AC 2007-2254: ENERGY SCAVENGING FOR WIRELESS SENSOR NODES WITH A FOCUS ON ROTATION TO ELECTRICITY CONVERSION

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Introduction

Today, sustaining the power requirement for autonomous wireless sensor network is an important issue. In the past, energy storage has improved significantly. However, this progress has not been able to keep up with the development of microprocessors, memory storage, and sensor applications. In wireless sensor networks, battery-powered sensors and modules that are expected to last for a long period of time, since conducting battery maintenance for a large-scale network consisting of hundreds or even thousands of sensor nodes may be difficult, if not impossible. Ambient power sources, as replacement of batteries, come into consideration, to minimize the maintenance. Power scavenging may enable wireless sensor nodes to be completely self-sustaining so that battery maintenance can be eventually freed.

Researchers have performed wide spread studies, in alternative energy sources that could providing small amount of electricity to low-power devices. Energy harvesting can be obtained from different energy sources, such as vibration, light, acoustic, airflow, heat, temperature variations. Table 1 below illustrates the comparisons of various energy scavenging sources derived from various number of research efforts. One of the physical phenomena that are being employed to satisfy the requirements for the generation of small amounts of electricity is the mechanical rotation.

This paper introduces an energy scavenging technique for low power wireless sensor nodes with a focus on conversion of mechanical rotation energy to electricity. Here we consider a hydraulic door closer as a potential energy resource where the door is moved by human power in daily life. The two phases of door hydraulic system operations are: the first phase is the opening phase that is generally activated by human power; the second one is the closing phase that is controlled by a spring and a hydraulic damping mechanism. The mechanical energy can be converted to electrical energy using appropriate device and provide energy to low power sensor nodes.

Table 1: Comparison of Energy Harvesting and Energy Storage Methods

Energy Source	**Power Density & Performance**	**Source of Information**
Acoustic Noise	0.003 $\mu W/cm^3$ @ 75Db 0.96 $\mu W/cm^3$ @ 100Db	M. Rabaey, et al.,2000[1]
Temperature Variation	10 $\mu W/cm^3$	Roundy et al. 2004[2]
Temperature Gradient	15 degree @ 10 C gradient	Stordeur and Stark 1997[3]
Ambient Radio Frequency	1 $\mu W/cm^2$	E.M. Yeatman, 2004[4]
Ambient Light	100 mW/cm^2 (direct sun) 100 $\mu W/cm^2$ (illuminated office)	Available
Thermoelectric	60 $\mu W/cm^2$	J. Stevens, 1999[5]
Vibration (using micro generator)	4 $\mu W/cm^3$ (human motion—Hz) 800 $\mu W/cm^3$ (machines—kHz)	P.D. Mitcheson et al., 2004[6]
Vibrations (Piezoelectric)	200 $\mu W/cm^3$	Roundy et all 2002[7]
Airflow	1 $\mu W/cm^2$	A.S. Holmes et al., 2004[8]

Push buttons	50 μJ/N	J. Paradiso & M. Feldmeier,2001[9]
Shoe Inserts	330 μW/cm^2	Stamer 1996 Shenck & Paradise 2001[10]
Hand generators	30 W/kg	T. Starner & J.A. Paradiso, 2004[11]
Heel strike	7 W/cm^2	O. Yaglioglu, 2002, N.S. Shenck & J.A. Paradiso, 2001[12-14]

System Design

The main objective of this study is to design an energy harvesting system for wireless sensor nodes. The low power wireless device will have ability to harvest energy from a hydraulic door closer. The block diagram of the system is shown in figure 1. When the door is pushed or pulled, the hydraulic door closer starts moving and continues until the door is completely closed. The hydraulic door closer has rotating parts that can provide a potential mechanical energy source. This energy source is converted appropriately to electrical energy to provide power to a low-power wireless sensor.

In the first phase of the project, an appropriate gear set is designed to increase the speed of the rotation so that it is able to provide enough rotation speed for the generator. Then a power circuit has been designed to implement and manage energy conversion. This circuit will regulate the voltage for a wireless sensor node. Before implementation of the experiment, necessary computer simulations were conducted. If the sensor node functions appropriately with the energy converter, then a wireless camera will be placed on the wall or ceiling to surveillance movements around the door and entrance. This camera will be activated only when it receives control signals from the sensor node. For example, activation time of the camera can be programmed for a specific period of time.

In the following sections, the gear set and gear box design are explained firstly. Then, the electrical circuit design, including the generator unit, a bridge rectifier and alternator circuit, a boost converter, and a battery charging control circuit is explained. In the last section, a wireless sensor node design is explained.

