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DEVELOPMENT OF A PROTOTYPE MICRO WIND ENERGY SYSTEM WITH ADJUSTABLE BLADE PITCH FOR EXPERIMENTATION PURPOSES AT LABORATORY LEVEL

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In this paper, the design of an efficient, operational and productive model of micro wind energy system has been proposed for experimentation purposes at laboratory level. The proposed model constitutes a proficient Horizontal Axis Wind Turbine (HAWT) model with multi-stage pulley system as a gear box and adjustable blade pitch. The wind turbine is coupled to Axial Flux Permanent Magnet Generator (AFPMG). The power density parameter of fabricated AFPMG has been improved to 35.7%. A wind tunnel is placed in front of wind turbine which behaves as the operational source of wind for proposed model. Multiple case studies: demonstration of different components of wind energy system, effect of variable wind speed, effect of variable blade pitch, effect of variable electrical loading, effect of variable pulley ratio, voltage regulation of AFPMG, runaway speed test of HAWT and peripheral speed test of AFPMG are successfully performed on this model. The results obtained from experiments show that proposed model is well suited for experimentation purposes at laboratory level.

Keywords: Wind energy system, Axial flux generator, Blade pitch, Wind turbine, Permanent magnet generator

1. Introduction

In this modern era, the renewable energy resources are replacing the conventional energy sources for electricity production because of the tremendously increasing cost and rapidly decreasing sources of fossil fuels. Out of various renewable energy resources, wind energy represents one of the cheaper sources of electrical energy production. The conversion of wind energy to electrical energy is carried out by deploying Wind Energy System (WES) which has two major operational components: Wind Turbine and Electrical Generator [1]. The wind turbine is composed of a propeller with three blades which are shaped aerodynamically and a shaft [2]. It converts wind energy to rotational mechanical energy. The electrical generator acts as intermediate energy conversion device which converts rotational mechanical energy to electrical energy. In general, the wind turbine and electrical generator are coupled through gear box which acts as intermediate shaft speed and mechanical torque conversion device [3].

There are two types of wind turbines: Horizontal Axis Wind Turbine (HAWT) and Vertical Axis Wind Turbine (VAWT) [4, 5]. Generally, the HAWT has higher value of coefficient of power and efficiency than VAWT [6]. There are two well-known types of electrical generators in literature for wind turbine applications as: Radial Flux Permanent Magnet Generator (RFPMG) and Axial Flux Permanent Magnet Generator (AFPMG) [1, 7]. The AFPMG is suitable for wind turbine applications because it has higher power density, low operating shaft speed, compact structure, minimized losses and higher efficiency [1, 7-9].

The Wind Energy System (WES) proposed in this research paper is composed of HAWT and AFPMG coupled through multi-stage pulley system as gear box which is shown in Figure 1.

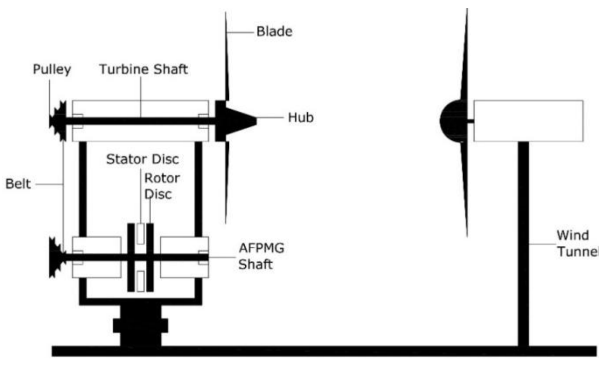

Figure 1. Proposed layout of micro WES model.

The fabricated AFPMG model has higher power density (113.82 W/kg) than 300 W RFPMG model discussed [1] (73.2 W/kg). The proposed design of WES is suitable for laboratory level for experimentation purpose. The WES has been fabricated and different types of experiments have been performed on this model.

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2. Design of Micro Wind Energy System (WES)

Basically, the WES consists of HAWT and AFPMG. The design considerations and procedures of both HAWT and AFPMG are presented in detail in subsequent sub sections.

