# Rotational Energy Harvesting To Prolong Flight Duration of Quadcopters

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***Abstract*—This paper presents a rotational energy harvester using a brushless dc (BLdc) generator to harvest ambient energy for quadcopter in order to prolong it flight duration. For a quadcopter, its endurance is essential in order to achieve operational goals such as scientific research, security, surveillance, and reconnaissance. Because quadcopters have a limitation on size and mass, they cannot carry a large mass of on-board energy thereby having short flight time. In this paper, BLdc generators are coupled with the propellers of the quadcopter to transfer kinetic energy from the propellers to the generator. Taking into consideration the power requirement of quadcopter, the output of the generator is amplified using dc–dc boost, and is regulated to power and charge the on-board battery. The BLdc generator is simulated in MATLAB/Simulink. A final prototype of the rotational energy harvesting system is built, and this comprises a quadcopter, power management system, and a battery charging system.**

***Index Terms*—Energy harvesting, power electronics, quadcopter, rotational generator, unmanned aerial vehicle (UAV).**

## I. Introduction

ENERGY harvesting from moving structures has been a topic of much research, particularly for applications in electrically powered unmanned aerial vehicles (UAVs) like the quadcopter. In recent applications, it is very advantageous to scavenge energy from ambient sources, since most of these energy sources have energy in abundance.

Most researchers have looked into improving the endurance of electrically powered UAV's also known as drones using energy harvesting technologies such as photovoltaic harvesting and vibration harvesting [1], [2]. However, none of their works reported on a design to harvest energy directly from continuous rotation of the UAV. This is an important application for indoor use of drones, since energy harvesting using solar has been developed extensively and efficiently for outdoor application of drones where ambient luminance is in abundance but cannot operate efficiently indoors. Use of linear generators for energy harvesting has also been investigated [3].

The work by Toh in [4] uses microgenerators to harvest power from continuously rotating structures to realize a self-powered sensor on a rotating body. Here gravitational torque is used instead of inertia. The harvester is essentially a dc motor deployed as a generator, and it is powered directly from machine rotation, with a single point of attachment to the rotation source. Experimental values of the setup in [4] with an offset mass of 20 g produced output power levels of 1 W at a source rotation speed of 8000 r/min, under matched load conditions. The authors used brushed dc motors as generators, which has a lower power density as compared to brushless dc (BLdc) generators. Also a BLdc generator has a longer life span and does require very minimal maintenance.

Grady [5] reports of a lightweight, solar-powered drone dubbed, Zephyr's with a massive 73-foot wingspan which flew above the clouds for 14 days. Built by British defense contractor QinetiQ, the drone's 336 h, 22 min, and 8 s marked the longest time an airplane flew without refueling. Likewise all solar implementations, this work cannot be used indoors since illumination is not that high making solar harvester inefficient for indoors applications.

In [6], a combination of piezoelectric devices and new thin-film battery technology was used to form multifunctional self-charging, load-bearing energy harvesting devices for use in UAV systems. The proposed self-charging structures contain both power generation and energy storage capabilities in a multilayered, composite platform consisting of active piezoceramic layers for scavenging energy, with thin-film battery layers for storing scavenged energy and a central metallic substrate layer. In [7], Anton and Leo presented a hybrid where two piezoelectric patches, a macrofiber composite and a piezo-fiber composite (PFC) placed at the roots of the wings and a PFC cantilevered piezoelectric beam installed in the fuselage to harvest energy from wing vibrations and rigid body motions of the aircraft.

Quadcopters have a lot benefits such as large amount of controllability, hovering, and maneuverability, because of this they are suitable for both indoor and outdoor applications. Harvesting rotational motion is an important application for both indoor and outdoor use of drones.

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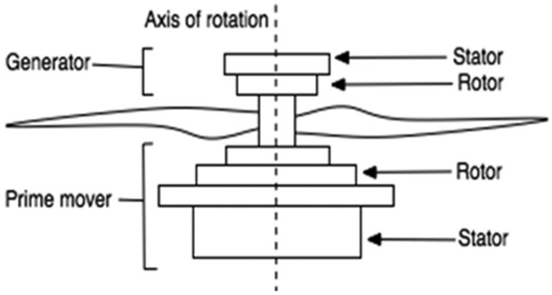


Fig. 1. Rotational harvester—prime mover coupled to generator.

The work reported in this research [13], focus on indoor application and it converts ambient continuous rotational motion from the rotors of a quadcopter to usable electrical power using a BLdc microgenerator, instead of harvesting vibrational energy from rotating machines or using brushed dc generator to harvest rotational motion. An interface electronic circuit of the harvester is used to condition the electrical energy harvested from the rotation, the final output of the harvester is used to augment the power supply of the quadcopter in order to increase its flight duration.

