Simulation of Gait Based Wearable Energy Harvesting using Human Movement

Mohankumar V., G. V. Jayaramaiah

Abstract: ***The portability of power for human health monitoring is considered a challenge for years to come and the recent development in wearable devices has encouraged this research area. This paper develops a composite energy harvesting paradigm that combines piezoelectricity and electromechanical energy production to energize the storage batteries powering wearable devices. A composite mathematical model that combines the piezoelectric process along with the electromechanical process comprising the piston action is developed using Matlab™. The piezoelectric power is considered to be generated from the pressure created by human weight on it while walking and electromechanical power generated from the limb movement of the human being. The energy thus harvested from both these inputs are consolidated and fed to charge the batteries that feed the wearable sensors. The Lithium-Ion battery of 1.2V rated voltage is charged using the power generated from the mathematical models of both the piezoelectric and electromechanical power generation. The energy generated is found to be satisfactorily charging the battery.***

Keywords: Gait based energy harvesting, Wearable Devices, Piezo-electricity, Composite Energy Model.

I. INTRODUCTION

The usage of electrical devices and gadgets when compared to previous years has increased exponentially. Nowadays wearable and portable devices have become an essential need in numerous everyday uses. In recent years evolution of electronic devices like, smart phones, smart watch, health monitoring devices, wireless headphones etc. is developing in a rapid pace. The portability in wearable devices requires uninterruptible power from the batteries. But the fast deteriorating power of the battery creates the problem that needs to be addressed. The need to extend the battery range portable charging device which stores electrical energy or generate energy from any other source is highly appreciable.

Piezoelectricity is the process where the property of piezoelectric material to convert the mechanical pressure applied on it is converted to electrical voltage. Only few crystal materials which do not possess the center of symmetry exhibits piezoelectricity.

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The amount of pressure or force applied on the crystal is proportional to the amount of power generated from the crystal. These piezoelectric crystals have applications including transducers, weighing machines applications etc. The application of these crystals surfaced during 1971 in a SONAR (Sound Navigation and Ranging) implementation [1]. Although the main contribution of introducing the piezoelectric material is to act as a transducer the micro-generation property of this crystal can be exploited to supply the wearable sensors. Micro energy harvesting applications that are propping up in combination with the wearable devices are going to make future technologies more portable. The Piezoelectric generators have the capability that can cater only low energy consumption gadgets or transducers due to its characteristics (high voltage, low current, high impedance).

A high power piezoelectric pulse generator is adopted with maximization technique to get maximum power generation from the stack of piezo-electric crystals [2]. The geometric dimension of the crystal material along with the circuital topology is developed for a maximum power output from the stack. Piezoelectric Pulse Generator (PPG) stores the energy from the mechanical force in the capacitance. The Piezoelectric devices are stacked to increase the internal capacitance and connected electrically in parallel [3] for generating higher power. The munitions are characterized with high acceleration and very less operation life. Piezoelectric is used in this environment with a low cost tool to harvest energy [4]. Validating mathematical equations for the new type of the material called Piezoceramic and real time models are developed for energy harvesting in munitions environment.

Different crystal materials are tried upon to study the performance including maximization topology of the crystal, energy density etc. Lead Zirconate Titanate (PZT) based crystal is used for a micro-generation application in [5]. The crystal wafer is placed inside the shoes converting the force exerted on it by the user is converted to electrical energy. While walking the amount of power the crystal used to produce is about 1.3mW with 3V terminal voltage. A total knee replacement setup is self-powered using the PZT crystal [5]. The concept of wearable computing is introduced in [6]. Although the power outlets are enough inside the city limits the important application of wearable power generation is prime when it is used in defence applications. All possible human based power generation units are discussed in [6] . Both electrical and mechanical model of the piezoelectric converter is detailed along with the provision to store the power generated from the piezoelectric crystal[7].