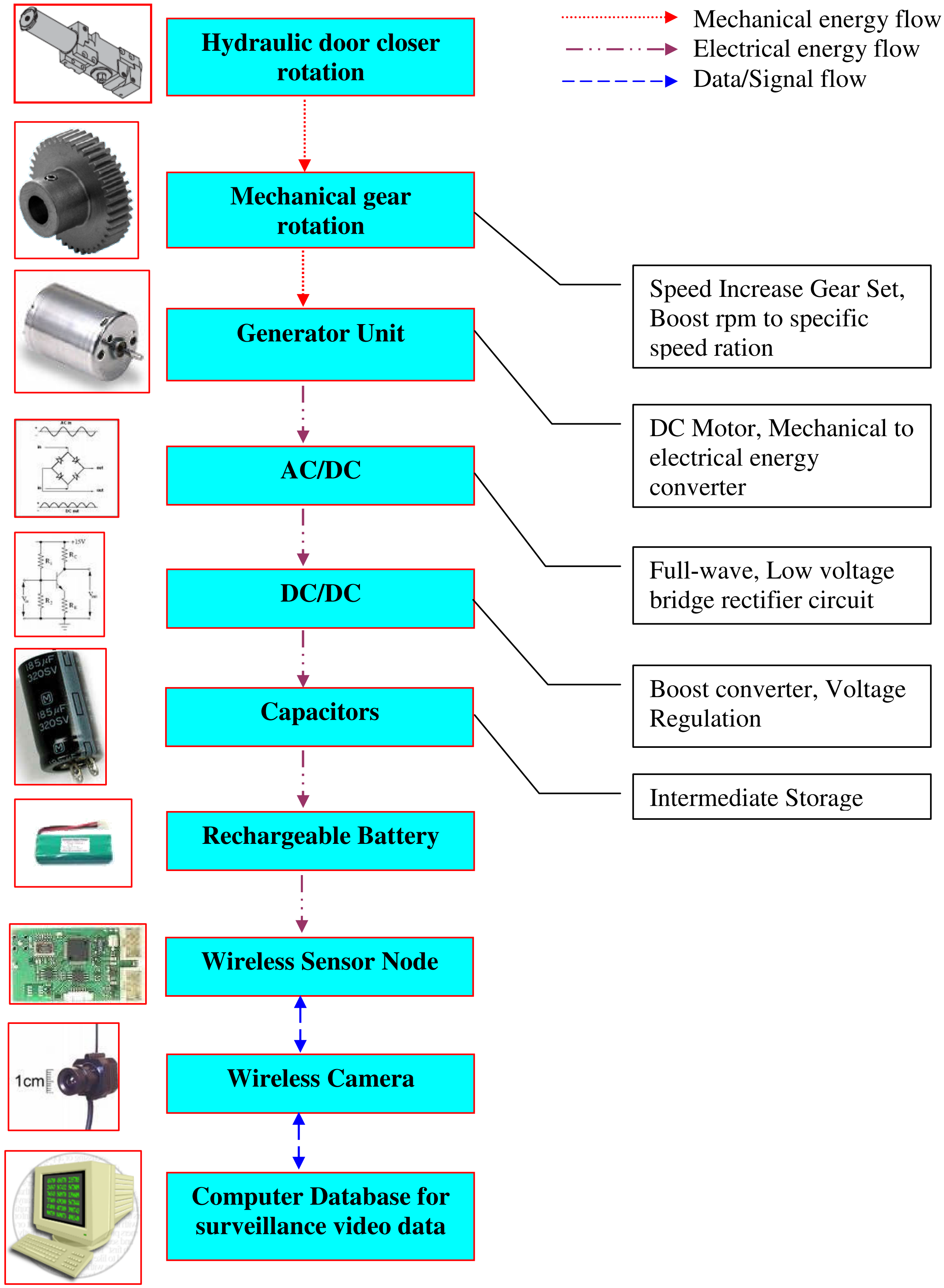

Figure 1: Overall Energy Harvesting Model

Gear Set Design

The aim of the gear set is to increase the speed of rotation generated from the hydraulic door closer to provide sufficient speed to a DC motor. The motor serves as a generator unit. This step up in speed is required because without the increase of speed, the rotation rate from door hydraulic closer will not be sufficient for generator. There are different types of gear sets which are mounted to where the door hydraulic rotation occurs. Gear ratios and the number of gear sets are determined by considering the average rotating speed of the door and the rotation required by the generator. The gear set has been designed to increase speed to provide enough rotation to turn on electricity generation.

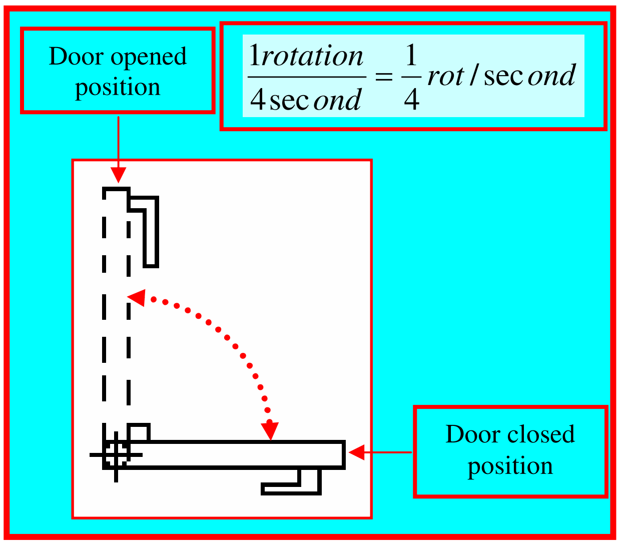

Figure 2: Door Mechanism

As represented in figure 2 above, assuming that the door is fully opened when the rotation is one fourth of the full rotation and the time it takes is one second; the rotation speed of the door can be calculated as follows:

$$Door\ Speed = \frac{1}{4}\left[\frac{rot}{\sec}\right] * \frac{60\sec}{1\min} = \frac{60}{4}\left[\frac{rot}{\min}\right] = 15rpm$$

Gear ratios for four gear level are selected as1/4. Hence the overall speed ratio of the gear box can be calculated as:

$$\rho_{all} = \prod_{i=1}^{n} \rho_i$$

where,

ρ_{all} = Overall speed ratio
ρ_i = Speed ratio for i^{th} layer (layer means speed of each shaft between gear sets)
n = Number of layers for speed ratio (there are total 4 shafts placed for gear sets)

If n = 4, then $\rho_{all} = \rho_1.\rho_2.\rho_3.\rho_4 = \frac{1}{4} * \frac{1}{4} * \frac{1}{4} * \frac{1}{4} = \frac{1}{256} rpm$.