## II. Methodology

Rotational motion can be converted into electricity by using an electromagnetic generator as a transduction mechanism. Functionally, the rotor of the generator is driven by a prime mover and the stator of the generator is bolted to the stationary. When current flows in the generator, a torque on the rotor acts to reduce the velocity of the prime mover which in turn causes a torque on the stator, which is coincidentally prevented from moving due to its fastenings. The prime mover being the rotor of the quadcopter has its stator fastened to the quadcopter frame to make it stationary and, on the other hand, the generator's stator is also fastened to make it stationary, shown in Fig. 1.

The output of the microgenerator is rectified due to the ac nature of the output to obtain a dc voltage. Based on the power requirement of the quadcopter, a dc–dc boost converter is used to step-up the output of the rectifier. The output of the boost converter is used to boost the power supply of the quadcopter and also charge the battery if enough energy is produced as shown in the flowchart in Fig. 2.

### A. BLDC Generator Model

The terminals of the generator is connected to a three-phase bridge rectifier circuit, the output of all the four generators are connected in parallel, this connection is done to sum up the current produced from each generator. Fig. 3 shows the equivalent circuit of the BLdc generator.

As presented in [8], [9], and [10], by using Kirchhoff's laws, phase voltage equations of the BLdc generator can be expressed as

$$ean = Ria + (Ls - Lm)\frac{\partial ia}{\partial t} + van = Ria + L\frac{\partial ia}{\partial t} + van$$

$$ebn = Rib + (Ls - Lm)\frac{\partial ib}{\partial t} + vbn = Rib + L\frac{\partial ib}{\partial t} + vbn$$

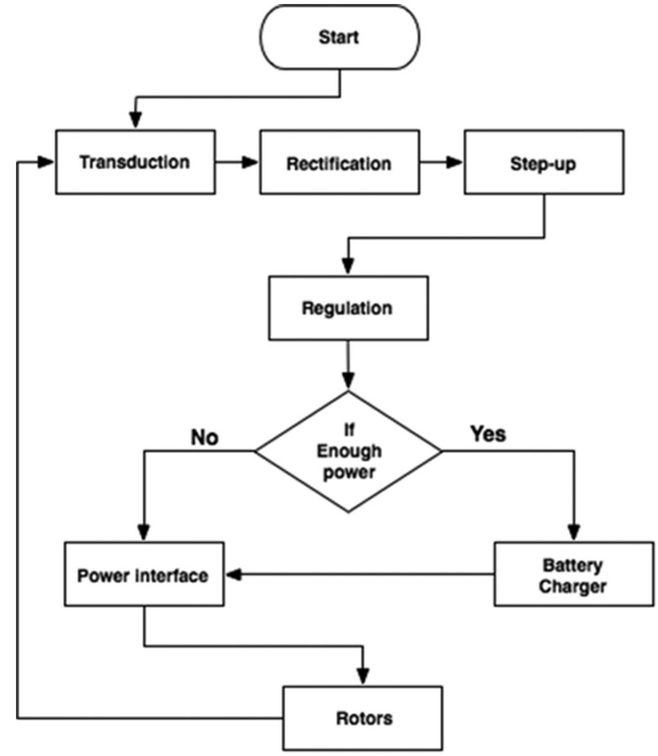


Fig. 2. Simplified topology flowchart of the energy harvesting system.

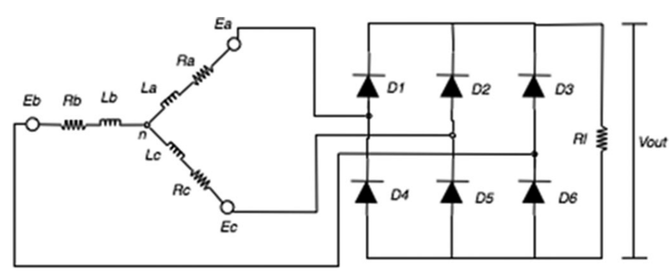


Fig. 3. Equivalent circuit of the BLdc generator.

$$ecn = Ric + (Ls - Lm)\frac{\partial ic}{\partial t} + vcn = Ric + L\frac{\partial ic}{\partial t} + vcn. \tag{1}$$

Simplified as

$$e_{xn} = Ri_x + L\frac{\partial i_x}{\partial t} + v_{xn} \tag{2}$$

where $e_{xn}$, $v_{xn}$, $i_x$, $R$, $L$, $L_s$, and $L_m$ represent each phase electromotive force (EMF), each phase-to-neutral voltage, each phase current, phase resistance, inductance, self-inductance, and mutual inductance, respectively.