Two different crystal material PZT and Polyvinylidene Flouride (PVDF) are compared for its performance by placing them in the tyre of the vehicle. The PZT material is found to have higher power delivery compared to the PVDF but lower flexibility in PZT crystal. Although the individual power generation is utilized for extending the battery that is portable the complete use of the human gait action needs to be utilized wisely.

This paper utilizes the multiple sources of the human gait to improve the energy harvesting efficiency of the system. The combination of both the piezoelectric and electromechanical energy harvesting paradigm increases the scope of utilization of the human gait.

II. HYBRID PIEZO-ELECTROMECHANICAL ENERGY HARVESTER

The overall block diagram of both the piezo electric and the knee movement based energy harvester are as shown in Figure 1. The importance of continuity in the power supply to the wearable devices insists the importance of hybrid micro generation sources. The piezoelectric power generator can have the power processed directly from the crystal and supplied to energy storage devices. While the knee movement based system is connected with the piston setup which generates the linear motion that is converted to the rotary motion using the crank shaft setup. This rotary motion is used by the DC generator to convert the rotary motion to the electrical energy that is stored in the energy storage devices after power processing.

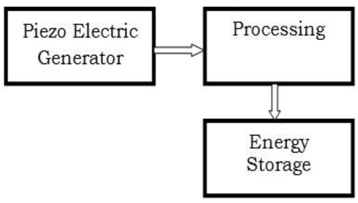

Figure 1a: Block diagram of Piezo electric energy harvester.

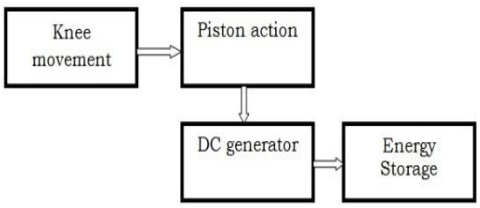

Figure 1b: Block diagram of Knee movement(DC generator) electric energy harvester.

The phenomenon in which the mechanical deformation of the crystal generates the electrical energy is called Piezoelectricity. The inherent property of the crystal which does not obey the center of symmetry in its cell level, exhibits this capability. The mechanical force applied on the crystal tends to move the number of positive and negative ions at the edges of the crystal such that voltage potential is generated. The piezoelectric crystal can work in two modes, generator mode and actuator mode. The generator mode is in which the mechanical pressure is converted to electric voltage and the actuator mode is that in which the voltage input will update the material expansion or compression called polling occurs.

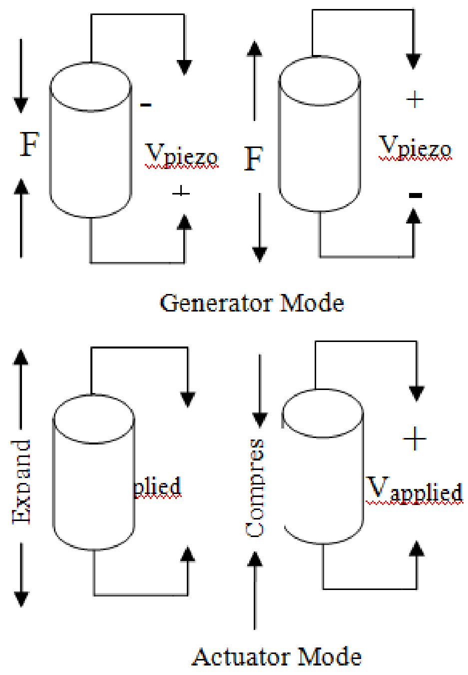

Figure 2: operation modes of piezoelectric device

Both the actions of polling and generation are as shown in Figure 2. The direction of the force applied on the crystal and amount of force applied influences the voltage generated from the crystal while in the generator mode. While in the actuator mode the polarity of the input power supply given to the crystal and amount of voltage provided to the crystal controls the mechanical deformation of the crystal.