2.1 Horizontal Axis Wind Turbine (HAWT)

The HAWT is the most widely used and addressed type of wind turbine in literature [2, 3]. The wind turbine is mechanical energy conversion device which converts wind energy into rotational mechanical energy. The extractable mechanical power (P_m) at the shaft of wind turbine from wind is expressed as given by [1, 3, 8, 10].

$$P_m = \frac{1}{2}\rho_a A_s V_w^3 C_p(\lambda, \beta) \quad (1)$$

where

ρ_a = Air density (kg/m^3)

A_s = Swept area of turbine blades (m^2)

V_w = Wind speed (m/sec)

λ = Tip speed ratio

β = Blade pitch (deg)

C_p = Power coefficient

The area that propeller of wind turbine covers in the air and faces the effective air, is represented as swept area. Swept area can be calculated, simply, by computing the area of circle when blade length is known.

$$A = \pi R^2 \quad (2)$$

where

R=Length of wind turbine blade (m)

The swept area of wind turbine is shown in Figure 2.

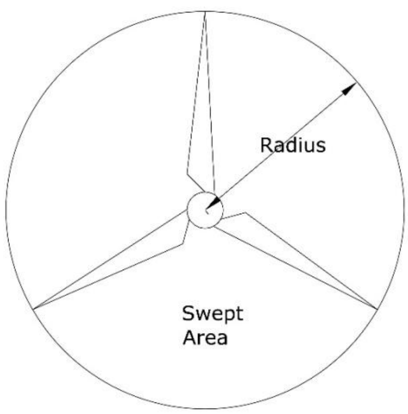


Figure 2. Swept area of propeller.

Tip Speed Ratio (λ) is defined as the ratio of speed of tip to speed of wind. The value of TSR varies during the operation of wind turbine and depends on the number of blades of wind turbine [11, 12].

$$\lambda = \frac{V_T}{V_w} \quad (3)$$

where

V_T = Blade tip speed (m/sec)

Blade tip speed of wind turbine is given by [1]

$$V_T = \frac{2\pi R}{60} n \quad (4)$$

where

R = Length of wind turbine blade (m)

n = Shaft speed of wind turbine (rpm)

Tip speed ratio (λ) is function of shaft speed of wind turbine and wind speed as given by:

$$\lambda(n, V_w) = \frac{2\pi R}{60} n \frac{1}{V_w} \quad (5)$$

The extent of extractable power from wind is specified in terms of power coefficient (C_p). The power coefficient of wind turbine depends on number of blades of turbine and blade pitch angle. For a certain number of blades and blade pitch, the power coefficient varies with the variation of tip speed ratio[13]. Power coefficient is basically the factor less than 1 that shows the extent of extracted power from wind to shaft of wind turbine. The maximum value of C_p factor is 0.59 which is Betz limit [3, 5]. Wind turbines cannot operate above this limit. C_p is function of two parameters; tip speed ratio and blade pitch angle as given by:

$$C_p = (\lambda, \beta) \quad (6)$$

C_p can be modeled in different ways using suitable mathematical equation which describes this parameter [14]. C_p can be represented by multi-curve graph as shown in Figure 3.

Usually, the conventional wind turbines operate at low shaft speed [3]. Gearbox is the device which enhances the shaft speed of wind turbine and electrical generator is coupled at high speed shaft [3]. The specifications and dimensions of wind turbine are given in Table 1.

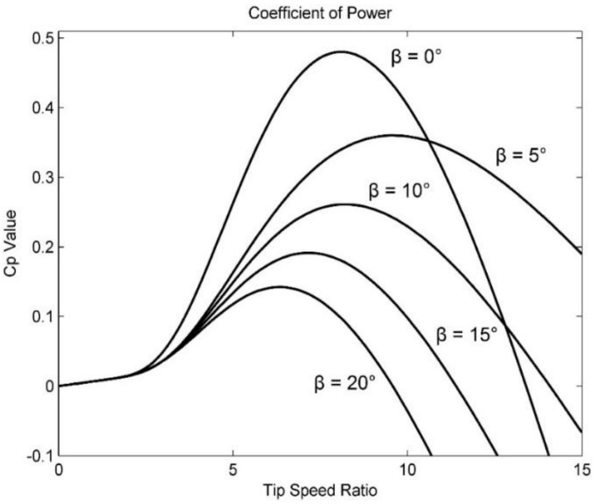


Figure 1. C_p Characteristics

Table 1. Specifications and dimensions of wind turbine.

