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Indirect Rotational Energy Harvesting System to Enhance the Power Supply of the Quadcopter

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ABSTRACT

This paper presents a simple energy harvesting system using unpowered freewheeling propellers mounted on the quadcopter without changing its actual design. Different layout configurations have been analysed and its thrust variation also tested to place the harvesting system in a suitable place in the quadcopter. The same and different size freewheeling propellers running coordination and its speed ratio are examined at various speed. To know the flow performance the freewheeling propellers Reynolds number is calculated. The freewheeling propellers rotational energy which creates an electrical power by means of micro BLDC generator. The harvested energy from the BLDC generator is maximized using three-phase MOSFET enabled controlled rectifier with hysteresis comparator. To meet the requirement of powering the quadcopter the output voltage from the generator is boosted and regulated using single DC-DC SEPIC boost converter with high voltage and current range. This energy can be directly charge secondary battery or power the other electronic payloads. The freewheeling propeller energy harvesting system has been implemented and tested in the laboratory at static condition which gives 51 per cent of harvested current.

Keywords: BLDC generator; Quadcopter; Energy harvesting; Unpowered rotors; Freewheeling propeller

1. INTRODUCTION

Recently, harvesting energy from rotating element has become a fascinating subject of research, specifically to power or extend the flight duration of unmanned aerial vehicle (UAV) or micro aerial vehicle (MAV) or Quadcopter. The researcher's main focus is on utilising the natural ambient sources like wind, solar, etc effectively in the aircraft for many purposes.

Sowah[1], *et al.* has proposed the rotational energy harvesting system to increase the endurance of the vertical take-off (VTOL) drone or quadcopter. The VTOL drone is preferred for this particular energy harvesting due to its advantages such as easy to build, provide stable flight, carry on excessive payloads. The energy harvesting has been investigated based on vibration[2] and solar energy harvesting[3] using fixed wing UAV. Hassanalian[4], *et al*. given new optimised design of multiple quantum well solar cells, to harvest the photovoltaic energy and proved that 30 per cent increase of flight endurance in MAV.Those researches conclude that, solar energy harvesting system is more effective in outdoor applications, which gives less efficiency in indoor due to poor illuminance. Moreover, fixed wing UAV gives better design structure to solar energy harvesting. But rotational energy harvesting system could be used in outdoor and indoor effectively suggested by Sowah[5], *et al.* tested the prototype of direct rotational energy harvesting system in quadcopter using micro BLDC generator. The generator was coupled with propeller and BLDC motor in a single point attachment. The system produced output power level of 4.98 W at 5400 rpm from four generators connected in parallel and gave 30 per cent of more energy and 10 mins extra duration in laboratory test without considering the payloads. This design would need extra entangles or components to fix the harvesting system in the quadcopter.

Rollefstad[6], *et al*. explained the new design structure of freewheeling unpowered rotors where the lift energy was improved by increasing the wing plan form area of the structure, thus the power drawn from the main battery reduced. In this system additional structure was added and it seems that additional components made the quadcopter design rather complex. The endurance[18] is an important issue in commercially used UAVs flying at various speeds. The propeller Reynolds number[16] play a vital role increasing the flight duration, means low Reynolds number insist to increase the flight duration.

As it has been already stated, this paper presents the energy harvested system by using freewheeling propellers with unpowered rotors being mounted on the quadcopter. The freewheeling propellers with rotors are knotted under the main motors without affecting the design structure of the quadcopters. The test has been done in static air condition, i.e., in laboratory without wind tunnel. During the time of test, necessary aerodynamic principles like thrust, speed, flow variations were taken into consideration. There are two main purposes to use the freewheeling propellers

a) They are used to increase the lift force at the time of operation
b) Connecting with the generators provides the harvesting energy to power the secondary battery or use to directly the other payload components.

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2. DESIGN CONSIDERATION AND SELECTION

The proposed harvesting system needs to be placed on the board without changing the actual design and structure of the quadcopter with minimum aerodynamic defects. To mount the freewheeling propeller on the appropriate place, three different layouts[7] have been taken for analysis and tested. Thrust, weight, power, and speed values have been measured for all the layouts individually using the test bench set-up as shown in Fig. 1. The results provide better suggestions regarding the suitable place to fix the harvesting system. Those layouts were compared and the inference is presented in Table 1.

Considering the requisites of minimum aerodynamic defects, out of three layouts explained, the second layout has been chosen for this proposed harvesting system. The thrust in terms of weight (gm) for motor with main propeller, motor and freewheeling propeller with generator and then load have been tested separately for various speeds. For different speeds the thrust variation (gm) and input power (w) have been noted and plotted in a graph as shown in Fig. 1. The variations for the three modes are almost linear and it has been shown that the thrust loss is minimum or less for the selected layout 2.