Capability of the crystal to convert the mechanical energy efficiently in to electrical energy and vice versa is defined as coupling constant or electromechanical coefficient denoted as ‘Kij’. The anisotropic property of piezoelectric material defines the coupling coefficient according to direction of action ‘i’ and the response direction ‘j’.

$$K = \sqrt{\frac{Mechanicle\ Energy\ Stored}{Electrical\ Energy\ Applied}} \quad \text{---(1)}$$

Or

$$K = \sqrt{\frac{Electrical\ Energy\ Stored}{Mechanicle\ Energy\ Applied}}$$

$$V_{Out} = n\frac{F_{in}\Delta T}{LW}\ \text{Volts} \quad \text{-----(2)}$$

Where, Fin is the applied force, T is the thickness, L is the length and W is the width of the Piezo generator. n is the number of piezo generators connected, if n increases the generator voltage is also increases.

III. PISTON ACTION AND DC MOTOR MATHEMATICAL MODEL

The knee motion based power generation is the combination of piston model with the DC machine model coupled with the piston based crank shaft. The torque generated from the piston model is coupled through the crank shaft with the machine which generates power due to electromechanical conversion. Subscript F indicates rotating crankshaft and B indicates translating motion of the piston. The knee movement is transferred as the input to the piston.

The piston force is converted to crank torque measuring the crank rod length and the crank angle. The ratio defining the piston force with the crank torque is defined as in equation (3).

$$\frac{T_F}{F_B} = -c\left(sin(\theta) + \frac{sin(2\theta)}{2\sqrt{\left(\frac{r}{c}\right)^2 - \sin^2(\theta)}} \right) \quad \text{-- (3)}$$

where:

- Force exerted from the piston 'FB' at any instant
- Torque due to rotary motion of the crank 'TF' at any instant
- Length of the crank 'c'
- Crank angle at any instant 'θ'
- Length of connecting rod 'r'

The Figure 3 depicts the dimensional details of the crank and the piston as defined in [11]. The torque that is generated from the crank and piston setup is supplied to the DC machine which acts as the electromechanical generator is followed.

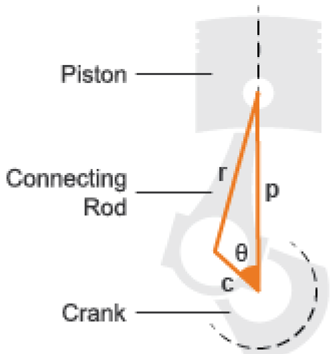

Figure 3:Piston and Crank action

The torque that is generated from this model is defined in a fraction between 0 and 1. The output from this piston and crank setup is amplified accordingly to provide the input to the machine model. The DC machine model[10] is as shown in Figure 4.

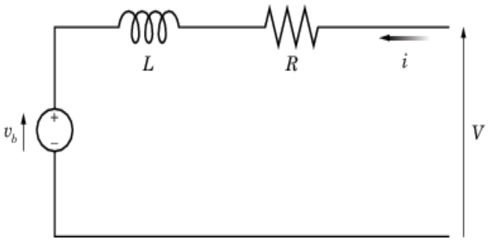

Figure 4: DC motor Matheatical model

The PMDC motor model with the equivalent circuit with the armature resistance R and inductance L . The permanent magnet induces the back emf v_b in the armature .

$$v_b = k_v \omega \quad \text{------- (4)}$$

The back emf generated from the angular velocity 'ω' due to the torque generated from the piston and crank setup connected to the knee. Where k_v is the back emf constant. The electromagnetic torque is defined using the equation (5) with the motor current *i*:

$$T_E = k_t i \quad \text{--------(5)}$$

where k_t is the Torque constant**.** The complete machine is assumed to have no losses meaning that the whole mechanical power input to the machine is converted to electrical energy.

