Optimization for Augmentation of Primary Power supply to Improve the Endurance of the Quadcopter

Siranthini Balraj and Anitha Ganesan ,

Division of Avionics, Department of Aerospace Engineering, Madras Institute of technology, Anna university, Chennai, India
(email- id: jesirithvi0512@gmail.com)

ABSTRACT

The flight endurance is the major challenge in Quadcopter or Quadrotor or Drone applications. This paper presents the rotary power harvesting system using Permanent Magnet Brushless DC Generator (BLDCG) to harvest the electrical energy from the rotors of Quadcopter to extend its flight duration. The Energy Harvesting (EH) system is mounted rigidly to the propeller shafts of Quadcopter. This work mainly focuses on the optimization technique to maximize the power generated from BLDCG using controlled rectifiers and to compare the results with the state of the art. To detect the position of the rotor, Sensorless back emf detection technique is adopted. Literature survey reveals that the conventional uncontrolled rectification methods using diodes, have its own limitations which may not maximize the possible power due to non-optimal current and low power per ampere ratio. Moreover, Diode rectifiers generates harmonics to the source side and also permits only one side power flow. This problem is solved using Controlled rectifiers with MOSFET. A Hysteresis comparator along with the PI controller is used to regulate the DC link voltage. Followed by the Energy Harvesting system, the Generated output voltage is boosted and regulated using Single Ended Primary Inductor Converter (SEPIC) to power and charge the Quadcopter on board Lipo Battery. This proposed optimized harvesting system is simulated using MATLAB simulation and a complete hardware setup is built and tested in the laboratory.

Keywords:

BLDC generator, Quadcopter, Energy Harvester, Hysteresis controller, SEPIC converter, Lipo battery.

1. INTRODUCTION

Electrically powered UAV like Quadcopter or drone's usage is increased nowadays, because of its huge applications in various fields such as Scientific research, surveillance, military, law enforcement, mining, constructional, surveying, security and etc., The drawback of drones are its shorter flight time when predominantly used in commercial purpose and longer duration of downtime due to battery limitations and recharging. The conversion of rotational energy into electrical energy is a well-known conventional technique right from bicycle dynamos to wind / hydroelectric power plants. Adapting this basic ideology in unmanned aircraft to generate back-up power is also proved in several researches using photo voltaic, vibrational etc.. However most of the photo voltaic (solar) energy harvesting only efficient at outdoor applications, due to less illumination in indoor.

Out of many types of Permanent magnet generators, Brushless DC generator[BLDCG] is the best one and gives more benefits, such as wide speed range with high efficiency, large durability, less maintenance, compactness and higher power density. The energy Harvesting using BLDCG from continuously rotating assemblies of the quadcopter to power and prolong the duration is proved in [1] used conventional rectifiers and two boost converters were used to boost up the DC link voltage, without any optimization technique. Conventional rectification methods cannot achieve the optimum or maximum power possible due passive elements (diodes) presence and it leads to significant amount of energy loss [2 to 9]. Many advanced control techniques to maximize the power from BLDCG has presented as, zero sequence elimination method [3,4], minimization of torque ripples and joule losses [6], Digital control technique using FPGA [7], current control shaping algorithm using hysteresis and PI controller [8], direct power control technique [9]. These survey gives one of the best way to maximize the power using active rectifiers.This paper progresses the analysis and implementation of power using controlled rectifier technique. Sensorless back emf zero cross detection method is adopted to know the position of the rotor of BLDCG and Hysteresis, PI controller is used limit the DC link voltage. After controlled rectification process a Single Ended Primary Inductance Converter [SEPIC] is used to boost the voltage to the required level of onboard battery Lipo of the quadcopter. The SEPIC converter has many advantages [17] compared with conventional DC to DC boost converter. In order to use any dc/dc converter in renewable energy sources, it should have a high voltage gain and continuous input current. Their Voltage conversion gains are not enough for renewable energy applications due to high voltage gains in high duty ratios of power switch severely deteriorated [14] and this could be rectified using SEPIC converter.

To increase the flight duration of the quadcopter using maximum source power is the main objective of this proposed plan. Whenever, the quadcopter running, the mounted BLDC generator coupled with the BLDC motor act as a Harvester circuit. The shaft of both generator and motor are joined with a single point attachment to rotate properly, if the alignment is missing it will mislead the rotation and produce heat. This paper is organized as follows. Section 2 reveals that the analysis of Brushless DC Generator, Section 3 describes that the proposed design and requirements, Section 4 is testing and result, 5 is conclusion and references.

2. ANALYSIS OF BLDC

Permanent Magnet Brushless DC machines (PMBLDC) operated in a generator mode provides lot of advantages such as high efficiency, less maintenance, wide operating range, compactness, grater durability and higher power density. Based upon the back EMF induced in the stator winding PM machines having two types: Trapezoidal Type (BLDCG) and Sinusoidal Type (PMSG).

