Modeling and Simulation of an Energy Harvesting System

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***Abstract*—Over the years there has been a growing interest in applications in the field of miniature sensor nodes. Energy harvesting systems are playing here a more and more important role. Therefore long-lasting and autonomous sensor nodes are implementable. Simulations are very valuable for the dimensioning and correct interpretation of the individual components of a node. In the paper, a model is presented which a piezoelectric generator, the step up rectifier circuit and holistically describes a low energy microcontroller. Simulations show the results clearly.**

***Index Terms*—energy harvesting, sensor node, modelling, simulation**

I. Introduction

There are a wide range of applications that have been integrated starting from medical implants to embedded sensors in buildings. One aspect of research in this area has always been to power such devices in a way that would increase their life time. Originally majority of such devices were powered using electromechanical battery. One essential drawback of using battery is that the lifetime of the device is directly linked up with the battery size(especially when the millimeter size of the devices are considered). It is for this purpose that energy harvesting methods came to be explored, studied and utilized. Such an, let say, intelligent sensor node consists of different components, see figure 1 below.

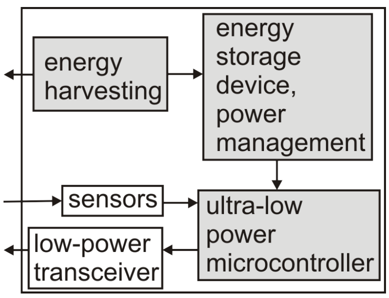

Fig. 1. Components of an intelligent sensor node

The goal was to create models of the various components involved in the end- to- end process,starting from using energy harvesting methods to generating voltage to processing this voltage to convert it into a usable form and then consume this to evaluate its usage with low power microprocessors. The first component is the energy harvester or generator. A micro power generator has been utilized for consuming vibrations from the environment and eventually converting them into alternating voltage. It has been observed that common vibration sources such as household appliances, manufacturing equipment etc. vary from $0.2 \rightarrow 10\frac{m}{s^2}$ in vibration acceleration amplitude and their frequencies range from $60 \rightarrow 200Hz$ [1], [2]. Bearing this in mind, our study here has considered a vibration source of input acceleration amplitude $2.5\frac{m}{s^2}$ at a frequency of $120Hz$. The formulations of the analytical model used uses the input acceleration amplitude as an input to produce the required generated voltage. The generator would in-turn generate an AC voltage of around $2.5V$ at $120Hz$ (simulation result). The next component is the step-up rectifier model. This model would consume the AC voltage generated, rectify it and convert it to DC. This DC voltage is stepped up for consumption by the load, which could be a low power microprocessor or a radio transmitter. In this paper the third component calculates the numerous aspects of consumption such as frequency and number of operations based on the stepped up DC voltage obtained from the step-up rectifier model. An Atmel processor has been used as a standard for this part of the analysis and study. The combined model thus created in Matlab Simulink is as shown in the figure 2.

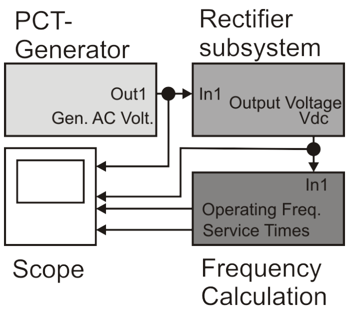

Fig. 2. Overall piezoelectric generator simulink model

It should be noted that the power generated by the generator device would be in the range of micro-watts. The Microsystem would generally have an ultra-low power controller with a low power RF communication module, sensors and maybe a battery for energy storage.

II. Piezoelctric generator

In this section a piezoelectric generator based on a two-layer bending element has been designed and modeled using mathematical /analytical expressions and Matlab Simulink. This model has been studied based on the findings in [2], [8] and [10]. An analytical model of the generator has been studied and then validated using Simulink. A vibration source of around $2.5\frac{m}{s^2}$ at $120Hz$ has been identified as the vibration source input and the results have been obtained based on the effects of such a vibration source on the generator model developed.

One method of modeling piezoelectric elements is to include both the mechanical and electrical portions of the piezoelectric system as circuit elements [2], [3]. Such an electrical model that was attempted based on the study in the reference [2], [9], is shown in the figure 3. It must be noted that the generator can be modeled both in the form of an electrical circuit as well as by using the transfer function. In the simulation studies however we have investigated the design parameters by using the transfer function to represent the system with a resistive load.