3. SYSTEM DESIGN IMPLEMENTATION AND REQUIREMENTS

As per the selected layout 2, the harvester is designed and the proposed model type is shown in Fig. 2. The rotational energy can be converted into electrical energy by using the transduction mechanism. A suitable generator is needed to convert the harvested mechanical energy into electrical. Amongst all generators permanent magnet Brushless Direct Current Generator[8] (BLDCG) is the best one to convert rotational energy into electrical with good efficiency. It has high power density, light weight, compactness, easy control, and lesser maintenance. The freewheeling propeller is connected to the micro BLDC generator without changing the actual design of the quadcopter and the proposed architecture is shown in Fig. 3.

According to the electrical energy generation, the BLDC generator's three-phase output is of alternating current (AC) nature, which is required to be converted into direct current (DC) output. The conventional (diode) uncontrolled three-phase rectifier[1] has its own limitations such as no control over the parameters and low power per ampere capability.

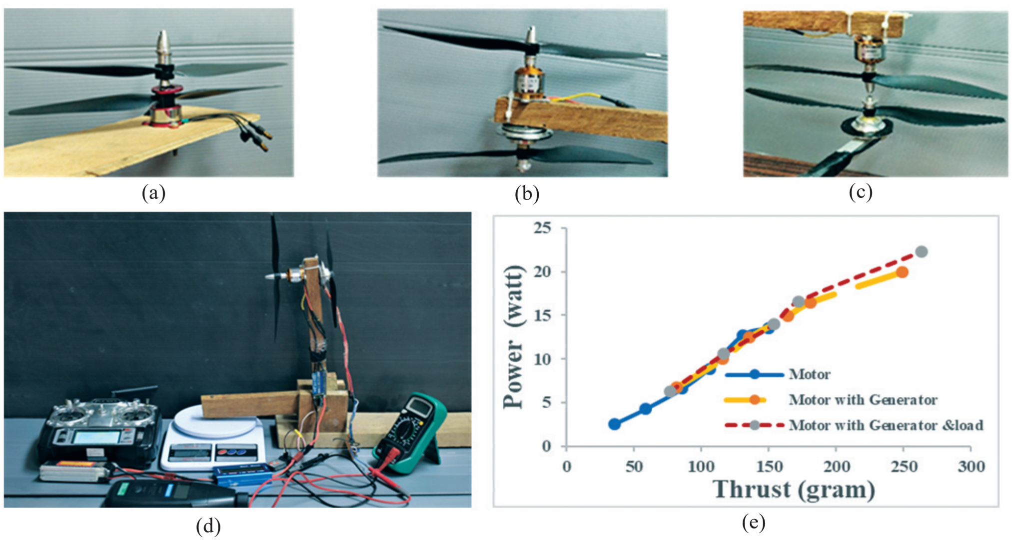
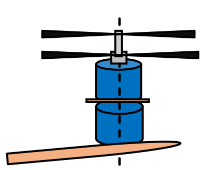
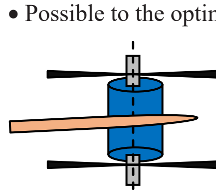
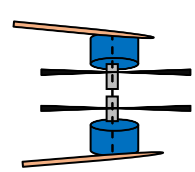


Figure 1. Different layouts ((a), (b) and (c)), (d) Test set-up, and (e) Power vs thrust.

Table 1. Different layout comparisons

	Layout 1	Layout 2	Layout 3
Connection	Motors along with Freewheeling propellers in same single lengthy shaft (*Contra rotating*)	Motors and freewheeling propellers are mounted at the common supporting structure (*Up and down*)	Motors and freewheeling propellers are mounted in a separate column facing each other (*Opposite*)
Advantage	• Clear inlet • Possible to adjust the distance • Does not change the original design of quadcopter.	• Thrust and torque separated • Not having complex mechanics	• Thrust and torque separated • The distance between the propellers were freely adjustable
Disadvantage	• Lengthy inner shaft • Complex physical setup and mechanics • Very hard to separate the torques and thrusts	• The distance between two propellers is too large • Distance cannot be adjustable • Possible to the optimum distance	• Strong • Rigid frame and supports need
Layout design			

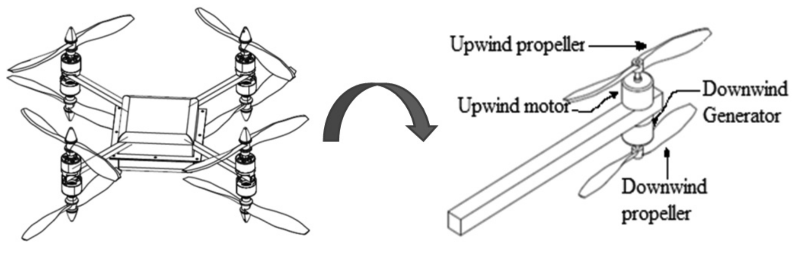


Figure 2. Proposed model prototype.