Before going to the analysis, to simplify it Some assumptions are presented [9]:

- The generator is operated within the rated condition, so the generator is not saturated
- R and L values of all the windings are equal
- Induced Back emf waveform shape is same for all three phases
- Power semiconductor devices are ideal

Generators are characterized by their back emf constant (K_e) and winding resistance (R), the equivalent circuit of BLDC generator [3] is shown in Fig 1.

The induced Backemf is given in equation,

$$\left.\begin{aligned} E_R &= R_s I_R + (L_s - L_m)\frac{\partial IR}{\partial t} + V_R \\ E_Y &= R_s I_Y + (L_s - L_m)\frac{\partial Iy}{\partial t} + V_Y \\ E_B &= R_s I_B + (L_s - L_m)\frac{\partial IB}{\partial t} + V_B \end{aligned}\right\} \qquad (1)$$

Where,

E_R, E_Y, E_B = Back emf of phase R,Y, and B [V]

I_R, I_Y, I_B = Stator current of Phase R,Y and B [A]

V_R, V_Y, V_B = Terminal voltage of Phase R,Y,B [V]

R_s = Stator resistance [Ω]

L_s, L_m = Stator Self , Mutual inductance [H]

The mechanical motion equation is represented as:

$$T_r = T_g + B\,.\omega_r + J\,.\frac{\partial \omega r}{\partial t} \qquad (2)$$

$$\frac{\partial wr}{\partial t} = \frac{1}{J}\left(T_r - Tg - B\omega_r \right) \qquad (3)$$

Where,

T_r , T_g , B, J, ω_r represent Torque of the rotor, Torque of the Generator, viscous friction and inertia, rotational angular speed .

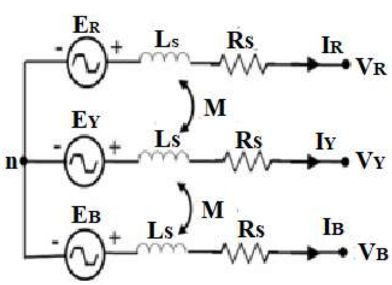


Figure 1. Equivalent Circuit of BLDC

3. PROPOSED SYSTEM DESIGN AND REQUIREMENTS

3.1 System Topology

Electrical energy can be extracted from the continuously rotating structures using transduction mechanism [1]. The system topology is shown in the Fig 2. The bldc generator connected to the BLDC motor by using a single point shaft attachment. When the quadcopter rotates, torque is transferred to the connected generator which initiates to rotate the generator to spin. This torque difference in equation 2, produces the emf generation in the stator winding of the generator. The generated Alternate Electromotive force (emf) is converted to DC using rectifier and filter circuit is used to get the ripples free DC output. This rectification and control circuits are fabricated in Power management circuit.

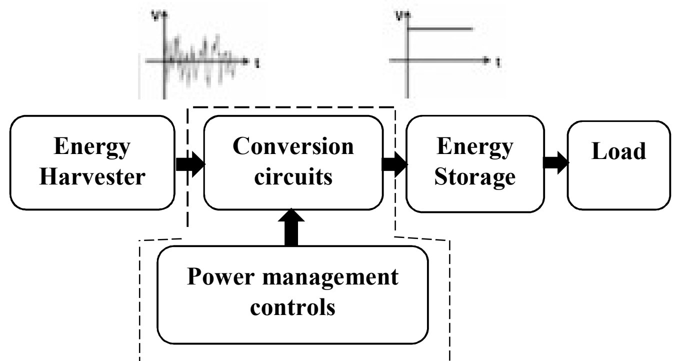


Figure 2. Energy harvesting topology

3.2 Power calculation of BLDC generator

In the Three-phase BLDC generator, the average air gap power [3] is obtained using the following equation:

$$P_{avg} = \sum_{k=R,Y,B} \frac{1}{T}\int_0^T \{ E_k(t)\; I_k(t)\}\, dt \qquad (4)$$

$$= \frac{1}{T}\int_0^T \{ E_R(t)\, I_R(t) + E_Y(t)\, I_Y(t) + E_B(t)\, I_B(t)\}\, dt \qquad (5)$$

The induced back emf and current in all the phases are same as referred in the assumption then,

$$= \frac{3}{T}\int_0^T (E_R(t)\; I_R(t))\, dt \qquad (6)$$

Power output from the generator is,

$$P_{output} = \sum_{k=R,Y,B} \frac{1}{T}\int_0^T \{ V_k(t)\; I_k(t)\}\, dt \qquad (7)$$

