An Integrated Approach to Energy Harvester Modeling and Performance Optimization

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ABSTRACT

This paper proposes an integrated approach to energy harvester (EH) modeling and performance optimization where the complete mixed physical-domain EH (micro generator, voltage booster, storage element and load) can be modeled and optimized. We show that electrical equivalent models of the micro generator are inadequate for accurate prediction of the voltage booster's performance. Through the use of hardware description language (HDL) we demonstrate that modeling the micro generator with analytical equations in the mechanical and magnetic domains provide an accurate model which has been validated in practice. Another key feature of the integrated approach is that it facilitates the incorporation of performance enhanced optimization, which as will be demonstrated is necessary due to the mechanical-electrical interactions of an EH. A case study of a state-of-the-art vibration-based electromagnetic EH has been presented. We show that performance optimization can increase the energy harvesting rate by about 40%.

1. INTRODUCTION

Energy harvesting is the process by which ambient energy from the environment is captured and stored [6]. Various devices have been reported to scavenge energy from different sources, such as light [10], heat [5], RF [7] and mechanical vibrations [11]. Significant research interest has been attracted to the development of energy harvesters because it addresses the energy issue of the recent growth in mobile electronics and several emerging applications including wireless sensor networks [9]. Most mobile devices and wireless sensor nodes are currently powered by batteries, which need charging or replacement after a period of time. Clearly, there will be measurable benefits in terms of cost if these devices could be self-powered in part by energy harvesters. In addition some applications with limited accessibility such as biomedical implants and structure embedded micro sensors will also benefit from energy harvesting. Among all the available sources, kinetic based EH seems to be the most popular since mechanical vibrations are widely present [2]. There are three main transduction mechanisms in vibration-based energy harvesting: electromagnetic, piezoelectric and electrostatic, each of which has various implementations [2]. Because ambient vibrations in the environment are usually of small amplitudes, the generated voltage from a micro generator may not be able to power an electronic device directly. In most cases, external circuits are necessary to boost the voltage and store the energy into a battery or a super capacitor. Thus an EH normally has three main components: the micro generator which converts ambient environment energy into electrical energy, the voltage booster which pumps up and regulates the generated voltage, and the storage element (Figure 1).

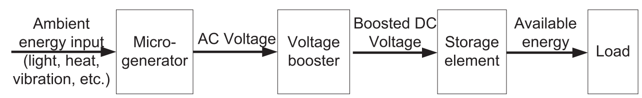

Figure 1: Block diagram of an EH.

Such an EH consists of components from several physical domains, including mechanical, magnetic and electrical, as well as external circuits which regulate and store the generated energy. Therefore performance optimization should be based on a model that describes the EH as an integrated system. However, the thrust of the research efforts in EH at present has focused on efficient design of either the micro generators [13] or the circuit boosters [1] separately. There has been little reported research on systematic modeling and optimization of EH so the aim of this paper is to propose such an approach. Some reported circuit designs treat the micro-generator as an ideal voltage source [14] but we show that modeling the micro generators using ideal voltage source correlates poorly with practice. Other reported designs use a simple linear equivalent circuit model [1] but we also show that simulation results from such a model are not accurate. Based on this motivation, we developed a mixed physical-domain behavioral model. Mixed-technology HDL modeling itself is not new, but what is new here is that HDL provides accurate modeling technique for EH. Also, enhanced performance of EH is achieved through the use of HDL-based optimization. Several HDLs that support multiple domain system modeling and simulation are available, such as VHDL-AMS, Verilog-AMS and SystemC-A. In this paper VHDL-AMS [3] has been chosen as the modeling language.

2. EH MODELING APPROACHES

Existing modeling approaches tend to replace the micro generator of an EH with either an ideal voltage source (Figure 2 (a)) or an equivalent circuit model (Figure 2 (b)) when designing the voltage booster. However, as will be shown in this paper, neither of these approaches is suitable for accurate voltage booster design.