EMF calculation can be accomplished by sensing each phase current ($i_x$) and voltage ($v_{xn}$). And motion equation can be represented as

$$T_{\text{rotor}} = T_{\text{generator}} + B\omega_r + J\frac{\partial \omega_r}{\partial t}$$

$$\frac{\partial \omega_r}{\partial t} = \frac{1}{J}\left(T_{\text{rotor}} - T_{\text{generator}} - B\omega_r\right) \tag{3}$$

where B and J represent viscous friction and inertia.

The back-EMF and electrical torque ($T_e$) can be expressed as

$$T_e = \frac{1}{\omega_r}\left(e_a i_a + e_b i_b + e_c i_c\right) \quad (4)$$

$$e_a = \frac{k_e}{2}\omega_r F\left(\theta_e\right)$$
$$e_b = \frac{k_e}{2}\omega_r F\left(\theta_e - \frac{2\pi}{3}\right)$$
$$e_c = \frac{k_e}{2}\omega_r F\left(\theta_e - \frac{4\pi}{3}\right) \quad (5)$$

$$Te = \frac{kt}{2}\left[F\left(\theta_e\right) i_a + F\left(\theta_e - \frac{2\pi}{3}\right) i_b + F\left(\theta_e - \frac{4\pi}{3}\right) i_c\right] \quad (6)$$

where $k_e$ and $k_t$ are the back-EMF constants and torque constant, respectively. The electrical angle $\theta_e$ is equal to the rotor angle times the number of poles pairs ($\theta_e = p\theta_m$). One period of the trapezoidal waveform of the back-EMF is given by

$$F\left(\theta_e\right) = \begin{cases} 1, & 0 \le \theta_e < \frac{2\pi}{3} \\ 1 - \frac{6}{\pi}\left(\theta_e - \frac{2\pi}{3}\right), & \frac{2\pi}{3} \le \theta_e < \pi \\ -1, & \pi \le \theta_e < \frac{5\pi}{3} \\ -1 + \frac{6}{\pi}\left(\theta_e - \frac{5\pi}{3}\right), & \frac{5\pi}{3} \le \theta_e < 2\pi \end{cases} . \quad (7)$$

## III. System Requirements and Design

To achieve the design process in the above section, the following requirements need to be satisfied, rotational transduction, low power rectification, dc–dc boost converter, power regulation, and Lithium Polymer (LiPo) battery charger.

With the aim of converting ambient rotational energy to electrical energy, the rotational transducer is coupled with the rotor of the quadcopter. The output of the microgenerator is rectified and stepped-up using dc–dc boost converters, which gives an output base on the power requirement of the quadcopter. To ensure a stable voltage supply to the quadcopter and other electronic payloads, the output of the dc–dc boost converter is regulated. The LiPo battery charger is required to charge a secondary 3 s LiPo battery of the quadcopter whilst it is in flight.

The specific microgenerator used in this paper is the BLdc generator which has more advantages than its dc counterparts. A low voltage three-phase bridge rectifier is achieved using Schottky diode for the rectification process, this selection is made to reduce the voltage drop by the diodes and also to keep the design simple.

Because the rotation on the quadcopter is dynamic, thus the RPM of each rotor is varied in order to cause motion, the output voltage of the generators vary, as such a step-up converter with a wide range of input voltage is used. The choice of a two-stage boost is made first to boost and condition the wide range and low input voltage to a higher voltage, and second to boost the output of the first boost converter to a much higher voltage with regulation and high current capabilities. A charger with a balancing circuit is designed to charge the 3 s LiPo battery of the quadcopter. The architecture in Fig. 4 is employed where the rotors of the quadcopter are each coupled with a BLdc microgenerator. The ground pilot control is used to control the flight of the quadcopter to arm or spin the rotors.

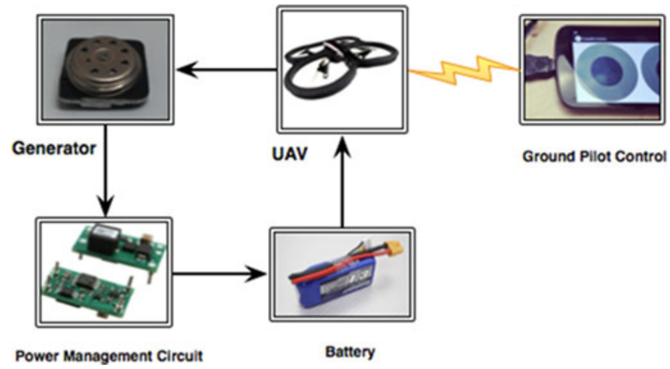


Fig. 4. System architecture.