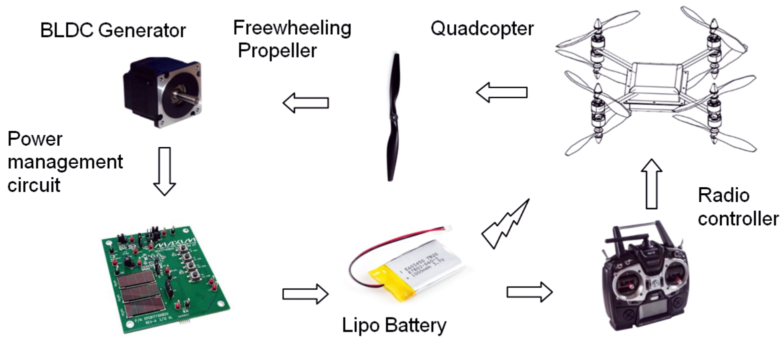


Figure 3. Proposed system architecture.

So, it cannot maximize the power generated from the BLDC generator[9]. The power maximisation[10] from the BLDC generator is possible only with the use of controlled rectifier[11] which is enabled with three-phase MOSFET circuit. In this proposed system both uncontrolled and controlled rectifiers are separately tested for comparison and the results are presented. After the rectification, to ensure the stable voltage supply to the charging unit (battery) or other electronic payloads, the voltage needs to be boosted using single stage DC to DC boost converter named as single ended primary inductor converter (SEPIC).

As per the dynamic behaviour of the quadcopter, when each BLDC motor's speed is varied, the freewheeling propeller's speed also gets varied and it leads to change in the harvested output. With a lot of advantages and control actions, whatever the variation in the output DC voltage, SEPIC boost converter regulates the DC voltage to a much higher value and high current capabilities. The generated energy could be stored in the secondary battery or used to power directly the other electronic payloads (camera, sensor etc.,) which would reduce the main power consumption and cause to increase the endurance. Another way is, the harvested power could be directly used to charge the main on-board battery, but special charger unit would be needed and which will increase the additional payload.

3.1 Brushless Direct Current Generator and Power Maximisation Technique

Permanent magnet BLDCG is of two types: one is sinusoidal type (Permanent magnet synchronous generator-PMSG) and the other one is trapezoidal type (BLDCG) having 15 per cent of higher power density compared to PMSG. Generally, generators are characterised by their back-EMF constant (K_e) and winding resistance (R). The induced back-EMF of the generator is given in the Eqn. (1)[11].

$$
\begin{aligned}
e_a &= R_a i_a + (L_s - L_m)\frac{\delta i_a}{\delta_t} + V_a \\
e_b &= R_b i_b + (L_s - L_m)\frac{\delta i_b}{\delta_t} + V_b \\
e_c &= R_c i_c + (L_s - L_m)\frac{\delta i_c}{\delta_t} + V_c
\end{aligned} \tag{1}
$$

where e_a, e_b, e_c Back-EMF of phase *a, b*, and *c* [*V*]
i_a, i_b, i_c Stator current of phase *a, b,* and *c* [*A*]
V_a, V_b, V_c Terminal voltage of phase *a, b, c* [*V*]
R_s Per phase Armature resistance [Ω]
L_s, L Per phase armature self, mutual inductance [*H*]

The induced back-EMF in the three phase BLDC generator is in trapezoidal waveform and due to the structure of the machine design it contains harmonics. To reduce the harmonics and maximize the power a three phase MOSFET configured rectifier circuit is incorporated in the system.

To control the gate signal, hysteresis comparator is engaged with pre-set band limit values. The main objective of this circuit is to maximise the energy extracted from the BLDC generator and to deliver the actual power per ampere to the DC link side. The commutation of BLDC generator relies on its rotor position, so sensorless zero cross detection technique[12] is applied to detect the position of the rotor. The output DC voltage is fed back to the PI controller[11] and the error signal is coupled with the reference back-EMF signal. This estimated output is given to the hysteresis comparator[13] which reduces the ripples from the signal and produces the gate pulses using the logic circuit. After the triggering of the gate pulses SEPIC[14] converter is employed with simple controller and active components allowing a range of DC voltage to be maintained constant. This converter is able to perform both buck-boost actions and its minimum ripple current increases the average value of DC current and DC voltage with higher range[15]. The BLDC generator power maximisation circuit with controlled rectifier is shown in Fig. 4.

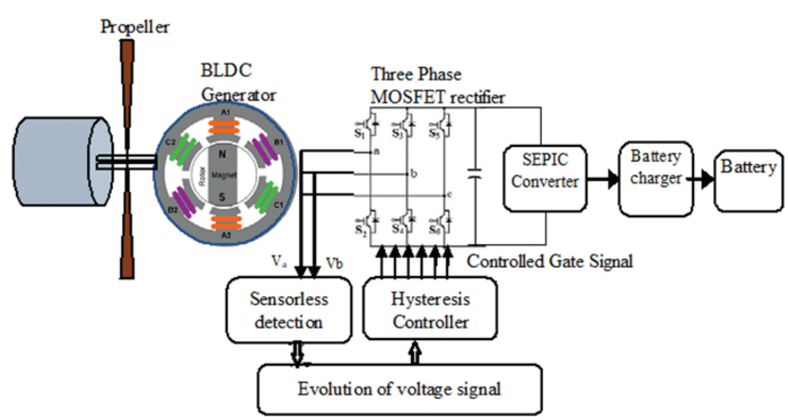


Figure 4. Power maximisation circuit.