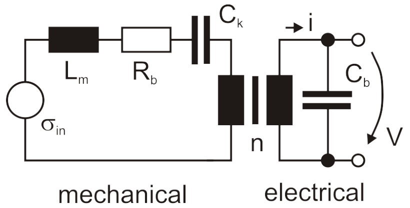

Fig. 3. Electrical circuit representation of the piezoelectric generator, see also [2]

From this electrical equivalent circuit, after applying Kirchhoff's current and voltage law we get the following 2 equations

$$\sigma_{in} = L_m \cdot \ddot{S} + R_b \cdot \dot{S} + \frac{S}{C_k} + n \cdot V \tag{1}$$

$$i = C_b \cdot \dot{V} \tag{2}$$

In the above equation σ_{in} is the input stress,S represents the strain, n represents the turns ratio of the transformer, V is the Voltage across the electrical side of the circuit and i is the current as shown in the figure above.

This mapping of the electrical elements shown in the figure 3 is done mainly by deriving relations between stress, voltage and the derivatives of strain. In this manner the coefficients of the different derivatives of strain will be mapped to design parameters of the piezoelectric cantilever beam model. Now it is to be developed the state space description of the piezoelectric generator. For more in detail see [4].

$$\begin{pmatrix} \dot{S} \\ \ddot{S} \\ \dot{V} \end{pmatrix} = (A) \cdot \begin{pmatrix} S \\ \dot{S} \\ V \end{pmatrix} + \begin{pmatrix} 0 \\ \frac{1}{k_2} \\ 0 \end{pmatrix} \cdot \ddot{y} \tag{3}$$

where A is

$$A = \begin{pmatrix} 0 & 1 & 0 \\ -\frac{k}{m} & -\frac{b_m}{m} & \frac{k \cdot d_{31} \cdot \frac{a}{2}}{2 \cdot m \cdot t_c} \\ 0 & \frac{2 \cdot t_c \cdot d_{31} \cdot C_p}{a \cdot \varepsilon} & 0 \end{pmatrix} \tag{4}$$

The above equation and constants were used in matlab functions to generate the required values which are utilized to calculate the transfer function. This transfer function of the generator model is used as a part of the ultimate model to represent the piezoelectric generator component of the comprehensive model.

For the purpose of retrieving the voltage generated on account of the piezoelectric generator a resistive load is utilized. This can also be used in order to estimate the power that can be delivered to an actual electrical load. The current equation in the case of a resistive load would then be

$$i = C_b \cdot \dot{V} + \frac{V}{R} \tag{5}$$

Substituting the equation, see [4] and after rearranging the terms we get

$$\dot{V} = \frac{2 \cdot t_c \cdot d_{31} \cdot C_p}{a \cdot \varepsilon} \cdot \dot{S} - (\frac{1}{R \cdot C_b}) \cdot V \tag{6}$$

Thus the resulting state space due to the resistive load is to be corrected. It is this state space that has been implemented as a part of the piezoelectric model generator.

III. Step-up rectifier circuit model

The voltage generated by the piezoelectric generator introduced in the previous section, generates AC voltage $\approx 2.5V$ at $120Hz$. Depending on the application this voltage might not be sufficient enough. For example: The operating voltage for an ARM based processor is $4V \rightarrow 6V$, below which the performance of the processor cannot be guaranteed. For this reason, the voltage needs to be stepped up to a certain operational value.

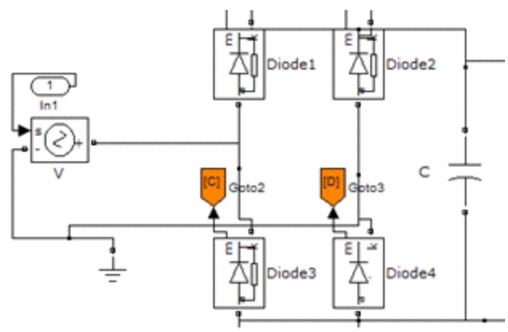

Fig. 4. Diode bridge rectifier model

A rectifier circuit converts an AC Voltage to DC voltage. A diode bridge rectifier is used in the model. This rectifier converts the incoming AC voltage from the piezoelectric generator source to a DC voltage and charges a capacitor, which then serves as the DC voltage source for the rest of the circuit.

An ideal diode model is used in order to simplify the analysis. The response of the rectifier circuit for a varying sinusoidal AC input is depicted in the figure 5 The AC input voltage is denoted in the graph below and the upper graph denotes the corresponding rectifier response. A simple switch based DC-DC boost converter is shown in figure 6. The model comprises of an inductor, a capacitor, a switch and a diode. The circuit works in two stages. In the first stage the switch is closed. So the inductor charges up as the whole current flows through only the inductor. In the second stage the switch is open. The charge in the inductor charges up the storage capacitor. With appropriate switching logic, the charge in the capacitor can be maintained near to a constant value. This is a DC-DC converter, so it needs a DC source to operate correctly. However the presence of the diode provides rectification capabilities to the circuit thereby converting the AC to DC, the purpose of the diode at this stage is different. Since the output capacitor gets charged up based on switching logic, in absence of an appropriate load there can be a case when voltage difference between the output capacitor and input source becomes high. This might result in current flowing in opposite direction. Since, ideally a diode can conduct only in one direction, this reverse current situation is avoided. For realisation of such a switching circuit, an IGBT [5] (insulated gate bipolar transistor) based circuit can be used.