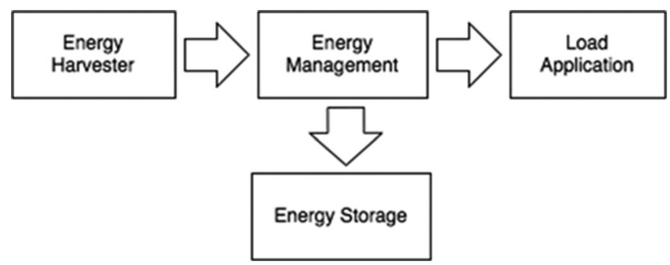


Fig. 5. Topology for energy harvesting systems.

As the rotor or the quadcopter spin's torque is transferred to the coupled generator which causes the rotor of the generator to spin, the torque of the generator opposes the torque generated from the quadcopter rotor and the difference in these torques causes power to be generated. For a BLdc generator, the generated voltage is a trapezoidal ac in three phases, therefore the generated voltage is rectified to produce a dc voltage using a three-phase bridge rectifier. The produced dc voltage is fed into a power management circuit to power and charge the quadcopter battery where necessary.

Fig. 5 describes a simplified topology of the energy harvesting system.

## IV. Simulation of BLdc Microgenerator

The simulation of BLdc microgenerator was done in MATLAB R2012a and simulink 8 using the default ode45 Solver. A load torque of 0.00875 N·m was applied. Fig. 6 shows a complete BLdc generator Simulink model. The core block implements (1)–(7).

Fig. 7 shows the mechanical block which takes in as input rotor torque ($T_r$) and electrical torque ($T_e$) and gives out angular velocity ($\omega_r$) as output. The trapezoidal signals are calculated using the electrical angle as input signals, Fig. 8. The electrical block set takes as input, $\omega_r$ and trapezoidal signal with a phase load of 100 Ω to produce the phase EMFs as shown in Fig. 9. The phase currents in conjunction with the trapezoidal signals

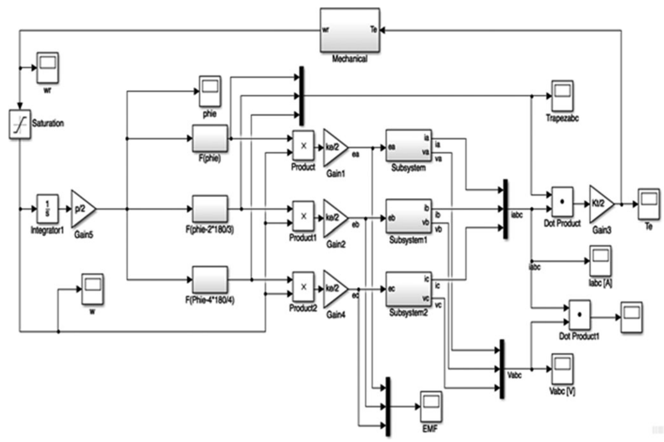


Fig. 6. BLdc generator model.

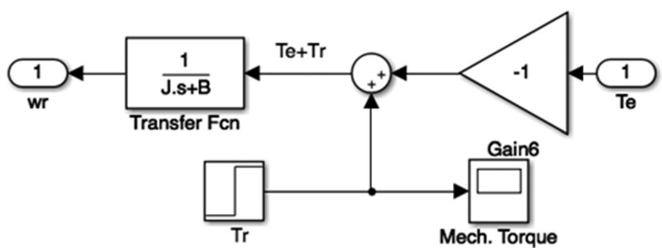


Fig. 7. Torque and angular velocity calculation.

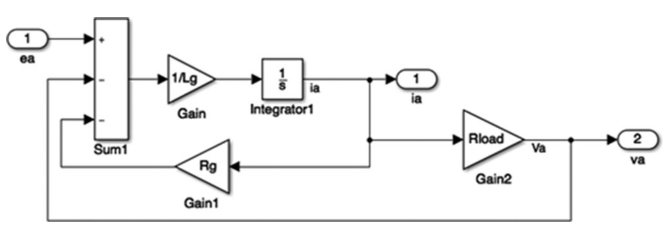


Fig. 8. Electrical subsystem: Phase a. (Similar for phases b and c).

TABLE I
PARAMETERS OF THE BL DC GENERATOR

| *Quantity* | *Value* | *Unit* |
|---|---|---|
| Line current (*I*) | $\sqrt{3}(0.55) = 0.95$ | A |
| Resistance (*R*) | 2.5 | Ω |
| Voltage (*V*) | 5 | V |
| Revolution | 5400 | r/min |
| Torque constant $(K_L)$ | 0.00540 | N·m/A |
| EMF constant $(K_e)$ | 0.01724 | V/rad/s |

and the generator tongue constant produce the electrical torque. The graph in Fig. 9 shows the trapezoidal nature of the back-EMF of the generator, it begins gradually from 0 to about 5 V. From the simulation, the current starts gradually from 0 to about 0.5 A while the voltage starts from 0 to 4.3 V, in both cases this occur as the generators speed increase from 0 to 5400 r/min. The generator parameters used for the experiment are summarized in Table I.