Substitute equation 1 in 7 then the three phase power is **,**

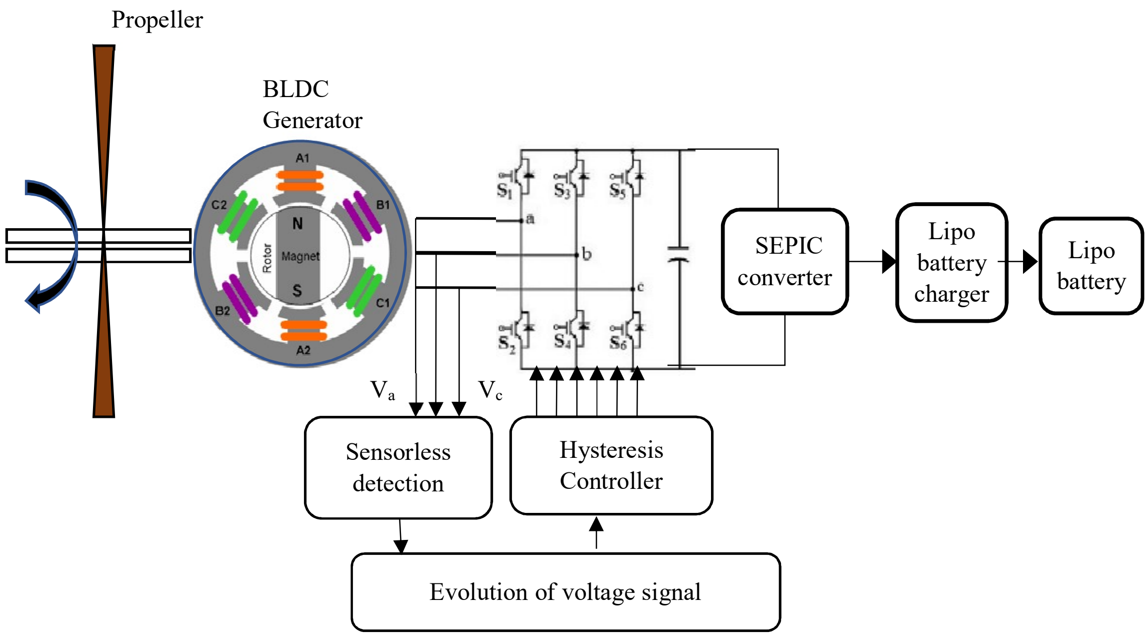


Figure 3. BLDC generator system topology with maximization of power

$$P_{output} = \frac{3}{T}\{\int_0^T E_R(t).I_R(t)\,dt - \int_0^T Rs\, I^2_R(t)dt - \int_0^T (Ls\frac{dIR(t)}{dt}\;\; IR(t)dt\}$$

$$= \underbrace{\frac{3}{T}\int_0^T E_R(t).\, I_R(t)\,dt}_{I} - \underbrace{3\, Rs\, I^2_R(t)}_{II} - \underbrace{\frac{3Ls}{T}\int_0^T IR(t)\, dI_R(t)}_{III} \qquad (8)$$

In the above equation I part indicates the average power generated in the airgap, II part indicates the stator copper loss and its constant value so neglected. III part is stator inductor average power will be becoming zero latter. So it is concluded the output power generated from the BLDC is purely depends upon the airgap power. To maximize the output power is related to the airgap power components of induced back emf and phase current.

Induced back emf in the three phase BLDC generator is a trapezoidal waveform and due to the structure of the machine design it contains harmonics. This is the major disadvantage of BLDC generators, because of the switching delay of trapezoidal waveform from one phase to others. The main objective of this paper is to maximize the energy extracted from the BLDC generator and to deliver the actual power per ampere to DC link side. The overall energy harvesting system outline using BLDCG with controlled rectification in quadcopter is shown in Fig 3.

The commutation of Brushless DC generator relies on its rotor position. To detect the position of rotor is must to know in which phase the emf is generated, usually hall effect sensors are employed for that purpose. There are several drawbacks using such sensors like high cost, low reliability of the system and extra wirings reduced the simplicity of the system. Moreover, Hall effect sensors are temperature sensitive when they mounted inside the windings, it increases the size and weight of the system and limit the operation. Henceforth a Sensorless zero cross detection technique is applied to detect the position of the rotor.

3.3. Sensorless technique with Hysteresis Comparator

This paper uses the Sensorless control technique using zero cross detection of induced emf. When quadcopter is running the coupled BLDC, generator rotate via shaft of the motor, the emf is induced in the stator winding. The terminal Voltage as per equation 1 is proportional to induced back emf, compared with back emf the voltage drop of resistor and inductor is very less and negligible. So, the magnitude of back emf and terminal voltage is almost equal and it can be measured using unenergized open phase because only two phases are energized at any time. This acquired information is transformed to commutate the energized phase pair to control the phase voltage using PWM modulation signal.

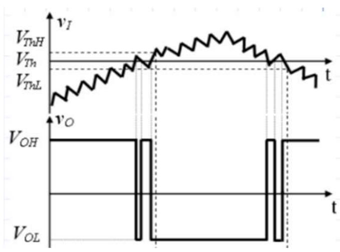


Figure 4. Hysteresis comparator

After commutation, to control the DC link output voltage in a desired value and to prevent it from the fluctuation of load changes is important. PI controller is employed to maintain the DC link voltage. The predefined reference voltage is compared with the DC link voltage, where feedback to the system and generate the error signal via PI controller. By Proper selection of K_p and K_i values the error is getting minimized and then the output signal is given to hysteresis comparator where to reduce the unwanted noises present. The Hysteresis comparator uses two different threshold voltages like, upper (V_{ThH}) and lower threshold (V_{ThL}) values to decide the exact output (V_0) shown in Fig. 4. The input signal exceeds the upper threshold the output, is transition low (V_{oL}) or below the lower threshold the output, is transition high (V_{oH}) therefore exact controlled output switching gate pulses are generated to open the MOSFET switches. The three phase output signals like Z_R,Z_Y,Z_B are combined to form logical equations and signals , the truth table I is given below. Each commutation signal has 60-degree phase difference.