Hence, the overall speed ratio= $\frac{input\ speed}{output\ speed} = \frac{1}{256}$ rpm (rotation per minute)

As we assumed above that the door opening speed is 15 rpm (this value can be changed according to intensity of door opening and closing), which is initial input to the gear box. So the resulting rotation speeds at each pair of gear sets can be found consequently as 60, 240, 960 and 3840 rpm maximum. Figure 3 shows the ratio between the initial speed and maximum speed of the gear set. The ratio can be changed simply by changing the place of the gears.

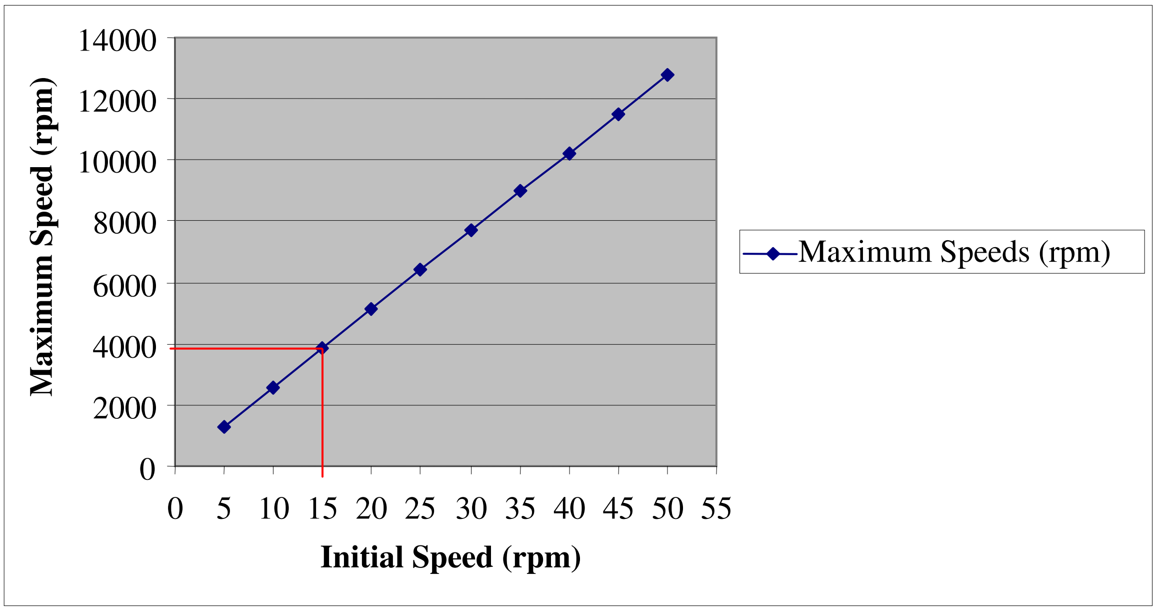

Figure 3: Gear rotation and speed analyses graph

The gear ratio simulation test was conducted using the MSC.Easy5 ® analysis interface[15]. The test indicates that the speed of the gear set reaches at its expected performance. The gear set design is illustrated in figure 4. The first shaft is tied between hydraulic door closer and gear set. The first shaft has only one gear which is connected to other gears. Second, third and fourth gear couples consist of two different diameters, interchangeable gears. The fifth gear couple includes a smallest diameter gear with the maximum rotation, which is fixed to the generator's shaft. The result of gear speed simulation is given in figure 5. This analysis is based on initial rotation of 15 rpm from the hydraulic door closer. The speeds of the rotations occurred on the shafts are designated as RPM_Shaft1, RPM_Shaft2, RPM_Shaft3, RPM_Shaft4, and RPM_Shaft5. With the 1:256 gear ratios, the last shaft RPM_Shaft5 has the highest speed 3840 rpm, as shown in the figure.