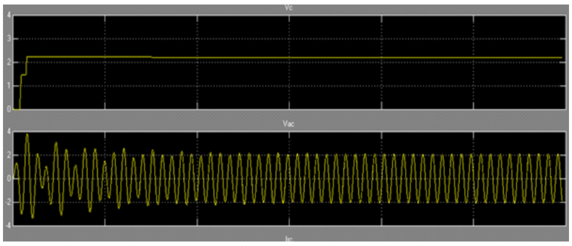

Fig. 5. Bridge rectifier response

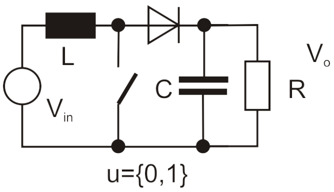

Fig. 6. Switch based voltage boost converter

Based on the logic applied to the gate of the IGBT the transistor switching behaviour can be controlled. Whenever the pulse occurs, the switch is opened there by allowing the inductor to charge the storage capacitor. If the pulse is 0, the inductor gets charged. By setting an appropriate pulse width the charging time of the capacitor can be changed. A pulse generator (powered by a small battery) can be used to provide the pulse signal to the IGBT gate. This can also be implemented with a feedback loop as shown in [6]. The response of the circuit at a constant DC voltage of $2.5V$ and a pulse width of 50% is shown in figure 7. Shown is from up to down: i_L, i_{diode}, V_{load}, i_c, V_{CE}. The model comprises of a diode bridge rectifier circuit followed by a DC-DC IGBT based step up converter circuit. The rectifier circuit rectifies the varying AC input and charges the storage capacitor C. This storage capacitor C serves as a DC voltage source for the DC-DC step-up converter. This is an open-loop model, so no voltage set-point is taken into concern. The DC-DC step-up converter charges the output capacitor C1 with a stepped-up voltage.

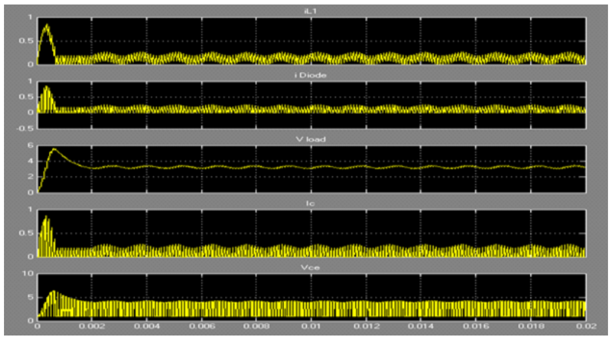

Fig. 7. Response of an IGBT based boost converter

Since the output storage capacitor is acting as a voltage source for the end application (microcontroller/ actuator), the time taken by the capacitor to discharge completely depends on the capacitance and resistance of the load attached. The discharge time of the capacitor is given by:

$$\tau = R \cdot C \tag{7}$$

Normally, the pin impedance of a microcontroller is very high, which results in frequent discharge of the output storage capacitor. The charge time of the output storage capacitor can be manipulated accordingly to generate power enough to finish specific tasks. The charge time can be controlled by the pulse width to the gate of the IGBT in the step-up circuit.

IV. APPLICATION MODEL

The technology today enables integration of computation, communication and control into a compact and economical device. This section introduces the concept of utilization of harvested energy from a piezoelectric generator considering an application that uses a microcontroller.

It is shwon a model of a single server with changing processing rate according to the input. Let us consider a specific device. Here we consider an Atmel microcontroller AT90S8535. According to the data sheet, the speed of processing can be selected from $0 \rightarrow 8MHz$ with a corresponding operating voltage of $2.7V - 6.0V$. It can be shown that, processing speed is a function of input voltage [7]. The function for a specific processor in question is shown below:

$$V = \frac{V_t}{1 - C_1 \cdot f} \tag{8}$$

Alternatively the operating frequency can be calculated as:

$$f = \frac{1}{C_1(1 - \frac{V_t}{V})} \tag{9}$$

Where, f is the processing speed in MHz, V is the input voltage, V_t is the reference voltage, the minimum operating voltage and C_1 is a device specific constant. For the AT90S8535, $V_t = 2V$ and $C_1 = 0.0833$ On the other hand, the energy the processor consumes to process a job can be expressed by the following formula:

$$P = C_2 \cdot N \cdot V^2 \tag{10}$$

Where, $C_2 = 0.4167 \cdot 10^{-3}$ is a device dependent constant, N is the number of operations needed to process the job (in million operations), V is the input voltage and P is the energy usage (in Joules), see also [7]. Therefore, we can calculate the number of operations by

$$N = \frac{P}{C_2(V^2)}. \tag{11}$$

The equivalent simulink model is shown below, figure 8.