Table I . Truth table for commutation signals

Z_R	Z_Y	Z_B	S1	S6	S3	S4	S5	S2
0	0	0	0	0	0	0	0	0
0	0	1	0	0	1	0	0	1
0	1	0	1	0	0	1	0	0
0	1	1	1	0	0	0	0	1
1	0	0	0	1	0	0	1	0
1	0	1	0	1	1	0	0	0
1	1	0	0	0	0	1	1	0
1	1	1	0	0	0	0	0	0

After getting the desired DC voltage, is boosted using Single Ended Primary-Inductor Converter (SEPIC). Only one boost converter is used in this method giving equivalent performance where two boost converters used in earlier system [1].

3.4. SEPIC converter

This is specially designed converter with simple controller and active components allows a range of DC voltage to maintain the constant output voltage [16]. It is able to act as buck and boost actions and its minimum ripple current increases average value of current and voltage. The exchange of energy between the inductors and capacitors so as to convert from one level of voltage to another [14].

When the MOSFET is turning on with high pulse, the inductor (L_1) is charged by the input voltage and inductor 2 (L_2) is charged by SEPIC capacitor 1 (C_1) shown in Fig 5. At that time the diode is in off condition and the output is maintained by the output capacitor (C_{out}). When the MOSFET is turning off with low pulse the inductors output through the diode to the load and both capacitors are charged. The SEPIC capacitor connected in series is doing to transfer the energy between input and output. Greater the percentage of duty cycle the output will be high and the duty cycle is calculated by using the below equation (9).

$$D = \frac{Vout+VD}{Vout+Vin+VD} \tag{9}$$

V_D is the forward voltage drop of the diode, V_{out} is the output voltage, V_{in} is the input voltage of the converter.

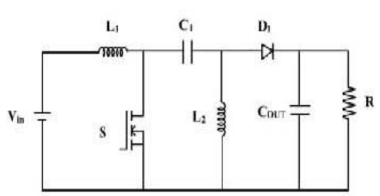


Figure 5. SEPIC DC/DC converter topology

The SEPIC converter output is given to the lipo battery charger unit. LiPo batteries are rechargeable battery, using voltage charging method is employed to charge it. It contains 3 cells of 3.7 Voltage, each cell charging individually and having 20c discharge rate. LiPo batteries are light in weight and keep large power in a small package. To meet the power requirements quadcopters, the discharge rate should be very high. The specification of the Lipo battery is used is, 11.1 V, 3s, 2200mA.

4. TESTING AND RESULTS

4.1 : BLDC generator simulation model

The simulation studies were carried out using MATLAB / Simulink ode23dp solver. The simulation model is developed for both uncontrolled and controlled rectifiers for the same BLDC simulation parameters.

Simulation design parameters of BLDC generator is listed in table II.

Table II BLDCG simulation parameters

Quantity	Value	Unit
Resistance	2.5	Ω
inductance	0.65	mH
Speed	5400	Rpm
Torque constant (Kt)	0.00540	Nm/A
Inertia (J)	1.6057e-6	Kg/m^2
Emf constant (Ke)	0.01724	V/rad/s

The BLDC generator with optimization technique Simulink model is given in Fig 6,7,8.