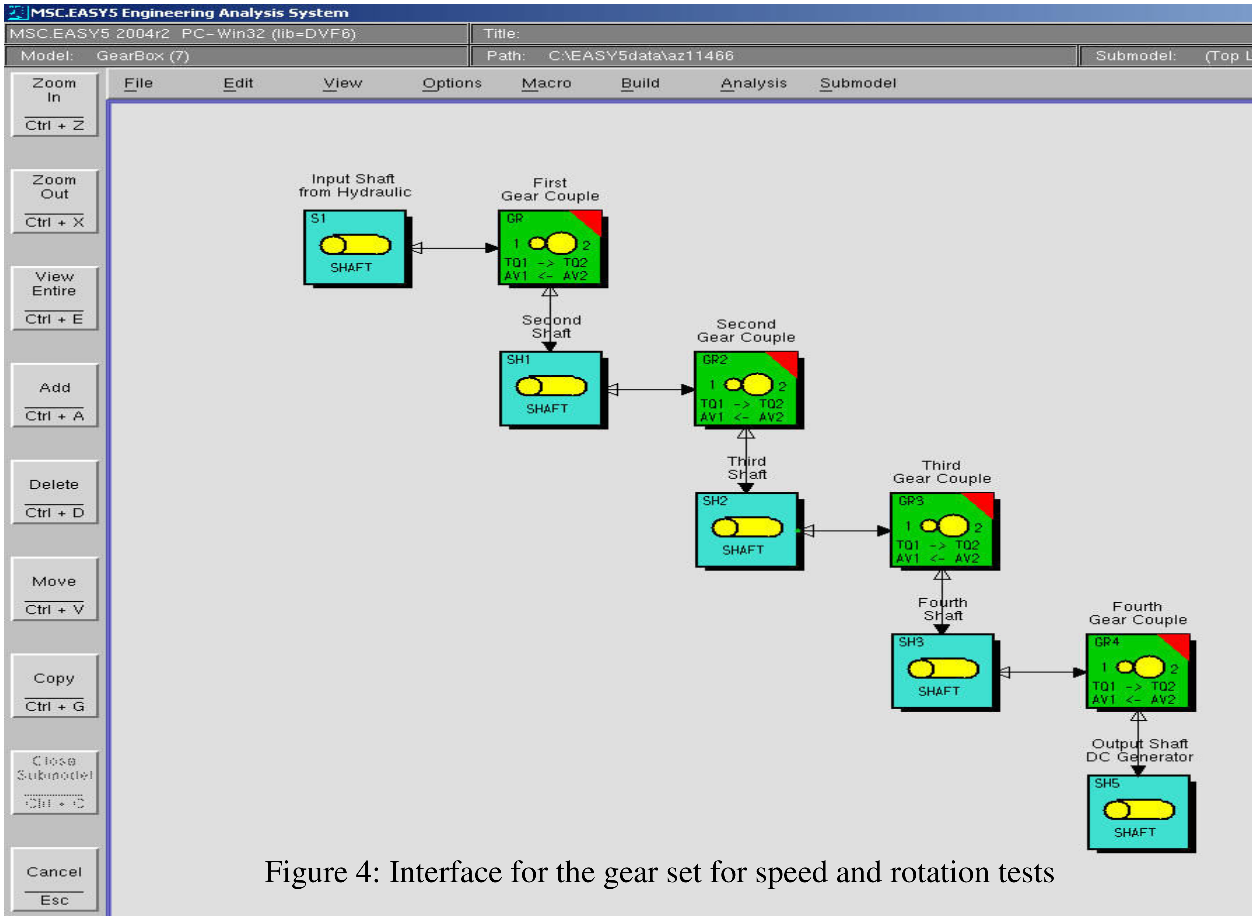

Figure 4: Interface for the gear set for speed and rotation tests

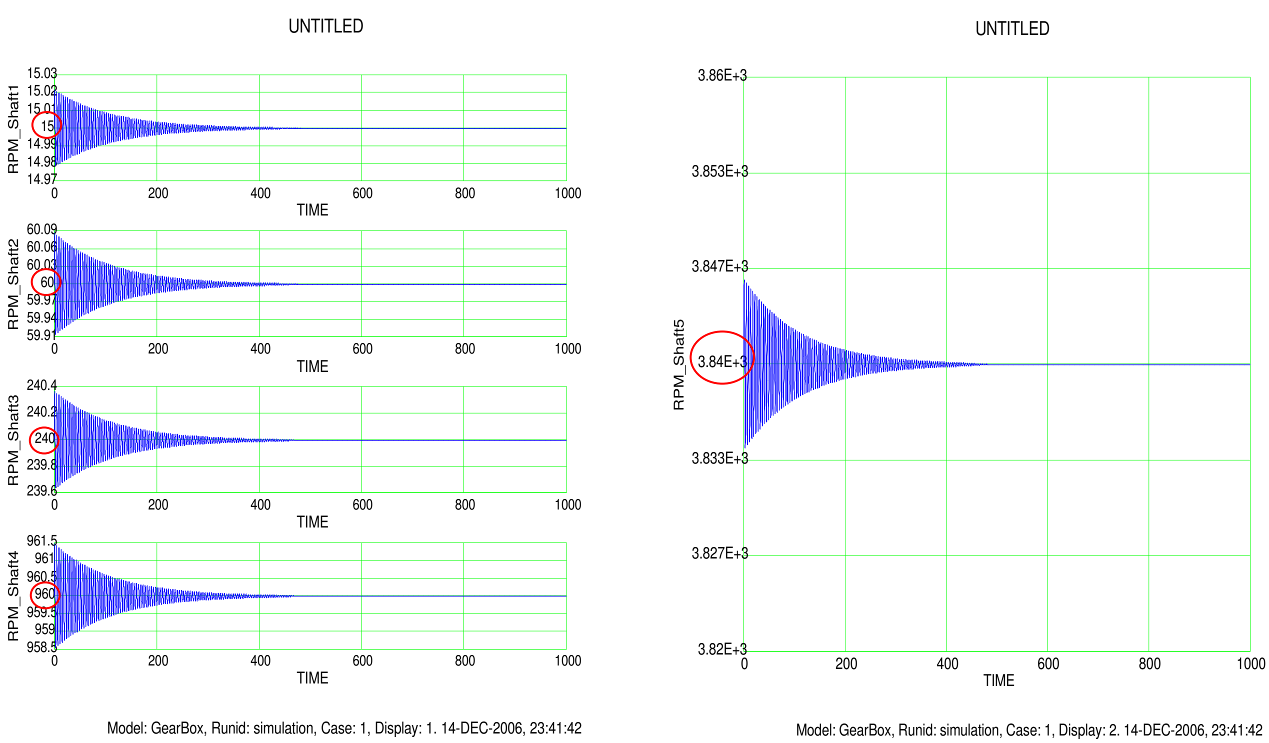

Figure 5: MSC.Easy 5 gear rotation and speed analyses screen shot for initially 15rpm

Generator and Circuit Design

In this section, we will explain the DC motor as a generator unit, electrical circuit, and the wireless sensor node. Three main issues need to be considered, the generator output power, the voltage regulation circuit, and the rechargeable battery type. Their design should be considered altogether to increase the system efficiency and reduce power losses. The generator unit and components of the electrical circuit are explained below with circuit simulation.

The electric motor is based on the fact that any wire that cuts a magnetic field and has a relative motion will generate an electric potential. Electric motors include rotating coils of wire that are driven by the magnetic force exerted by a magnetic field on an electric current[16]. They transform electrical energy into mechanical energy. So basically, any permanent magnet direct current (PMDC) motor back driven will make a generator. This procedure can denote its efficiency and the voltage generated[17]. The general view of mechanical to electrical energy conversion is shown in figure 6. The faster the generator turns, the higher the output