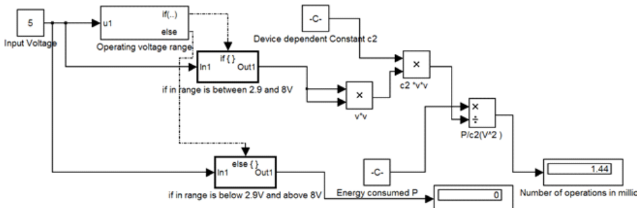

Fig. 8. Simulink model of equation 11

V. SIMULATION STUDIES

This section studies the behaviour of the over-all combined piezoelectric generator model based on an PZT5H with a brass centre shim. For usability analysis the model is combined with an Atmel microcontroller model.

Figure 9 shows the simulation results for the whole model. The microcontroller starts working only when the generated voltage due to harvested energy falls in the operating voltage range of the $2.7V - 8V$. For simplicity of analysis, no actual load is attached to the generator system and the output values are used for the calculation of processor operating frequency. As output voltage increases, the speed of operation of the microcontroller also increases based on the relation mentioned in equation above. Service time of jobs is inversely proportional to the operating frequency. In a simulation time of 3 seconds and the piezoelectric generator vibrating at a frequency of 120 Hz produced approximately 3.15 Volts resulting in an operating frequency of approximately 4.38 MHz.

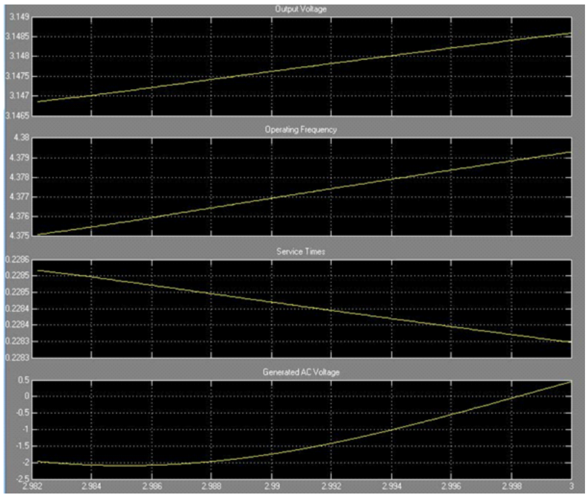

Fig. 9. Overall model simulation results at 120 Hz

From up to down is shown the output voltage, the operating frequency, the service time and finally the generated AC Voltage.

At an environmental vibration of frequency $60Hz$, the output voltage rises faster reaching approximately $4.23V$ Volts, resulting in faster operation of the microcontroller reaching an operating frequency of approximately $6.57MHz$.

VI. CONCLUSION

There is a wide potential for application of vibration-based power supply systems to wireless systems. From amongst the 3 technologies present - electromagnetic, piezoelectric and electrostatic, piezoelectric energy harvesting devices are the simplest means of scavenging power directly from structural vibrations. Thus this sort of device was studied and modeled with a view to develop an end-to-end structure for the purpose of having a one stop station to perform further experiments and studies. Various tests can be performed using this model by varying:

- the vibration amplitude or frequency of ambient vibrations
- the design parameters of the piezoelectric generator model
- the rectifier circuit parameters such as pulse width of the gate signal (charging time of the capacitor), forward voltage of the diode etc.
- the potential to alter operational voltage range, processor specific constants.

The model ultimately allows analyzing the generated output voltage based on ambient vibrations, operating frequency of the processor and service times of the incoming jobs. There are also provisions and output Graphs generated for the purpose of analyzing the behavior of the DC voltage converted from varying input AC voltage generated at $60Hz$ and $120Hz$. The eventual analysis of the outputs obtained and the presence of a one stop end-to-end model allows the designer to perform a comprehensive study about utilizing the harvested voltage by different types of microprocessors. The parameters such as operating frequency output and service time output also provides the designer an option to understand what type micro-system can be adapted to appropriately fit into the harvested energy based on numerous application requirements.

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