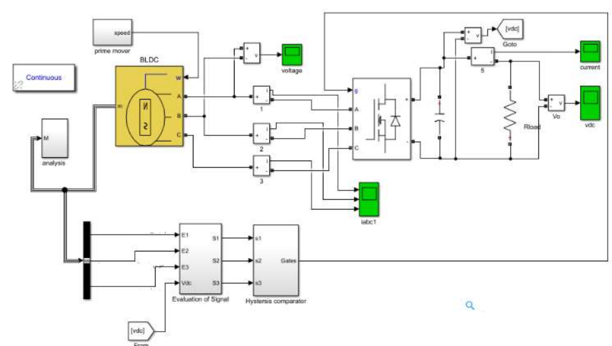


Figure 6. Simulink model of BLDC generator with power optimization technique

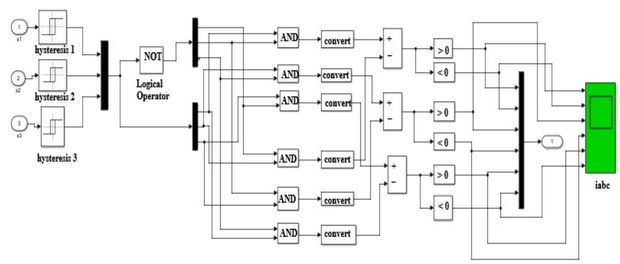


Figure 7. Hysteresis controller Block

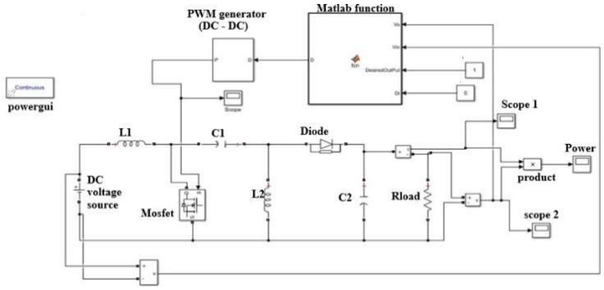
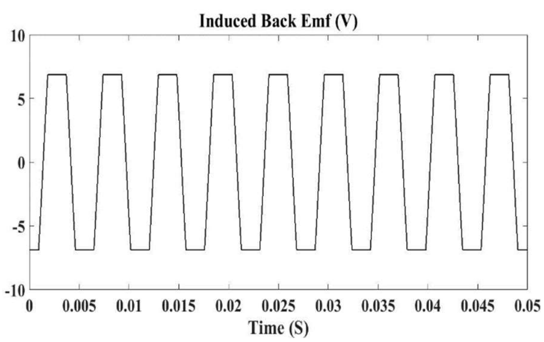


Figure 8. SEPIC DC to DC Boost converter

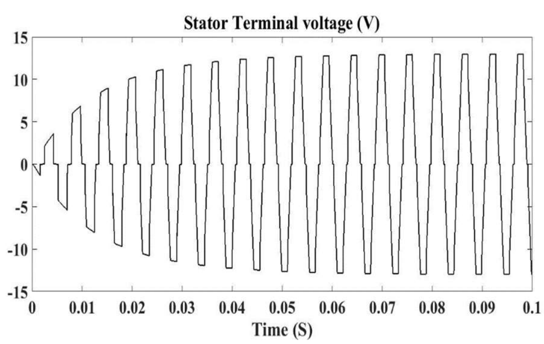
4.2 Simulation Results

At starting, the maximum speed of 10,000 rpm to minimum 1000 rpm is given to the BLDC generator. For doing analysis of charging the battery through harvesting the speed is taken as 5400 rpm, which gives better comparison with the existing harvesting system [1]. The speed has gradually increased from 0 to 5400 rpm, the generator output terminal voltage and induced back emf, stator phase current is shown in below. At this speed the induced back emf is 7.4 V , stator terminal voltage is gradually starts from 0 to 13 Volts, and Stator phase current 0.13 A at 100 Ω load resistor is shown in Fig 9 (a),(b),(c).

(a)



(b)



(c)

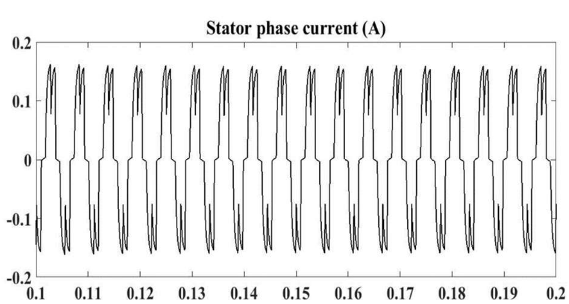
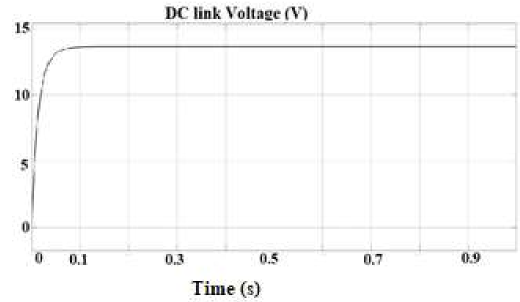


Figure 9. (a) Induced Back emf (V)
(b) Stator terminal Voltage Phase to Phase (V)
(c) Stator Phase Current (A)

After rectification the DC link voltage is given to the DC to DC boost converter SEPIC, the Simulink model is presented in Fig 8. The DC link Voltage and Current after controlled rectification is shown Fig 10(a),(b).

(a)



(b)

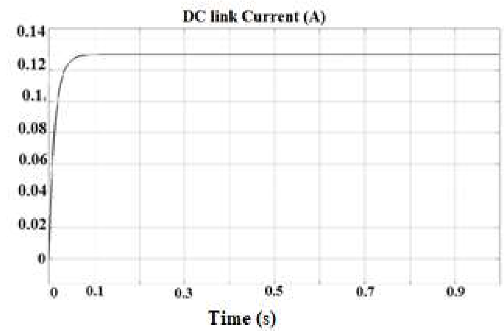


Fig. 10 (a) DC link Voltage (V)
(b) DC link Current (A)

The fluctuation of output voltage from SEPIC converter is controlled by adjusting the Duty cycle. The minimum and maximum value of the duty cycle is calculated based upon the formula given in equation [9]. The MATLAB function code has been written according to maintain the constant voltage at the output and generate the required PWM signal to SEPIC MOSFET. Based upon output requirement the minimum and maximum voltage is calculated and fixed. The minimum input voltage is 2.5 V to trigger and the maximum output voltage is fixed as 15 V, which is greater than the lipo battery rated voltage 11.7 Volt to charge shown in Fig 11. Beyond 15 Volts also the booster could boost, but not feasible for getting current, that means if output boost voltage will be high it will reduce the current value accordingly.