voltage. In similar cases, the old generators would not generate enough voltage when idling. They were geared by size of pulleys, to generate enough voltage to charge at a reasonable speed when powering a device[18]. The DC motor we used requires at least 2700 rpm input to generate electricity according to its optimal specifications[19].

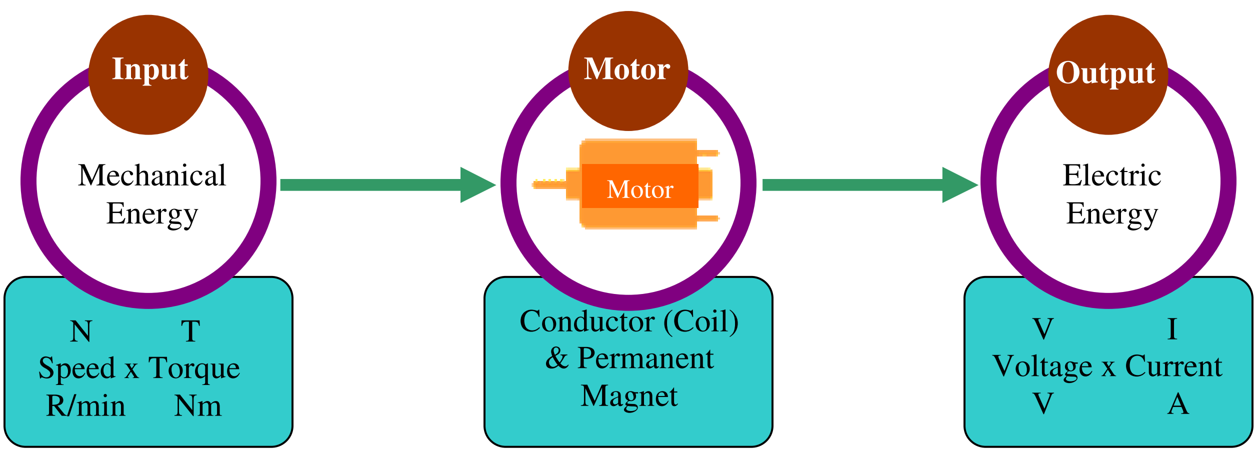

Figure 6: A motor can be a generator that converts mechanical energy into electrical energy

The circuit board is designed and simulated using SwitcherCAD™ III high performance spice III simulator from linear technology[20]. This program has a big library for the components useful for our needs. The schematic capture and waveform viewer is part of this software and very fast. These enhancements and models are useful for easing the simulation of switching regulators. The circuit design for our system purpose is detailed below in figure 7 drawn using SwitcherCAD™ III.

The circuit board is comprised of a full wave bridge rectifier circuit and this circuit has connection with alternator unit. After full-wave rectification occurs, the voltage is increased by DC to DC boost converter. A capacitor (C_{in}) is placed between rectifier circuit and DC to DC boost converter circuit to measure voltage and current after rectification. This capacitor functions as intermediate storage unit as well.