3.2 Propellers Co-ordination and rpm Ratio

To coordinate and to initiate the initial torque to the freewheeling propellers at the time of start, one factor must be considered i.e., the distance between the two propellers.

The distance between the propellers from the trailing edge of main propeller and the leading edge of freewheeling propeller was measured as 8.5 cm and this distance was kept as the minimum distance. This distance is important for the speed ratio test, and the test was conducted for the pair of identical or same size propellers, designated as 10 x 4.5 inch i.e., diameter 10 inch, pitch variation 4.5 inch and different size propellers as 10 x 4.5 inch and 12 x 4.5 inch. The set-up is shown in Figs. 5(a) and 5(b). Both propellers were right runners or clockwise direction rotation propellers.

The rotational speed ratio was tested and the results are given in Fig. 6. The identical or same size propellers have given the 1:0.35 ratio of speed, freewheeling propeller caught 35 per cent of the main propeller speed and the different size propellers have given 1: 0.6 ratio. The speed range varied from minimum 2000 rpm to maximum 9000 rpm. Due to technical limitations in the laboratory, the testing was performed within the above mentioned speed range. The purpose of this test was to find how much speed had been attained by the freewheeling propellers at the time of harvesting. Results showed that the different size propellers gave the best ratio compared with the identical propellers. Even good speed ratio would enhance the efficiency of the harvesting system.

3.3 Reynolds Number for Different Propellers

Propeller plays an important role in quadcopter in determining the power utilisation for necessary thrust[17]. Propeller's design and dimension is the main endurance reduction factor of the quadcopter. It is proved that low Reynolds number propeller increases the quadcopter endurance[16]. This dimensionless value is useful to predict the flow pattern of air passing over the propellers. Systems that operate at the same Reynolds number will have the same flow characteristics even if the fluid, speed, and characteristic lengths vary. The Reynolds number is calculated from the equation given,

$$R_e = \frac{\rho \Omega r c}{\mu} \tag{2}$$

ρ Density of air, at standard atmosphere it is 1.225 kg/m^3,

μ Viscosity of air, at standard atmosphere it is 1.81 x 10^{-5} Pascal

Ω Angular velocity is calculated by

$$\Omega = \frac{2\Pi N}{60} \tag{3}$$

c Chord of the propeller

r Radius of the propeller

In general Reynolds number range for UAV is between 10^3 and 10^5 for having smooth and laminar flow. Beyond this range the flow transition would be from laminar into turbulent. Laminar is smooth, constant flow of air. Turbulent flow is random and chaotic. If the speed attains the maximum value, Reynolds number will change and cause the turbulent flow. The variation of the propeller's Reynolds number with different speed range has been tested and the results presented in Fig. 7, show that Reynolds number of both propellers are increasing with respect to speed and the flow is steady and smooth.

4. HARVESTING RESULT

To validate the proposed harvesting system an experimental test-bed for overall system was designed,

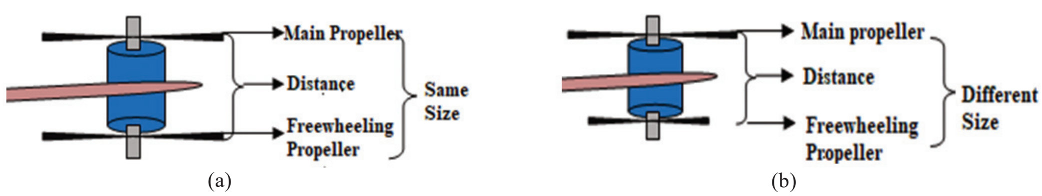


Figure 5. (a) Same size propeller (b) Different size propeller.