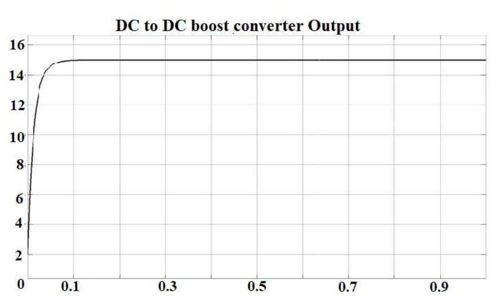


Figure 11. SEPIC converter Output DC Voltage (V)

At 5400 rpm the simulation result taken for uncontrolled rectifier and compared with proposed controlled rectifier. The output power Vs various load resistor for both rectifiers is given in Fig 12. It seems that for minimum load-controlled rectifier gives more output power than the uncontrolled rectifier.

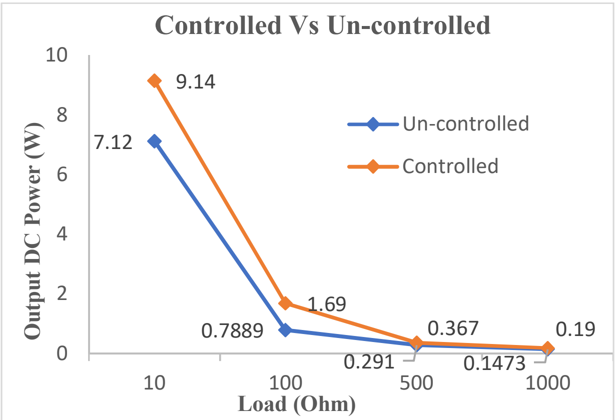


Figure12. Output DC power Vs Load (Simulation)

4.3 Experimental Result

A Single harvester set [one BLDC rotor + Generator] has been tested with minimum load practically, their maximum AC output voltage with maximum speed of 10,000 rpm and the current output is shown in Fig 13. The speed of the harvester is tested using the speed encoder with Arduino controller.

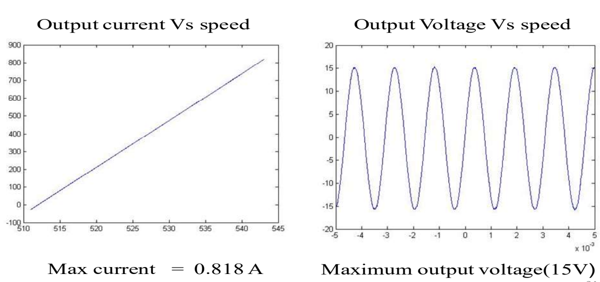


Figure 13. Harvester testing output

In existing energy harvesting system [1] they had tested only uncontrolled rectifiers, using two boost converters to boost the dc link voltage to charge the battery. The same setup is followed in practical, with application of optimized technique using single boost converter SEPIC.

The hardware test is done for both uncontrolled and proposed system and results were compared and presented in Fig 14. for output power Vs various load. In table II the simulation and hardware result of controlled and uncontrolled rectifiers are presented. Due to the same shipping and cost constraint [1] the BLDC generator has procured from scrabbled desktop Hard disk drive.

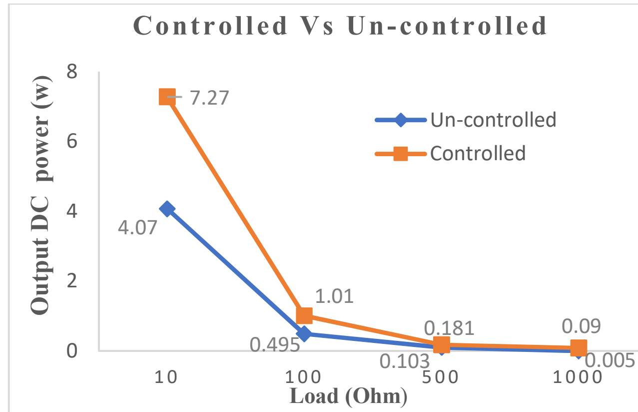


Figure 14. Output DC power Vs Load (Hardware)

4.4 Discussion of Results

Simulation and Hardware result seems that by using the controlled rectifier gives the better output power than the conventional uncontrolled system. The result comparison in table II, the output power is maximized to 52% compared with the conventional system. The simulation result is higher compared with the experimental result, because generator losses and time delay are not considered in simulation, current and induced voltage shape could be possible to keep in-phase in simulation.