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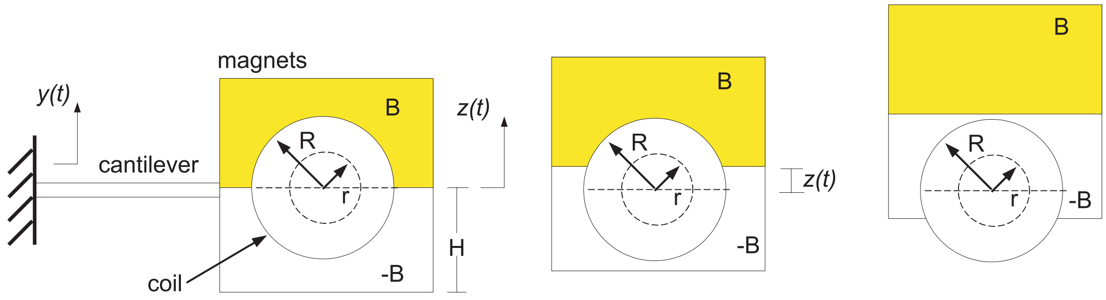
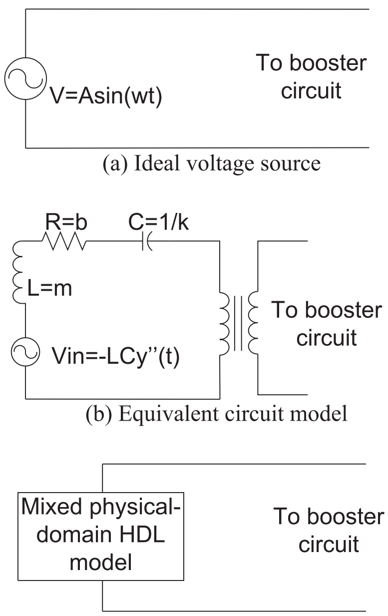


(a) Initial position $z(t)$=0
(b) Small displacement $|z(t)|<r$
(c) Large displacement $H-r<|z(t)|<H$

Figure 3: Relative displacement between the coil and magnets in the micro generator.



(a) Ideal voltage source
(b) Equivalent circuit model
(c) Proposed HDL model

Figure 2: Micro generator models.

The proposed approach in this paper uses VHDL-AMS to describe the micro generator as a series of analytical equations (Figure 2 (c)), which includes mechanical, magnetic and electrical behaviors of the micro generator. Through the presented case studies, comparisons have been made between different modeling approaches and we show that our HDL-based model is much more accurate than the circuit models.

The case study presented in this paper uses a vibration-based electromagnetic micro generator [12] as an example. The design is based on a cantilever structure. The coil is fixed to the base and four magnets, which are located on both sides of the coil, form the proof mass (Figure 3 (a)). This structure can be modeled as a second-order spring-damping system, which has been widely used [2], and whose dynamics is:

$$m\ddot{z(t)} + c_p\dot{z(t)} + k_s z(t) + F_{em} = -m\ddot{y(t)} \quad (1)$$

where m is the proof mass, $z(t)$ is the relative displacement between the mass and the base, c_p is the parasitic damping factor, k_s is the spring stiffness, $y(t)$ is the displacement of the base and F_{em} is the electromagnetic force.

The electromagnetic voltage generated in the coil is given:

$$v_{em} = \Phi(z) * \dot{z(t)} \quad (2)$$

where $\Phi(z)$ is the magnetic flux through the coil.

Although our HDL model is based on analytical equations, it can capture practical size and shape of the actual device. The coil in the actual micro generator consists of N turns and has an inner diameter r and outer diameter R. Each of the four opposite magnets are of height H (Figure 3 (a)). So the actual magnetic flux through the coil is a piecewise non-linear function of the relative displacement $z(t)$: $\Phi = f\{z(t)\}$.

When the relative displacement is small $|z(t)| < r$ (Figure 3 (b)):

$$\Phi = (\sqrt{R^2 - z^2(t)} + \sqrt{r^2 - z^2(t)}) * 2 * B * N \quad (3)$$

When the relative displacement is large $H - r < |z(t)| < H$ (Figure 3 (c)):

$$\Phi = -(\sqrt{R^2 - (H - |z(t)|)^2} + \sqrt{r^2 - (H - |z(t)|)^2}) * B * N \quad (4)$$

There are 5 other sections of the piecewise function which have been implemented in the VHDL-AMS model but are omitted here due to space limitation.

The output voltage is defined by:

$$v(t) = v_{em} - R_c * i(t) - L_c * \dot{i(t)} \quad (5)$$

where R_c and L_c are the resistance and inductance of the coil respectively and $i(t)$ is the current through the coil.