IV. SIMULATION, RESULTS AND DISCUSSION

The MATLAB based simulation is carried out that models both the piezo electric generator defined in the previous section . While practically considering it the piezo electric sensor is considered to be fixed in the shoe. The electromechanical model which is considered to be connected to any of the limbs while considering practically is modeled. The force that is applied on the piezoelectric generator would eventually convert into needed voltage to charge the battery. The frequency at which the piezoelectric generator is triggered is 1Hz. The amplitude of the signal provided to the piezoelectric model is assumed to be force N. This force is applied across the piezo electric generator. The produced voltages are given to the battery of 1.2V li-on.

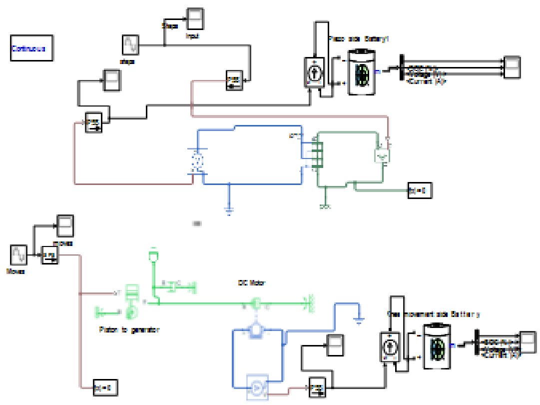

Figure 5: Proposed system simulation in MATLAB

Similarly, the movement of the knees are angular movement. This angular movement is a considered as one stroke at 1 sec. so the frequency taken here also 1Hz. The amplitude is taken as the angular force in N. this is given to the piston and crank action which converters the angular force to mechanical force and it is given to the DC generator of 12V. The above Figure.4 shows the complete simulation of the proposed system.

The input of the piezo electric generator is given in fig.5. it looks like a sinusoidal wave. Then the output created at the battery side is shown with state of charge (SOC), voltage and current. Here SOC increases from 50% to approximately 51%. The voltage across the battery is more than the nominal value. And the current in negative shows the battery is getting the charge.

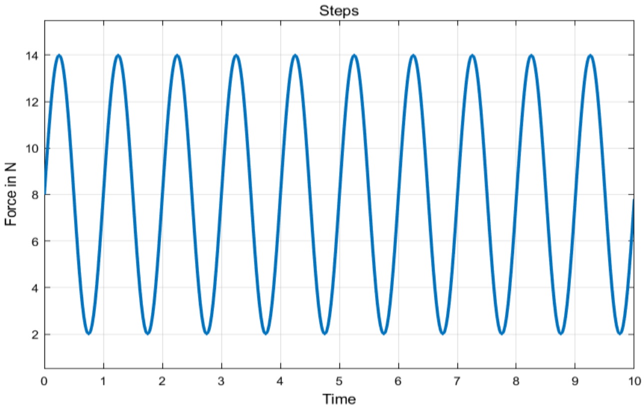

Figure 6: Input given to the piezo-electric generator

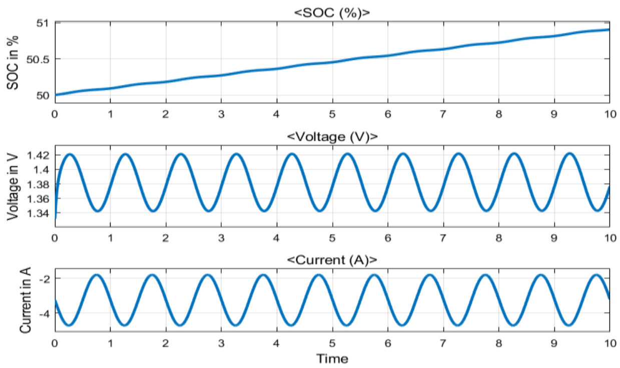

Figure 7: Output of the battery at piezo side.

The Figure 7 clearly indicates the rise of battery voltage as there is a rise in the State Of Charge (SOC) of the battery has rose from 50% to 51% in 10 secs.