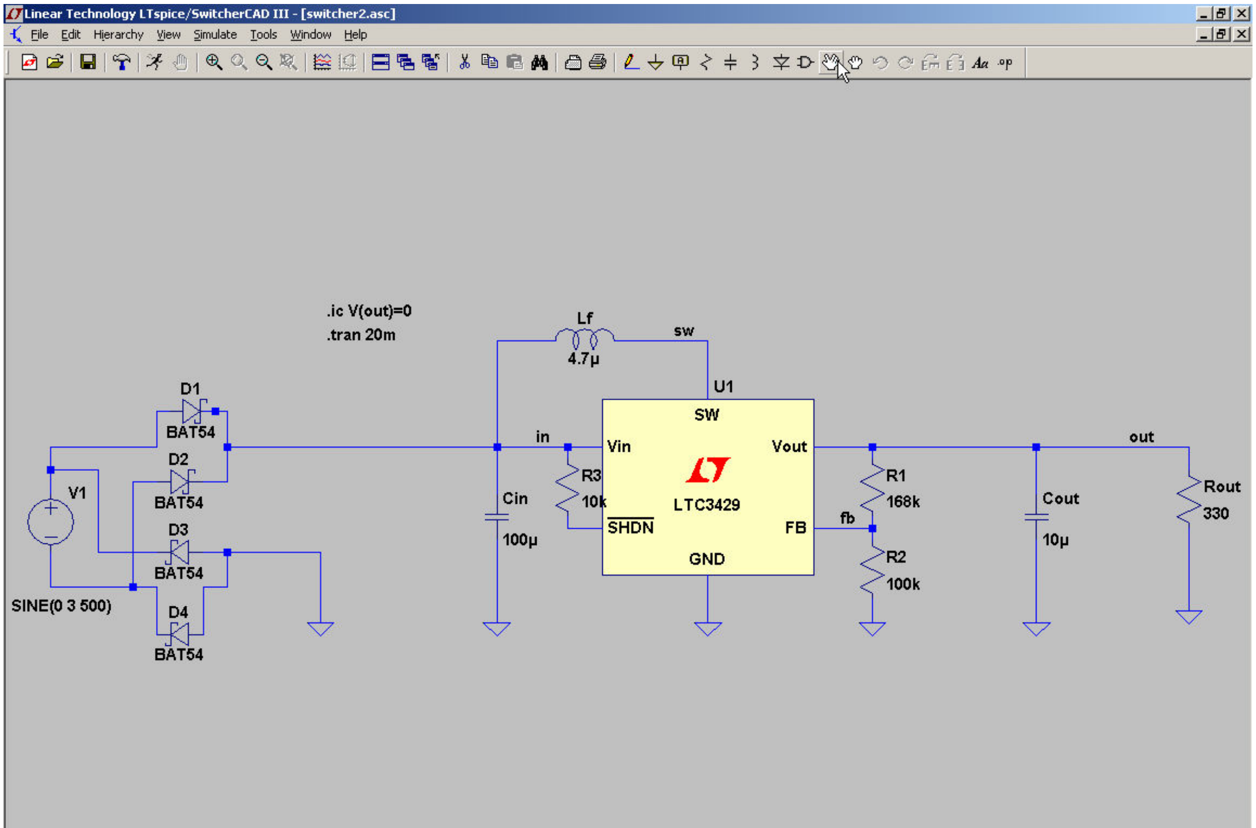

Figure 7: Voltage boost and regulation circuit

The boost converter circuit is increasing the voltage and current which is needed to charge rechargeable battery. As a storage device another capacitor is (C_{out}) placed to measure obtained power after boost converter circuit. The components are used for the circuit are considered with high priority because of the non-continues input voltage. Since input voltage is not constant, the boost converter is chosen considering this important point. LTC3429 regulator circuit only needs 0.8V input voltage to start execute its components[21].

The input voltage level is important for the circuit in order to achieve its function for this experiment. When input voltage is adjusted, then the component values should be considered according to the input voltage. In this simulation interface, the values for the circuit members are indicated on simulation interface. The calculations were made according to the data sheets of the circuit elements. Since the DC motors in this experiment generate electricity up to 4.5 volts DC voltage source which is V1 was configured to vary from 0V to 3V. The frequency is required for the circuit trigger is defined as frequency: 500Hz. The input voltage can be adjusted according to the energy source specifications. For example, instead of 3V generator unit 5V generator unit can be used. SwitcherCAD™ III software provides to simulate each of the elements on the circuit. By this way, it is possible to confirm voltage or current level any where on the circuit during simulation. The simulation results, including, I_{V1} (input current and duty cycle at V1), I_{Rout} (output current for the load), V_{out} (voltage level after boost converter), are shown in figures 8, 9, and 10. Figure 8 shows input current from generator unit source before rectification. Figure 9 depicts output current for the load or rechargeable battery. Figure 10 illustrates the output voltage after boost converter which is around 3.4V. I_{Rout} (output current) and V_{out} (output voltage) are sufficient to recharge a small scale rechargeable battery according to the simulation results.