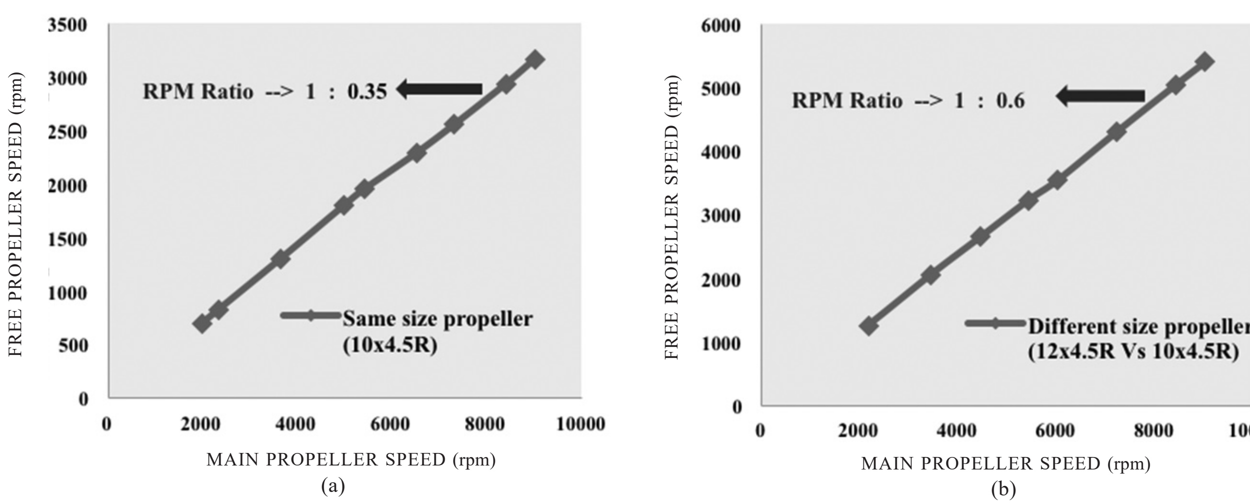


Figure 6. (a) Speed Ratio: Same size propellers and (b) Different size propellers.

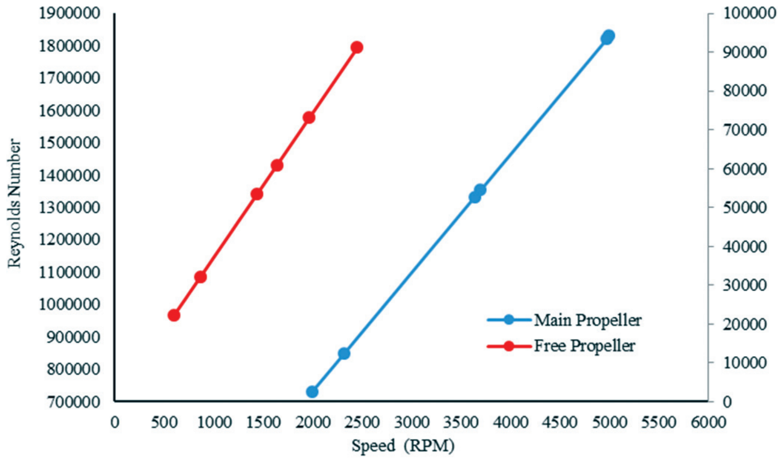


Figure 7. Propeller Reynolds number Vs Speed (rpm) for different size propellers.

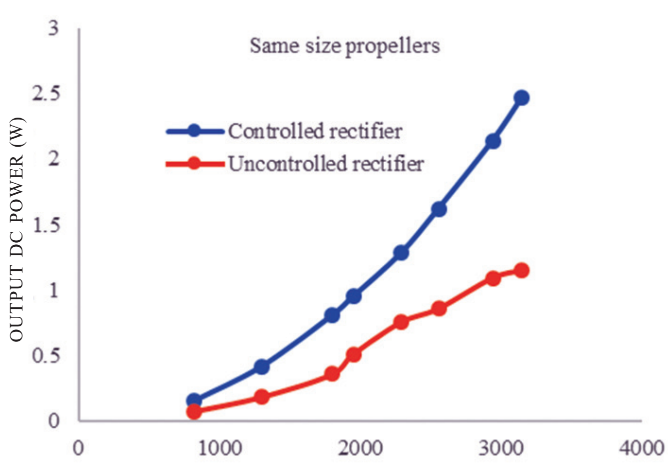
implemented, and tested in the laboratory with static open-air condition. The BLDC motor of the quadcopter ran at minimum 1000 rpm to maximum 9000 rpm, and due to the technical limitations inside the laboratory it was not possible to run the quadcopter beyond this range. Based upon the speed ratio, the same and different size propellers were coordinated to run along with their BLDC motor and energy was harvested. The three-phase output of the BLDC generator was connected to the uncontrolled and controlled rectifiers to convert AC into DC output; both rectifiers were tested separately and the corresponding results are presented in Table 2. A comparative study between the outputs of the uncontrolled and the controlled rectifier design for the same and different size propellers was performed to understand the extent of possible power maximisation in each case. The test was conducted using resistive load of 10 Ω and the ripples were reduced using a 3000 μF capacitor as the filter. The Table 2 indicates that with the main propeller speed being fixed at 9000 rpm, the same size propellers attained a speed of 3150 rpm, whereas the different size propellers attained 5400 rpm. For various speeds the controlled and the uncontrolled output DC power for freewheeling same and different size propellers was tested and shown in Fig. 8. The results revealed that when the speed was gradually increased, the corresponding DC output power also increased proportionally. It could be noted that the controlled rectifier design gave better results in terms of output power compared with the uncontrolled rectifier design.

The output power increased to 40.9 per cent compared with the uncontrolled output power for the same size propellers and 50.2 per cent for different size propellers. These results confirmed that the controlled rectifiers with hysteresis comparator would be suitable for maximising the output power from the BLDC generator.