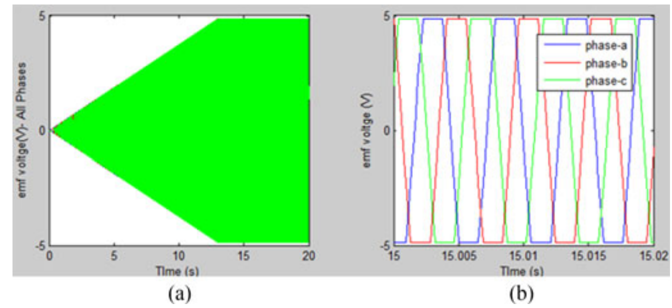


Fig. 9. Simulation results of the generated EMF voltages as speed is increased from 0 to 5400 r/min: (a) all phases; and (b) zoomed-in.

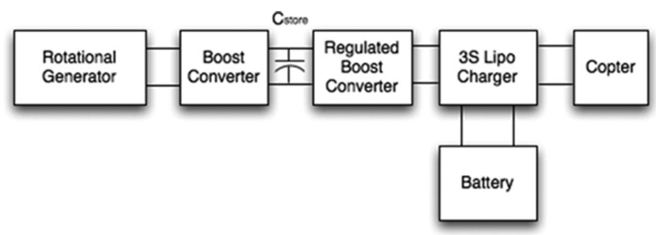


Fig. 10. Block diagram of the rotational harvester circuit.

## V. IMPLEMENTATION

In order to meet the requirement to power the quadcopter and charge the 11.1-V battery, the 3.2 V generated from the BLdc generator needs to be stepped up and regulated. Two boost converters are employed to step up the generated voltage.

The first boost converter steps up from 3.2 to 5.2 V which is then fed to the second boost converter. The second boost converter steps up from 5.2 to 18 V, which is used as an input to a LiPo charger to charge and power the quadcopter as in Fig. 10.

The first boost converter is implemented using TI BQ25504 from Texas Instruments (TI) to step up the voltage from rectifier circuit to 5.2 V. BQ25504 is an ultralow power, high-efficiency dc/dc boost converter/charger with battery management. The choice for this integrated circuit (IC) was made because the design starts with a dc–dc boost converter/charger that requires only microwatts of power to begin operating and designed for energy harvesting. A PSpice (using OrCAD 16.3 version) implementation of the circuit is shown in Fig. 11. This was done to verify functionality before the actual circuit was built and soldered.

The boost converter is used to step up the voltage from the rectifier circuit to 5.2 V. The main priority of BQ25504 is to charge up the V_STOR capacitor across its output terminal, C_STOR, then power additional internal circuitry via V_STOR with the energy available from the dc input source.

For the first 32 ms after the main converter is turned ON, the charger is disabled to let the input go up to its open-circuit voltage. This is needed to get the reference voltage which will be used for the remainder of the charger operation till the next sampling cycle turns ON. In addition, a bulk capacitor of at least 4.7 $\mu$F should be connected between Pin 15 and ground to

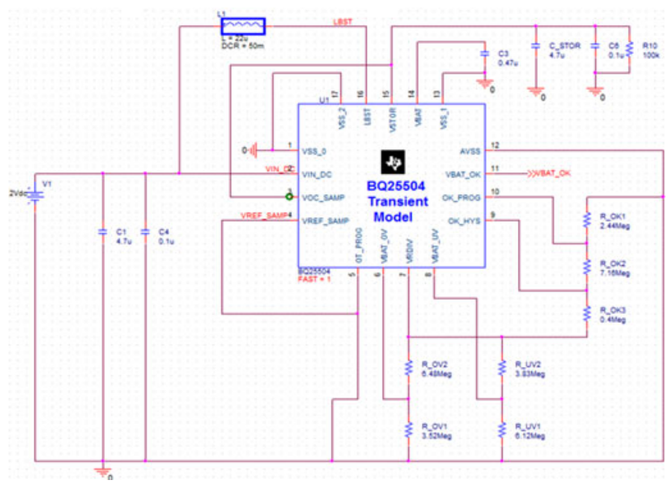


Fig. 11. PSpice implementation of the 5.2 V boost converter circuit.