PIC16F877A controller has employed for controlling action of all controls including Hysteresis and PI control via program. At the time of operation each rotor requires a power of 2000mA at its level flight, and four rotor needs 8000mA, Uncontrolled rectifier, Sepic converter needs 300mA, and for controlled rectifier, Sepic converter needs 500mA approximately. At 5400 rpm single harvester with un controlled rectifier produces 600 mA , and controlled rectifier produces 900 mA with minimum load resistance 10 ohm. If four rotors are connected parallel the current could be added and the flight duration for both rectifiers is compared in table III. It shows that the duration extended by controlled optimization method is 29 % higher than the uncontrolled rectifier method. This result is given in table IV tested in laboratory without calculating the overall payload of quadcopter.

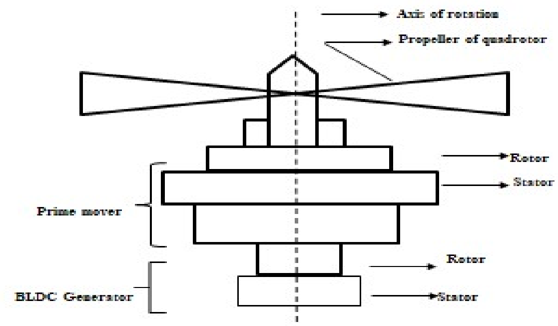
Table III Simulation Vs Hardware

	Simulation		Hardware	
Parameter	**Uncontrolled Rectifier**	**Controlled Rectifier**	**Uncontrolled Rectifier**	**Controlled Rectifier**
Speed [rpm]	5400	5400	5400	5400
Load Resistance [Ω]	100	100	100	100
Output DC Voltage[V]	11.77	13.00	7.4 V	10.1 V
Output DC Current [A]	0.0784	0.13	0.067A	0.1 A
Output Power [W]	0.9227	1.69	0.49W	1.01 W
Increase [%]	-	76.7	-	52

Table IV. Flight Duration Comparison

Parameter	Harvested Current (mA)	Total Voltage (V)	Total Power (W)	Total Amps Required for Flight operation	Actual Duration (mins) for 2200mA Battery	Harvested current in %	Extended Duration (mins)	Overall gain (%)
Uncontrolled rectifier	2400	15	36	8300	15.5	28.9	6.8	43.8
Controlled Rectifier	3600	15	54	8500	15.5	42.3	11.3	72.4

The BLDC generator is mounted to the rotor of the quadcopter should be fixed in same axis is an important one, to reduce the unwanted heat loss. The generator is mounted at the top of the rotor and tested the overall circuit test setup shown in Fig 15. For this setup the mounted bldc generator with the rotor is clamped using some external components and need special frame setup for wires to extract the harvested energy. Without changing the design frame, the harvester can be connected at the extended shaft of the rotor at the bottom, the structure and harvester connection is explained .



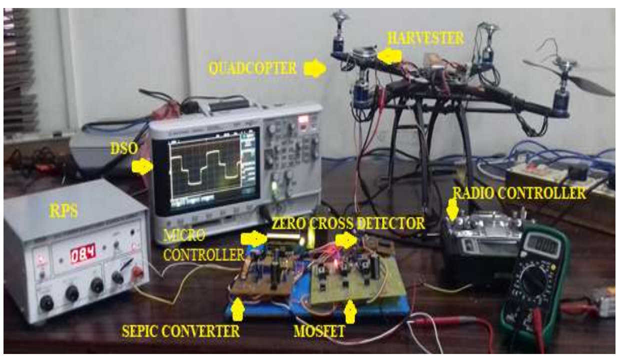


Figure 15. Hardware Test setup

Figure 16. Bottom fixed harvester

4.5 Harvester Connection

To increase he flight duration of the quadcopter using maximum source power is the main objective of this proposed plan. So, to connect the generator at exact place of the rotor of the Quadcopter is an important one. The shaft of both generator and motor should be joined with a single point attachment to rotate properly, if the alignment is not proper it will mislead the rotation and produce heat. All hardware test has done as per the existing harvesting system [1]. But to avoid the entangles of the wire the harvester can be placed at extended shaft part of the rotor. The diagram and picture shown in Fig 16, the connection of bottom fixed generator at the extended shaft of the rotor. The advantage of this connection is there is no any extra designing proposal not required. The output wires from the generator can be easily taken out without disturbing the propeller of the quadcopter.

5. CONCLUSION

An optimization technique for maximizing power harvested from the BLDC generator using the rotational propellers of the quadcopter has been demonstrated. By comparing the conventional (Uncontrolled)method with that of our proposed method it is evident that 52 % more output power is achieved using this technique. A MATLAB simulation for the energy harvesting was carried out and the results are validated using the laboratory experimental setup. It is also observed that compared to two boost converters used in earlier works single boost SEPIC converter has given equivalent performance and it is economical. It is concluded that from table IV , 42.35% of the harvested current is sufficient to increase the extra flight duration of quadcopter by 11.4 mins which is 29 % higher compared with conventional technique. Testing has occurred at a speed range of 5400 rpm. If the speed is increased further at flying time, the current generation level, charging of onboard battery can be improved further.