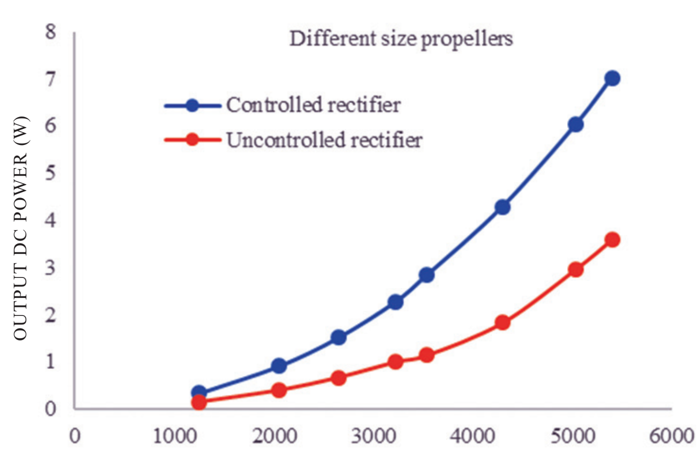
The harvested Energy can be used directly to charge the

Table 2. Output test result comparison

Parameter	Same size propeller		Different size propeller	
	Uncontrolled rectifier	Controlled rectifier	Uncontrolled rectifier	Controlled rectifier
Main propeller speed [rpm]	9000	9000	9000	9000
Free propeller speed [rpm]	3150	3150	5400	5400
Load resistance [Ω]	10	10	10	10
DC output voltage[V]	4.6	5.8	7.2	9
DC output current [A]	0.22	0.42	0.49	0.78
DC output power [W]	1.012	2.473	3.528	7.02
Increase [%]	-	40.9	-	50.2



(a)



(b)

Figure 8. (a) Freewheeling propeller speed *vs* output DC power same size propellers and (b) Different size propellers.

secondary battery or to charge the other electronics payloads. The DC voltage output generated was minimum 2V and maximum 7V. To meet the quadcopter's battery requirement this voltage was boosted upto 15V without much variation in the DC current using specially designed SEPIC converter. The SEPIC converter test result is shown in Fig. 9. This boosted voltage would be sufficient to charge the main onboard Lipo battery of 2220 mAh, 12.4 V. But a special charger with balancer circuit will be needed to charge the LiPo battery which will add additional payload. However, the other power electronics payloads of the quadcopter can utilise this harvested energy directly without the need of any special charging unit.

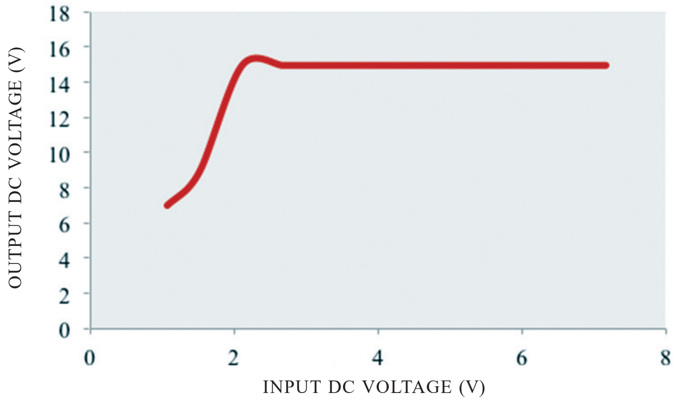


Figure 9. DC to DC boost SEPIC converter output.

From the test results, the harvested current was taken into account to calculate the flight duration[18] possible using the proposed system. Current requirement for individual BLDC motors, harvesting system, ESC control and other power management systems excluding the overall payload was estimated approximately and found to be around 8300 mA to 8,500 mA which was drawn from the 2200 mA, 11.1V Lipo battery continuously during the operation. For the above estimate, the flight duration was calculated as 15.5 minutes. As per the harvested current at the maximum rpm shown in Table 2, for both rectifiers and propellers the flight duration was calculated and presented as a bar graph Fig. 10.