assure stability of the boost converter [11]. Battery undervoltage threshold is set to prevent rechargeable batteries from being deeply discharged and damaged, and to prevent completely depleting charge from a capacitive storage element. This protection measure is set using external resistors. The VBAT_UV threshold voltage when the battery voltage is decreasing is given by

$$V_{\mathrm{BAT\_UV}} = V_{\mathrm{BIAS}}\left(1 + \frac{R_{\mathrm{UV2}}}{R_{\mathrm{UV1}}}\right). \tag{8}$$

The sum of the resistors, $\boldsymbol{R}_{\mathrm{UV1}}$ and $\boldsymbol{R}_{\mathrm{UV2}}$ should be 10 MΩ. $\boldsymbol{V}_{\mathrm{BIAS}}$ is a voltage node which is used as reference for the programmable threshold voltage and has a value of 1.25 V. Battery overvoltage threshold is set to prevent rechargeable batteries from being exposed to excessive charging voltages and to prevent over charging a capacitive storage element. This protection measure is set using external resistors and is given by

$$V_{\mathrm{BAT\_OV}} = \frac{3}{2}V_{\mathrm{BIAS}}\left(1 + \frac{R_{\mathrm{OV2}}}{R_{\mathrm{OV1}}}\right). \tag{9}$$

The sum of the resistors, $\boldsymbol{R}_{\mathrm{OV1}}$ and $\boldsymbol{R}_{\mathrm{OV2}}$ should be 10 MΩ. The IC allows the user to set a programmable voltage independent of the overvoltage and undervoltage settings to indicate whether the VSTOR voltage is at an acceptable level, (10) set the threshold when the battery voltage is decreasing

$$V_{\mathrm{BAT\_OK\_PROG}} = V_{\mathrm{BIAS}}\left(1 + \frac{R_{\mathrm{OK2}}}{R_{\mathrm{OK1}}}\right). \tag{10}$$

Equation (11) sets the threshold when the battery voltage is increasing

$$V_{\mathrm{BAT\_OK\_HYST}} = V_{\mathrm{BIAS}}\left(1 + \frac{R_{\mathrm{OK2}} + R_{\mathrm{OV2}}}{R_{\mathrm{OK1}}}\right). \tag{11}$$

A transient simulation result of the above boost converter using the BQ25504 chip is shown in Fig. 12 below. With an input of 2 V to represent the expected rectified output of the BLdc generator, the output voltage can be seen to be increasing to its rated value of 5.2 V.

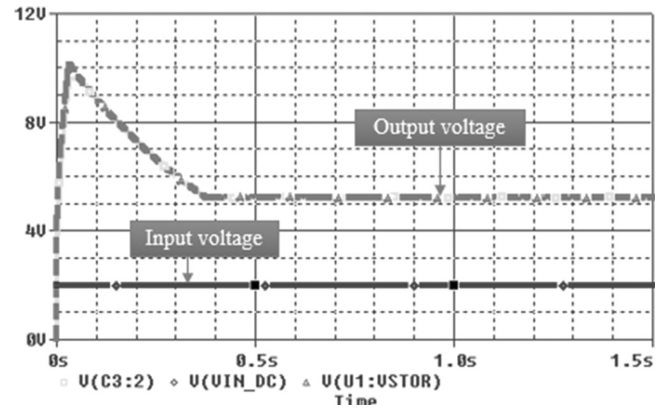


Fig. 12. Simulation results for the 5.2 boost converter using BQ25504.

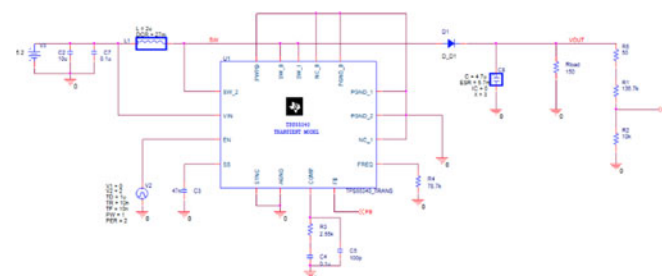

Fig. 13. PSpice implementation of the 18 V boost converter circuit.

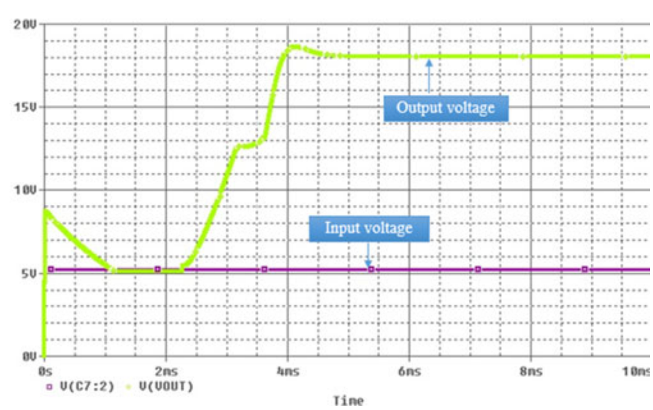


Fig. 14. Simulation results for the 18 V boost converter circuit.