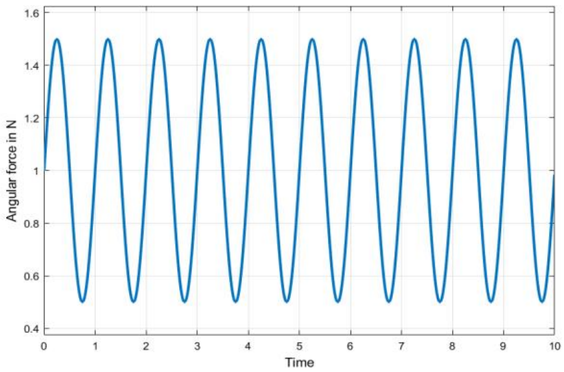

Figure 7: Input at the electromechanical movement-based piston

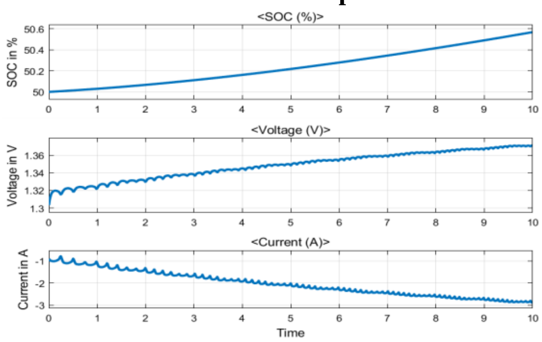

Figure 8: Output at the electromechanical movement generator side battery

The input of the electromechanical movement-based generator is given in fig.8. It looks like a sinusoidal wave. Then the output created at the battery side is shown with state of charge (SOC), voltage and current. Here SOC increases from 50% to approximately 50.6%. The voltage across the battery is more than the nominal value. And the current in negative shows the battery is getting the charge. Then the movement is like a 90degree movement of the leg. So, the waveform is consisting of the ripple. Then the piston stoke time delay also responsible for the ripples. The entire simulation is run for 10 secs and significant charging is done on the small battery cells. The table-I shows the results obtained for every second in both the energy harvesting devices.

Table -I Simulation results obtained

Time In Secs.	Voltage in V		SOC in %	
	Piezo (mean value)	Electro -mech -anical	Pi -ezo	Electro -mech -anical
1	1.38	1.328	50.1	50.1
2	1.39	1.331	50.21	50.15
3	1.38	1.341	50.29	50.18
4	1.38	1.347	50.35	50.2
5	1.38	1.352	50.4	50.25
6	1.38	1.358	50.5	50.3
7	1.38	1.362	50.6	50.34
8	1.38	1.367	50.7	50.41
9	1.38	1.369	50.8	50.45
10	1.38	1.37	50.9	50.55

Table -II Simulation results obtained

Time In secs	Current in A	
	Piezo (mean value)	DC Gen -erator
1	3.2	1.3
2	3.21	1.4
3	3.22	1.6
4	3.2	2
5	3.2	2.2
6	3.2	2.5
7	3.2	2.8
8	3.2	2.9
9	3.2	2.99
10	3.2	3

The observed results of the composite model comprising of the piezo and the electromechanical model clearly indicate that the possibility of the efficient energy harvesting is possible if the frequency of input that is defined in the paper is utilized. The real time use can be tested further to realize the simulation output when applied on situation.

V. CONCLUSION

A mathematical modeling approach of the composite energy harvesting model is developed and found to be working satisfactorily. The piezoelectric device and knee movement to piston acts as an efficient energy conversion device. 1.2V batteries are charged using both the knee movement and walking pressure applied on the piezoelectric crystal.

The MATLAB Implementation thus developed reckons a real time implementation using better piezo electric generators and efficient electromechanical energy harvesters. The future work on this research is that the optimized charging of the battery and indicating system which supplies a continuous supply to the battery.

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