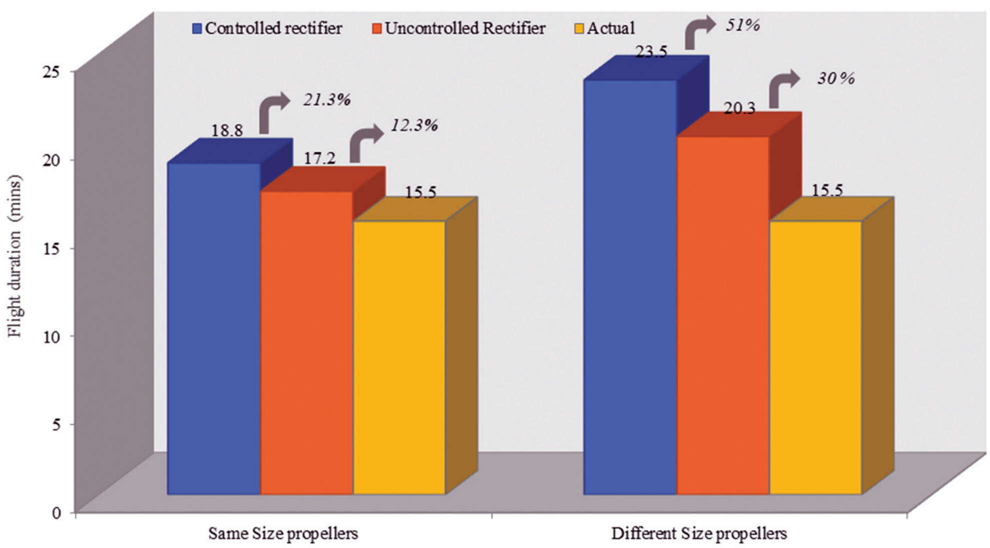


Figure 10. Flight duration comparison (based upon harvested current output).

In the case of the same size propellers, harvested current could add 21.3 per cent of its actual current to the quadcopter power supply which translated to about 3.3 mins extra duration. This was achieved to connect all four generators in parallel. For different size propellers, harvested current could add 51 per cent of its actual current drawn and it translated to about 8 mins of extra duration. Therefore, the overall comparative study led to the conclusion that the different size freewheeling propellers harvesting system using controlled rectifiers gave better performance than the same size freewheeling propellers. The overall laboratory test set-up is shown in Fig. 11.

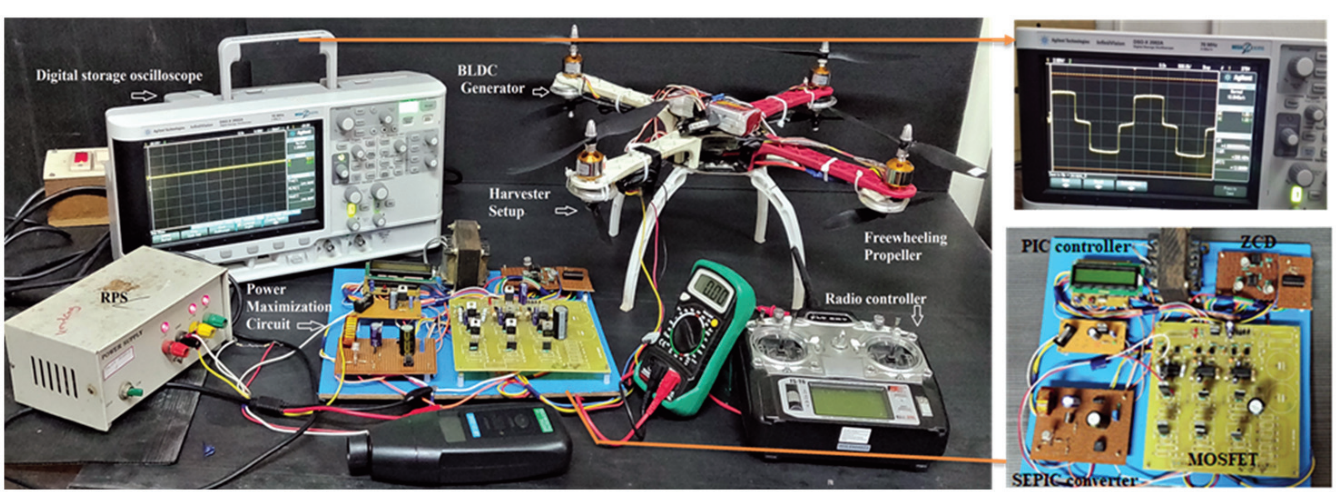


Figure 11. Freewheeling energy harvesting system laboratory test set-up.

5. CONCLUSIONS

This work has demonstrated the rotational energy harvesting system by using freewheeling propellers and micro BLDC generators. The aspects of aerodynamic stability have been analysed to choose the best layout for the harvesting system. Layout design has been established and tested in quadcopter at laboratory. Speed ratio between the propellers has proved that the different size propeller achieves more speed compared with the same size propellers. The calculation of the Reynolds number of the freewheeling and the main propeller helps to understand the flow characteristics of harvesting system. In power maximisation, uncontrolled and controlled rectifier output results have been compared for the same and the different size propellers and it is learnt that the different size propellers with controlled rectifier harvesting system give the best performance. The static laboratory experimental results show an increase of 51 per cent of harvested current over the actual current which results in 8 mins of extra flight duration with the use of different size propellers.

6. FUTURE SCOPE

Any fault or failure in the main BLDC motor is very critical to the safety of the quadcopter and the BLDC generator which is proposed in the harvesting system having the capability to be operated as a motor with the appropriate reversal of the power supply and ESC control could be used to overcome this criticality. Using the freewheeling propellers, the quadcopter could be landed safely. However, aerodynamic stability, switching time, transition time to change generator to motor, sensors action etc. need to be analysed to implement this proposal. If the analysis gives positive and constructive results, then the proposed harvesting system could be used for fault tolerant control also.