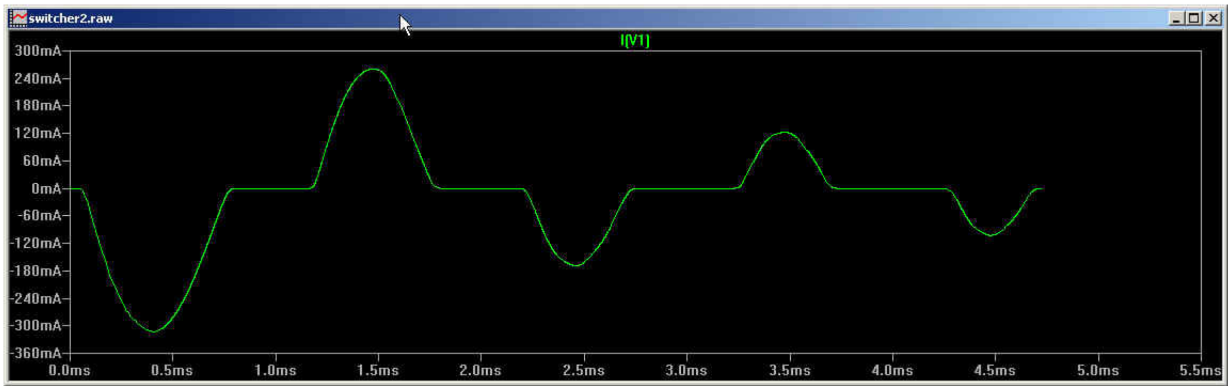

Figure 8: Input current I_{V1}

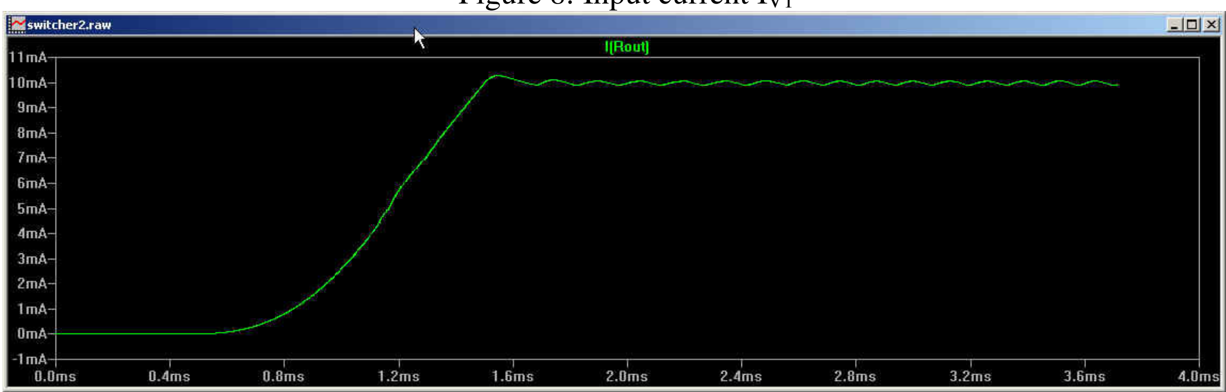

Figure 9: Output current I_{Rout}

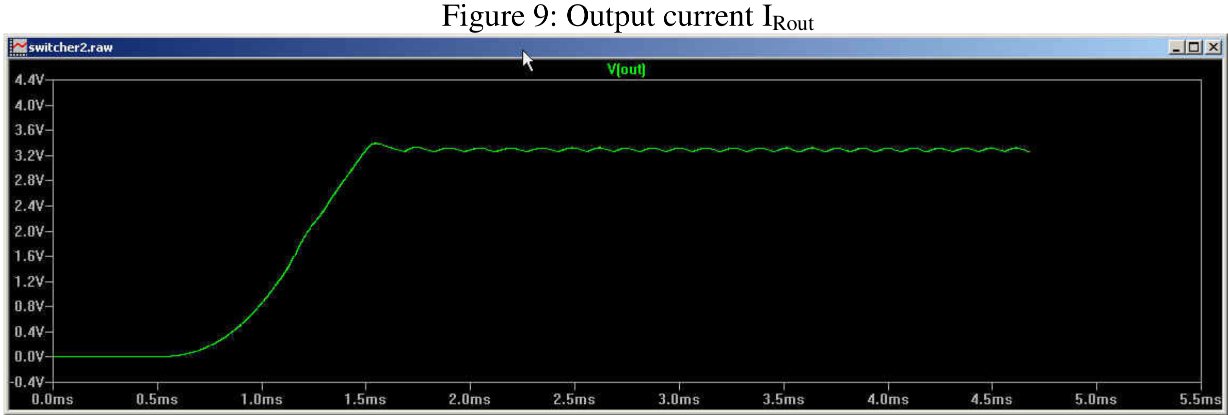

Figure 10: Output voltage V_{out}

The voltage output of the alternator unit is rectified by the bridge rectifier that includes Schottky diodes and capacitor. Schottky diodes require less energy to operate compared with other diodes. Schottky diodes need 0.4V forward voltage instead 0.7V to operate within a circuit[22]. The capacitors in the circuit mainly used to store energy until a specific voltage rate is reached, then discharges giving the energy to the rechargeable battery. Since our power source has no constant and stable energy, input and output capacitors operate as a temporary storage units.

The sensor node in this project is a simple signal transmitter to the wireless camera with only one-way transmission. The signal transmission is activated only in a specific time intervals to send a warning to the wireless camera that the door is opened. Obviously, one-way transmission does not require high calculation and energy if compared with two-way transmissions. The sensor node is only responsible to transmit control signals to the wireless camera because of our limited energy source. For test purposes, the sensor node is purchased and modified for conducting tests. Depends on the application requirements the design of wireless sensor node can be extended or changed later.

V. Experimental Results and Discussions

A picture of the experimental system is depicted in figure 11. The actual system is tested using the oscilloscope and multi meter measurement devices. Initially, the output of the gear set is measured in order to test if a maximum 1:400 ratio is occurred. The gear ratio can vary with a change in gear members. The ratio is crucial since DC motor input requires certain spins to generate electricity.