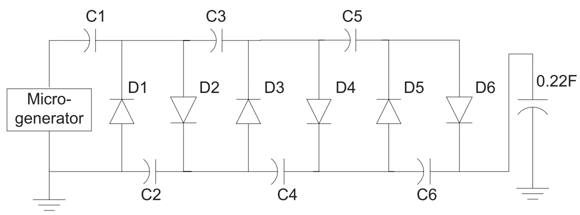
Finally, the electromagnetic force is calculated as:

$$F_{em} = \Phi(z) * i(t) \quad (6)$$

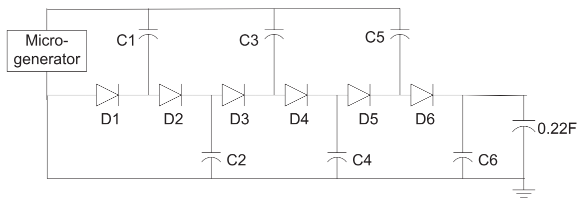
3. SIMULATION AND COMPARISON

In this section we will compare the performance of the micro generator models shown in Figure 2 when used in an

EH (Figure 1). There are two types of voltage multiplier (VM) often used as voltage booster, Villard (Figure 4(a)) and Dickson (Figure 4(b)) [14].



(a) Villard VM.



(b) Dickson VM.

Figure 4: Voltage multiplier configurations.

All the comparisons presented below are based on the charging of a 0.22F super capacitor. Figure 5 shows the VM charging waveforms when the micro generator is modeled as an ideal voltage source. The input frequency is 50Hz and the amplitude is 640mV. Both voltage multipliers have 6 stages. Simulation results show that the Villard multiplier can charge the super capacitor to 2V in 11 minutes and 14 seconds and the Dickson type can reach that voltage in only 3 minutes and 9 seconds (Figure 5).

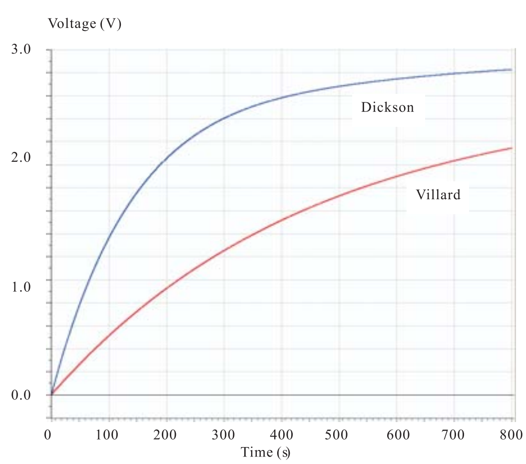


Figure 5: Simulation of VMs with ideal voltage source.

To verify the accuracy of the modeling approach, in which micro generator is replaced by an ideal voltage source, we have carried out experimental measurements on the actual EH device. Figure 6 shows part of the setup, where the micro-generator is sitting on a vibration generator. Figure 7 shows the charging waveforms measured experimentally. Because in practical measurements the capacitors all had a bit of initial charge, adjustment on the timing has been made so that both the curves start at the same voltage (about 0.6V).

Figure 6: Experimental measurement setup.

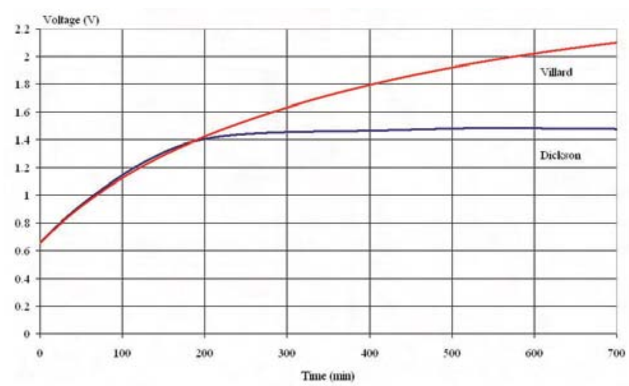


Figure 7: Experimental measurements of EH.

As can be seen from Figure 5 and 7, the circuit simulation results correlate very poorly with the practical measurements. The EH with Villard voltage multiplier takes more than 10 hours to charge up the super capacitor to 2V while the Dickson configuration, which shows better performance in the circuit simulation, has even not reached the required value.

Figure 8 shows the voltage booster performance of EH when the micro generator is based on the proposed HDL model. As can be seen, there is close correlation between the experimental measurements and that of the proposed model.