REFERENCES

1. Sowah, R.; Acquah, M.A.; Ofoli, A.; Mills, G.A & Koumadi, M. Rotational Energy Harvesting to prolong flight Duration of Quadcopters. *IEEE Trans. Industry Applications*, 2017, **53**(5), 4965-4972. doi: 10.1109/TIA.2017.2698037.
2. Anton, S.R & Inman, D.J. Vibration energy harvesting for unmanned aerial vehicles, In Proceedings of the SPIE 6928, Active and Passive Smart Structures and Integrated Systems, 2008. doi: 10.1117/12.774990.
3. Anton, S.R.; Erturk. A. & Inman, D.J, Energy harvesting from small unmanned air vehicles. *In* IEEE. International conference of application of ferro electrics, 2008. doi: 10.1109/ISAF.2008.4693947.
4. Hassanalian, M.; Radmanesh, M. & Sedaghat, A. Increasing flight endurance of MAVS using multiple quantum well solar cells. *Int. J. Aeronaut. Space Sci*., 2014, **15(2)**, 212–217. doi: 10.5139/ijass.2014.15.2.212.
5. Sowah, R.; Acquah, M.A.; Ofoli, A.; Mills, G.A. & Koumadi, M. rotational energy harvesting to prolong flight duration of quadcopters. *IEEE Society Annual Meeting*, 2015, 1–7.
6. Rollefstad, S.B. Unmanned aircraft system (UAS) with active energy harvesting and power management, US patent No: US 9,527,588 B1, 2017, December 27.
7. Storch, V.; Brada, M & J., Nozicka, Experimental setup for measurement of contra rotating propellers, Research gate Prague, 2017, 15-17. doi:10.14311/TPFM.2017.036.
8. Lee, H.W.; Kim, T. H.& Ehsani, M. Maximum power throughput in the multiphase brushless DC Generators. *IEEE Electric Power Applications*, 2006, **152**(3), 1762 - 1768. doi: 10.1049/ip-epa:20045051.
9. Lee, H.W.; Kim, T. H.& Ehsani, M. Practical Control for Improving Power Density and Efficiency of the BLDC Generator, *IEEE Trans. Power Electron*, 2005, **20**(1), 192-197. doi: 10.1109/TPEL.2004.839805.
10. Salinamakki, G.; Vivek, A. & Archana, S. Optimal energy harvesting from a high-speed brushless DC generator-based flywheel energy storage system, *IET Electric Power Applications*, 2013, **7**(9), 693-700. doi: 978-1-4799-8586-9.
11. Halvaei Niasar, A. & Sabbaghean, A. Design and implementation of a low-cost maximization power conversion system for brushless DC generator. *Ain Shams Eng. J.*, 2017, **8**(4), 571-580. doi: 10.1016/j.asej.2015.11.001.
12. Kim, D.; Lee, K.W. & Kwon, B. Commutation torque ripple reduction in a position sensorless brushless DC Motor Drive. *IEEE Trans. Power Electron.,* 2006*,* **21**(6), 1762-1768. doi: 10.1109/TPEL.2006.882918.
13. Chun, T. W.; Tran, Q.V.; Lee, H.H.& Kim, H. Sensorless control of BLDC motor drive for an automotive fuel pump using a hysteresis comparator. *IEEE Trans. Power Electron,* 2014, **29**(3),1382–1391. doi: 10.1109/TPEL.2013.2261554.
14. Moradpour, R.; Ardi, H. & Tavakoli, A. Design and implementation of new SEPIC based high setup DC to DC converter for renewable energy applications, IEEE conference*,* 2018, **65**(2), 1290-1297. doi: 10.1109/TIE.2017.2733421.
15. Texas Instrument, AN-1484 Designing A SEPIC converter. *Application Report SNVA168E*, 2013.
16. Brandt, J.B.; Michael, S. & Selig, Propeller performance data at low Reynolds numbers. *In* AIAA, Aerospace Science meeting, 2011, 4-7.
17. Deters, R.W.; Ananda, G.K. & Selig, M.S. Reynolds number effects on the performance of small-scale propellers. *In* AIAA Aviation and Aeronautics Forum and Exposition (Aviation 2014), 2014, 21-51.
18. Gatti, M.; Giulietti, F. & Turci, M. Maximum endurance for battery-powered rotary-wing aircraft. *Aerosp. Sci. Technol.,* 2015, **45**, 174–179, doi: 10.1016/j.ast.2015.05.009.

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She has contributed in the design and development of Freewheeling energy harvesting system and interpretation of results.

Dr Anitha Ganesan obtained her BE (EEE) from ACCET, Karaikudi, and MTech (Control and Instrumentation) from IITM, Chennai, and PhD in Avionics from Anna University, Chennai. Currently she is working as Associate Professor in Division of Avionics, Department of Aerospace Engineering, MIT, Anna University, Chennai. Her areas of interest are: avionics, aircraft navigation, guidance and control systems, and image processing.
She has contributed in the design and development of research overall methodology and guidance to improve the proposed method.