The TPS55340 chip [12] from TI was configured as the second boost converter and it regulates the output voltage with current mode pulse width modulation control. It has an internal oscillator which is used to generate the pulse-width modulation (PWM) cycle, which is used to control the switch on the boost converter. It was implemented to boost the 5.2 V output of the first boost converter to 18 V to power and charge the quadcopter battery. A PSpice (using OrCAD 16.3 version) implementation of the circuit is shown in Fig. 13 with simulation of the circuit with a 5 V input is shown in Fig. 14. This was also done to verify functionality before the actual circuit was built and soldered.

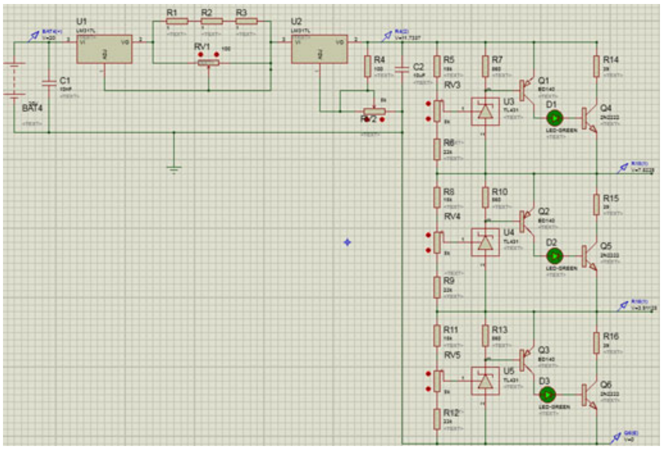

Fig. 15. LiPo charger with balancer circuit.

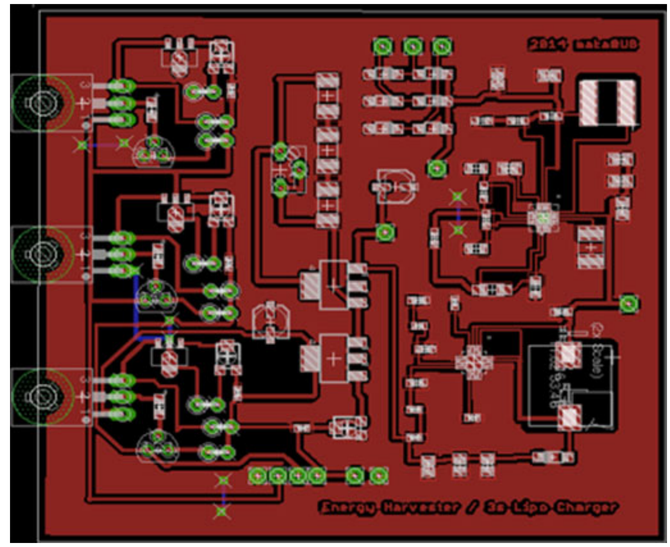

Fig. 16. Eagle PCB design of harvester circuit.

TABLE II
STEADY-STATE TEST RESULTS FOR THE 5.2 BOOST CONVERTER

| Input Voltage (V) | Output Voltage (V) |
|---|---|
| 0.5 | 5.2 |
| 1.0 | 5.2 |
| 1.5 | 5.2 |
| 2.0 | 5.2 |
| 2.5 | 5.2 |
| 3.0 | 5.2 |

TABLE III
STEADY-STATE TEST RESULTS FOR THE 18-V BOOST CONVERTER

| Input Voltage (V) | Output Voltage (V) |
|---|---|
| 1.5 | 7.2 |
| 2 | 15.4 |
| 3 | 20 |
| 4 | 20 |
| 5 | 20 |

## VI. LIPO BATTERY CHARGER

The battery charger shown in Fig. 15 is made up of LM317 voltage regulator IC used to regulate the input voltage and 5 W wire wound current regulating resistor to control input current.

The charger includes a balancer circuit which ensures that the three individual cells are charged to the same voltage. The charger is designed to charge the 3S LiPo battery aboard the quadcopter from the harnessed rotational energy by taking as input, the output of the second boost converter. The 3S LiPo is a 750 mAH battery pack made up of three individual cell each 3.7 V wired together in series to produce 11.1 V. This 11.1 V battery is the primary supply for the quadcopter.