The reason why HDL-based models correlate well with practice is that the HDL model can incorporate the actual shape and size of various components into the micro generator model by using analytical equations. For example, the nonlinear dependence of the micro generator's output voltage on the input displacement described in Section 2 can be accurately captured by our HDL model.

Equivalent circuit model (Figure 2 (b)) of the micro generator links mechanical mass(m), spring(k) and damper(b) to electrical inductor(L), capacitor(C) and resistor(R) by [1]:

$$L = m, \quad C = 1/k, \quad R = b \tag{7}$$

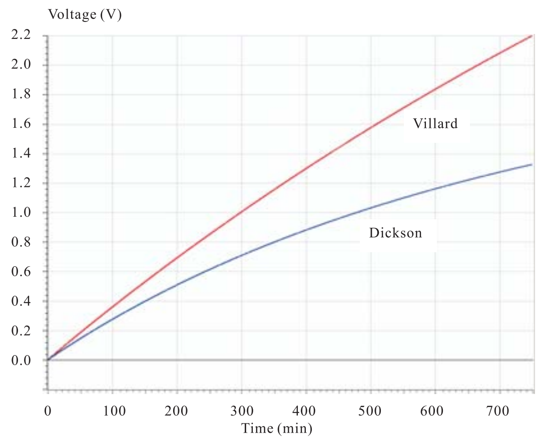


Figure 8: Simulation of EH using proposed HDL model.

But this approach faces difficulties when applied to the modeling of an actual EH since it can only accommodate a few basic parameters of the micro generator. Simulation results of the equivalent circuit model and HDL model are shown in Figure 9. As can be seen from the waveforms, when excited by a sine wave stimulus, the equivalent circuit model still generates sine wave output. But the HDL model can capture the situations when the coil and magnets are moving apart, which leads to non-sine wave output. Obviously the latter one is more accurate and close to practical scenario.

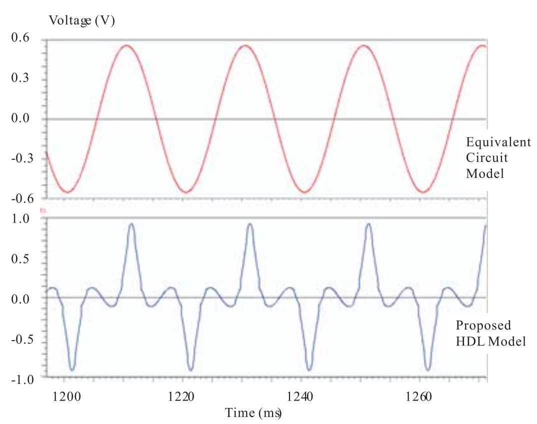


Figure 9: Output from micro generator.

4. EH PERFORMANCE OPTIMIZATION

Simulation and experimental results in Section 3 both indicate that the voltage booster can greatly affect the output from the micro generator. Due to this close mechanical-electrical interaction, performance optimization should be based on an integrated model. The object function in the performance optimization was the charging rate of the super capacitor. Firstly, to maximize the charging rate we have modified the voltage booster architecture. Instead of using voltage multipliers described in Section 3, we have investigated whether a voltage transformer (VT) and a rectifier could offer a superior performance. Secondly, we have optimized the voltage booster's parameters using the genetic algorithm outlined in Section 4.1.

Two types of rectifier configuration have been tested. Simulation results show that comparing to a common full-bridge rectifier, the configuration in Figure 10 gives better performance since it uses less diodes and thus loses less energy. The number of turns and the resistance value of primary $(N1, R1)$ and secondary winding $(N2, R2)$ are the four main parameters that determine the voltage transformer's performance. Figure 11 shows that an un-optimized VT working with the micro generator can charge the super capacitor to 2V in 8 hours, which is already better than the VMs. The value of parameters are listed in Table 1. Through the incorporation of performance optimization into the proposed approach, the EH model could be further improved. Here we use VHDL-AMS testbench to implement a genetic algorithm (GA) [8] to optimize the EH with voltage transformer. Other optimization methodologies may also be applied based on the integrated model.

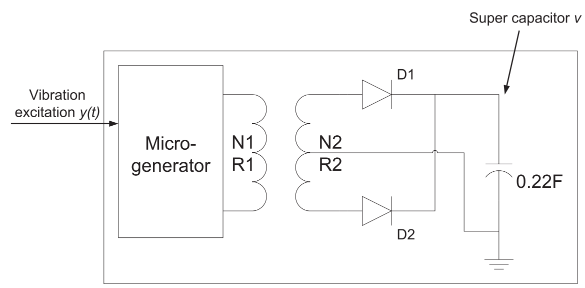


Figure 10: Voltage transformer configuration.