REFERENCES

1. Sowah, Moses A. Acquah, Abdul R. Ofoli Godfrey A. Mills and Koudjo M. Koumadi, "Rotational Energy Harvesting to prolong flight Duration of Quadcopters", IEEE transactions on industry applications, vol. 53, no. 5, September/October 2017
2. R. Krishnan, G.-H. Rim, "Modelling, simulation, and analysis of variable-speed constant frequency power conversion scheme with a permanent magnet brushless DC generator", IEEE Transactions on Industrial Electronics, vol. 37, No. 4, pp. 291 – 296,1990.
3. Lee, H.-W., Kim, T.-H., and Ehsani, M. "Power density maximization of the brushless DC generator', published on IEEE Pro Conf. IECON'03, Nov 2003, pp. 2162–2166.
4. H-W Lee, T-H Kim and Ehsani "Maximum power throughput in the multiphase brushless DC Generators", IEEE Electric power applications., vol.152, No.3, May 2005.
5. Hyung-Woo Lee, Tae-Hyung Kim, and Mehrdad Ehsani, "Practical Control for Improving Power Density and Efficiency of the BLDC Generator" IEEE transactions on power electronics, vol. 20, no. 1, Jan 2005.
6. G. Gatto, 1. Marongiu, A. Perfetto, and A. Serpi, "Brushless DC generator controlled by predictive algorithm," published in IEEE International conf. on clean electrical power, Aug 2009, pp.727-732.
7. Nikola Milivojevic, Mahesh Krishnamurthy, Ali Emadi, and Igor Stamenkovic, "Theory and Implementation of a Simple Digital Control Strategy for Brushless DC Generators "IEEE transactions on power electronics, vol. 26, no. 11, Nov 2011.
8. Halvaei Niasar, A.,Sabbaghean, A. "Design and implementation of a low-cost maximization power conversion system for brushless DC generator", Elsevier Ain Shams Engineering Journal, vol. 8, issue 4, pp. 571-580, Dec 2017.
9. Halvaei Niasar, A., Majid Moazzemi, "Design and Implementation of Direct Power Control System for Brushless DC Generator in Standalone DC Applications", Taylor & Francis , Electric Power components and systems, vol.45, no.7, pp 752-762, May 2017.
10. R. Sowah, M. A. Acquah, A. Ofoli, G. A. Mills, and K. M. Koumadi, "Rotational energy harvesting to prolong flight duration of quadcopters," IEEE trans. on Industrial Applications. pp. 1–7, 2015.
11. M.H. Rashid, "Power Electronics Handbook: Devices, Circuits, and Applications", Academic Press, Vol. 19, pp.525-530, 2006.
12. E. M. Suhara, M. Nandakumar, "Analysis of Hysteresis Current Control Techniques for Three Phase PWM Rectifiers." Published on IEEE Internatioal conf. on Signal Processing, Informatics, Communication and Energy Systems (SPICES), pp. 1-5, 2015.
13. Salinamakki Gurumurthy, Vivek Agarwal, Archana Sharma "Optimal energy harvesting from a high-speed brushless DC generator-based flywheel energy storage system "IET electric power applications, vol.7, issue.9, pp 693-700 ,Aug 2013
14. Reza Moradpour, Hossein Ardi , and Abdolreza Tavakoli "Design and implementation of new Sepic based high setup DC to DC converter for renewable energy applications" IEEE transactions on industrial electronics, vol. 65, no. 2, Feb 2018.
15. Yu Wang, Zhuoran Zhang, Li Yu, and Yuting Wang "Investigation of a Variable-Speed Operating Doubly Salient Brushless Generator for Automobile On-Board Generation Application "IEEE transactions on magnetics, vol. 51, no. 11, November 2015.
16. Texas Instrument "AN-1484 Designing A SEPIC Converter" Application Report SNVA168E, May 2006, Revised April 2013.
17. John Betten Applications Engineer, Texas Instrument "Benefits of a coupled-inductor SEPIC converter" High-Performance Analog Products www.ti.com/aaj 2Q 2011.

Siranthini Balraj obtained her BE (EEE) degree from Madurai Kamaraj University and ME (Power Systems Engineering) degree from Anna University. Currently she is a research scholar in the Department of Aerospace Engineering at MIT Campus, Anna University, Chennai, her research interest includes Power optimization, Power Applications of Avionics, All electric Aircraft.

E-mail: jesirithvi0512@gmail.com

Anitha Ganesan obtained her BE (EEE) degree from ACCET, Karaikudi, and MTech (Control & Instrumentation) degree from IITM, Chennai, and PhD degree in Avionics from Anna University, Chennai. She is working with the Division of Avionics, Department of Aerospace Engineering, MIT, Anna University, Chennai. Her research interest includes avionics, aircraft navigation, guidance and control systems, and image processing.

E-mail: anitha_g@annauniv.edu.