## VII. OVERALL SETUP AND EXPERIMENTAL RESULTS

Experimental steady-state test for the two boost converters are presented below in Tables II and III. The BLdc generator was able to harvest continues rotation from the rotor of the quadcopter to electrical energy. At a revolution of 5400 r/min, the generator produces 3.2 V.

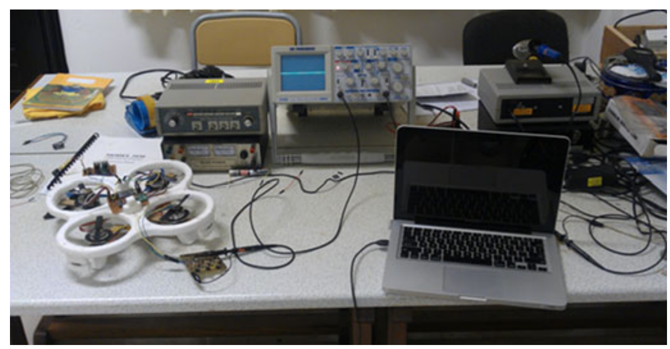

Fig. 17. Test setup.

TABLE IV
TEST RESULTS FOR ONE GENERATOR CIRCUIT WITH 100 $\Omega$ LOAD

| | 100 $\Omega$ Load |
|---|---|
| Input Voltage | 3.2 V |
| Input Current | 1 A |
| Output Voltage | 18.03 V |
| Output Current | 150 mA |
| Efficiency | 82% |

The overall physical model was built on a printed circuit board (PCB) board using the Eagle PCB design software (EAGLE 6.4.0 Light) interface shown in Fig. 16.

Having verified the individual circuit units, the various units were put together and tested. The output of all the four generators are connected in parallel to sum up the current produced from each generator. Fig. 17 shows the test setup for the system.

As in the case for testing the generator, an Arduino code was written to drive a motor coupled with the BLdc generator. The output of the generator was fed to the complete circuit. The recorded results for one generator are presented in Table IV. The circuit implementation produces about 2.7 W of output power for one generator at 82% efficiency. With 150 mA from one generator, a total of 600 mA of current from the four generators connected in parallel could be supplied by the system.

For the setup, each rotor requires 0.4 A, making a total of 1.6 A for four rotors. A total of 0.26 A is also required for both the microcontroller and the Bluetooth shield. In total, 1.86 A is drawn from the battery during operation of the quadcopter. With a fully charge 750 mAh battery, the maximum flight duration of the quadcopter can be estimated to be approximately 22.5 min assuming 2 A is continuously drawn from it. With 600 mA of current from the generators which is about 30% of the 2 A needed to run for about 22.5 min will translate into approximately 9.5 min of extra flight time, thus gaining about 42% in flight duration.

*Some Challenges during Setup*

One of the major challenges faced during this research was with the implementation of the system design. Some of the components used in the design include surface-mount device (SMD) electronic components, 3s LiPo battery, Arduino Microcontroller, Copper clad PCB board, propellers, high-speed BLdc motor, and Bluetooth module. Some components were also not easy to come by, for example, the microgenerator was obtained from a crashed laptop hard disk drive. Also coupling the generator to the rotors of the quadcopter was difficult, the process requires that the axis or rotation for both the generator and the motor are perfectly aligned. That can be done on a lab bench fitted with a clamp.

Recommendation for future work will include using a gearbox to increase or decrease the speed of the generator. A gearbox will be needed to step up RPM in the case where the prime mover speed is relatively low as compared to that of the generator, also a gearbox will be needed in a case where the prime mover has excessive speed that might contribute to the heating of the generator. In addition, a proper alignment of the generators axes of rotation to that of prime mover during the coupling process could reduce the vibrations that is introduce into the system as a result of this process.

## VIII. Conclusion

The work has demonstrated a rotational energy harvester powered by rotors using a BLdc generator. The mathematical model of the BLdc generator is used to analyze the waveforms of the output of the generator; results from the physical model of the generator verified the results of the mathematical model implemented in MATLAB/Simulink. The BLdc generator was able to harvest continuous rotational energy from the rotor of the quadcopter to electrical energy. At a revolution of 5400 r/min, the generator produces 3.2 V. After simulating the harvester circuit, the physical model was built on a PCB. The harvester interface circuit takes an input of 1.5 to 3.2 V from the rectifier circuit and produces a regulated output of 18 V with 2.7 W output power per generator at 82% efficiency. About 30% of the current required to keep the quadcopter in operation is achieved form the rotational harvester, resulting in a gain of about 42% in flight duration.

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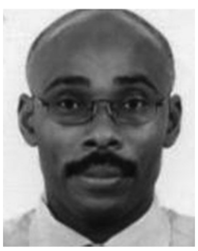

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