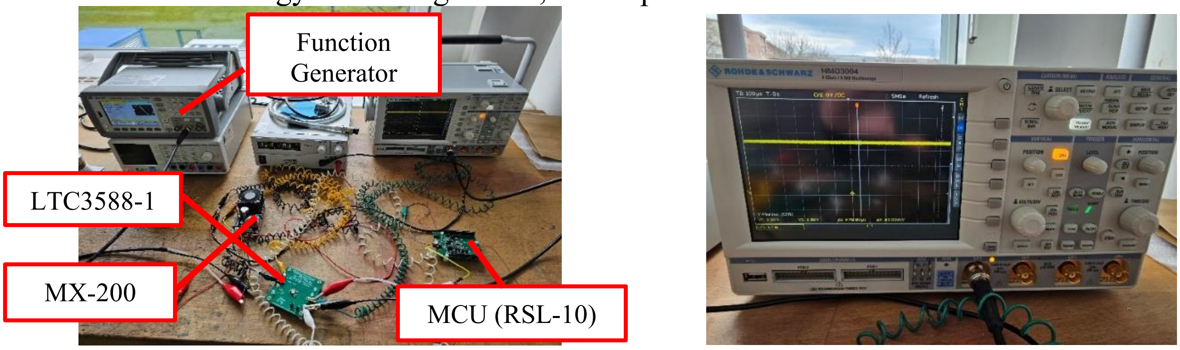


Figure 15: (a) Experiment setup to measure the current consumption (b) Output voltage (3.3 V)

To measure the current consumption in different modes, two different programs were flashed into the MCU, only the MCU is on and both MCU and Bluetooth are on, respectively. After the measurement with the multimeter, the current consumption was 0.14 mA when only the MCU was on, and when the MCU and the Bluetooth module were both on, the current was 0.189 mA.

4 CONCLUSION

This paper provides a simulation model of a complete energy harvesting sensor system in Simulink, using the LTC 3588-1 as the harvesting circuit. This model can simulate the system conditions by providing the equivalent load resistance in different modes, providing an intuitive method for determining the boundaries of the system. The input of the whole system is the force loaded on the piezoelectric material, which can be in different forms, including the sinusoidal form used in the simulation. After comparison it shows that there are errors between the simulation results and the experimental results, the main reason is that the RSL-10 chip used in the experiment is integrated on the evaluation board, as a result, the measured current is inevitably including the current consumption of other components of the board.

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