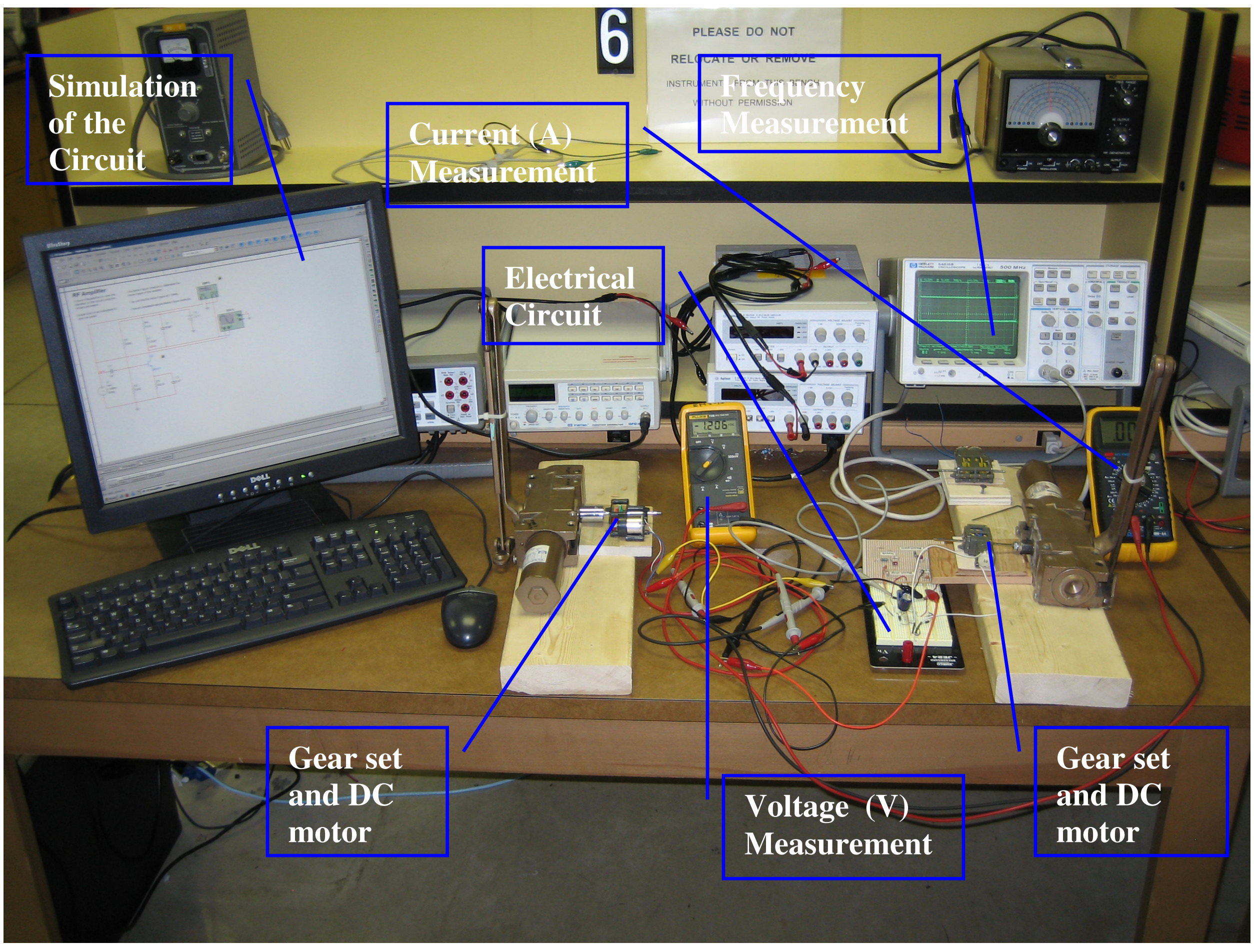

Figure 11: The picture of system in our electrical laboratory during tests

The PMDC motors selected for our experiments are: the FA-130 and RC-260 PMDC[23]. The experimental results are given in table 2. In this experiment, the hydraulic door closer handle is moved by hand without any stop for 90 degree. But in real life, the rotation can be stopped at any time due to the human interactions. The gear ratios were sufficient to generate at least 3 volts for generator unit. The results shown in table 2 are average values and can vary around small ranges (+/-0.4V) depending on the door opening/closing speed. But, this does not affect the system operations since we place capacitors as intermediate storage units. The overall system efficiency may be increased by modifying the elements of the circuit. There are variety of boost converters available in the market and will be tested with our design.

Table 2: Test results with different gear ratios and DC motors

Tested Gear Ratios	Number of door closer triggers	Torque of type DC Motor	Voltage after rectification (V_{in})	Output Current for the load (I_{Rout})	Output voltage for the load (V_{out})
1:64 rpm	9 times	RC- 260 (3-4.5V)	1.9 Volts	9mA	3.3 Volts
1:203 rpm	6 times	FA-130 (1.5-3V)	1.8 Volts	9mA	3.1 Volts
1:344 rpm	4 times	FA-130 (1.5-3V)	1.9 Volts	10mA	3.4 Volts
1:400 rpm	2 times	RC- 260 (3-4.5V)	2.1 Volts	10mA	3.3 Volts

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