	Resistance(Ω)	Number of turns
Primary winding	400	2,000
Secondary winding	1,000	5,000

Table 1: Parameters of un-optimized VT.

4.1 Parallel GA in VHDL-AMS testbench

The aim of GA optimization is to maximize the charging rate of the super capacitor. In the VHDL-AMS implementation, the chromosome is modeled as a component with 4 genes as input parameters $(N1, R1, N2, R2)$, the base vibration $y(t)$ as the excitation and the charging speed of the super capacitor $v'dot$ as the output fitness (Figure 10).

Unlike most existing computer implementations of GA that evaluate one chromosome iteratively to form a population, in the VHDL-AMS based optimization here, the chromosomes of a population are implemented in parallel. The genes are initialized by uniformly distributed random numbers. The same stimulus is applied to the population and all the chromosomes are evaluated simultaneously to get a vector of fitness values. The tournament selection is chosen as the parent selection method, because it prevents premature convergence with efficient computations [8]. The selection method uses fitness values in which parents with higher fitness (i.e. higher $v'dot$) are more likely to be selected to produce offspring. Elitism is also used to improve GA's efficiency by artificially inserting the best solution into each new generation. Since the genes are real numbers, arithmetic crossover is used to generate the offspring [4]. Finally, gene mutation is employed to introduce new solutions into the new population. The evaluation-selection-crossover-mutation process is repeated until all the chromosomes converge to the same fitness. In VHDL-AMS, this loop is controlled by a finite state machine.

4.2 Optimization results

In the genetic optimization, the population size is 100 chromosomes. The crossover and mutation rate are 0.8 and 0.02 respectively. The chromosome's fitness is updated every 50ms. After simulating the testbench for 30 seconds, which corresponds to 600 generations in the GA optimization, the gene values converge to an optimum. The values of the genes are listed in Table 2.

	Resistance(Ω)	Number of turns
Primary winding	140	1,500
Secondary winding	16,000	6,800

Table 2: Parameters of optimized VT.

Simulation waveform of the GA-optimized EH model is shown in Figure 11. For comparison, the un-optimized VT and two VM boosters are also presented.

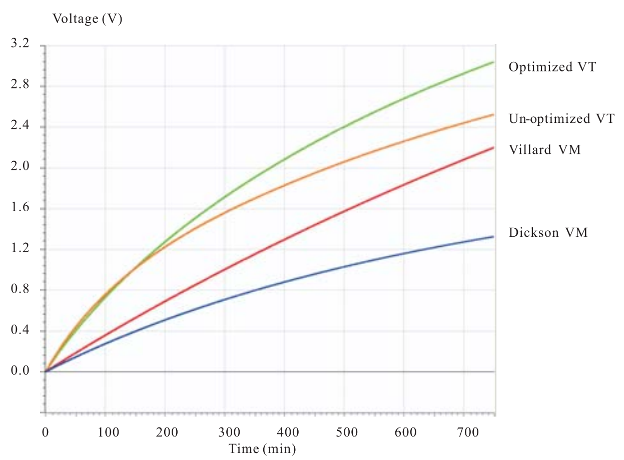


Figure 11: Simulation waveforms of super capacitor charging by different EH models.

As can be seen from the simulation results, the optimized EH can charge up the 0.22F super capacitor to 2V in 6 hours, which is 25% improvement to the un-optimized transformer and 40% improvement comparing to the Villard voltage multiplier.

5. CONCLUSION

It is likely that energy harvesters will have a key role to play in providing the energy needed to power up the electronics present in several emerging applications. To maximize the performance of the energy harvesters, we believe that various parts of the energy harvesters (mechanical and electrical) need to be optimized in a holistic and integrated approach. This paper presented such an approach to the modeling and optimization of energy harvesters through the employment of mixed-technology hardware description languages. We have shown that the existing modeling approaches to EH are inadequate and we have demonstrated the effectiveness of the proposed approach through the case study of an electromagnetic EH. To further maximize the EH performance, the proposed approach develops a genetic optimization that has been wholly implemented in the HDL testbench to optimize the performance of an integrated EH model. It has been shown that transformer based voltage booster has superior performance to that of voltage multipliers and through optimization it is possible to achieve 40% improvement.

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