No.	Rating	Value
1	Blade length	0.508 m
2	Number of blades	3
3	Cut-in wind speed	4 m/sec
4	Rated wind speed	8 m/sec
5	Rated Shaft speed	375 rpm
6	Rated Blade Pitch	20°

2.2 Axial Flux Permanent Magnet Generator (AFPMG)

The AFPMG is rotating electromechanical device which converts rotational mechanical energy into electrical energy. The axial flux machines are type of alternating current (AC) machines in which main field flux is parallel to shaft of machine. The axial flux machine consists of discs specifying stator disc sandwiched between rotor discs. Most often in literature, single stage axial flux machine is composed of one stator disc with two rotor discs on both sides of stator disc [7-9]. Single stage axial flux machines may be designed as single phase or 3-phase axial flux machines. In this research paper, single phase and single stage AFPMG is considered. The name plate ratings of axial flux machine are to be specified first before starting the design procedure as in Table 2.

Table 2. Name plate ratings of AFPMG.

No.	Rating	Value
1	Voltage	18 V
2	Frequency	50 Hz
3	Shaft Speed	750 rpm
4	Max. Current	2 Amp
5	Output Power	28 W

The rated electrical power of AFPMG is given by general purpose sizing equation [15, 16]

$$P_r = \frac{1}{1+K_\phi}\frac{m}{m_1}\frac{\pi}{2}K_e K_i K_p \eta B_g A \frac{f}{p}(1-\gamma^2)\frac{1+\gamma}{2}D_o^3 \qquad (7)$$

where

K_ϕ Ratio of electrical loading on rotor and stator of generator

m = Number of phases of generator

m_1 = Number of phases per stator disc

K_e = emf factor which also incorporates the winding distribution factor K_w

K_i = Current waveform factor

K_p = Electrical power waveform factor

η = Generator Efficiency

B_g = Air-gap flux density (T, Wb/m^2)

A = Electrical loading in ampere conductor per meter of stator disc (A/m)

f = Supply frequency (Hz)

p = Number of pole pairs of machine

γ = Ratio of inner to outer diameter of stator disc

D_o = Outer diameter of stator disc (m)

The expression for peak value of rated phase voltage produced across the terminals of AFPMG is given by: [15]

$$E_p = K_e N_t B_g \frac{f}{p}(1-\gamma^2)D_o^2 \qquad (8)$$

where

N_t = Number of turns of coil.

The expression for peak current of rated phase current is given by [15]

$$I_p = \frac{1}{1+K_\phi}K_i A\pi \frac{1+\gamma}{2}\frac{D_o}{2m_1 N_t} \qquad (9)$$

Before computing the design parameters, the initial design parameters have to be specified. The initial design parameters include the value of $K_\phi=0$ which shows that there is no rotor winding because permanent magnets are used on rotor disc [15]. The values of *m* and m_1 show that design computation has been conducted on per phase and per stage basis of stator disc. For sinusoidal waveform of output, the values of K_i and K_p are taken from data of typical prototype waveforms [16]. The design procedure has been followed and generator specifications and dimensions have been computed which are given in Table 3.

Table 3. Specifications and dimensions of AFPMG.

No.	Specification / Dimension	Aspect / Value
1	Number of poles	8
2	Number of coils of stator disc	8
3	Winding connection	Begin-to-begin connection
4	Coil pitch	1-4 coils
5	Winding type	Block winding
6	Number of magnets per rotor disc	8
7	Outer diameter of stator disc	150 mm
8	Inner diameter of stator disc	40 mm
9	Number of turns of coil	130
10	Length of Magnet	20 mm
11	Width of Magnet	12 mm
12	Thickness of Magnet	5 mm
13	Rotor disc diameter	110 mm
14	Axial length of stator disc	10 mm
15	Axial length of rotor disc	5 mm
16	Segment Arc	45°
17	Slot Arc	11.25°
18	Coil Arc	45°
19	Inter-magnet Displacement	45°
20	Active Mass of AFPMG	0.246 kg
21	Power Density	113.82 W/kg

An important parameter of AFPMG is power density which is the ratio of power rating of machine to active mass of machine. The high value of power density parameter reflects in reduction of machine mass in kilograms [1]. The fabricated AFPMG has been compared in design parameter of power density with existing RFPMG model addressed [1]. The comparison is listed in Table 4.

Table 1. Generator Results Comparison

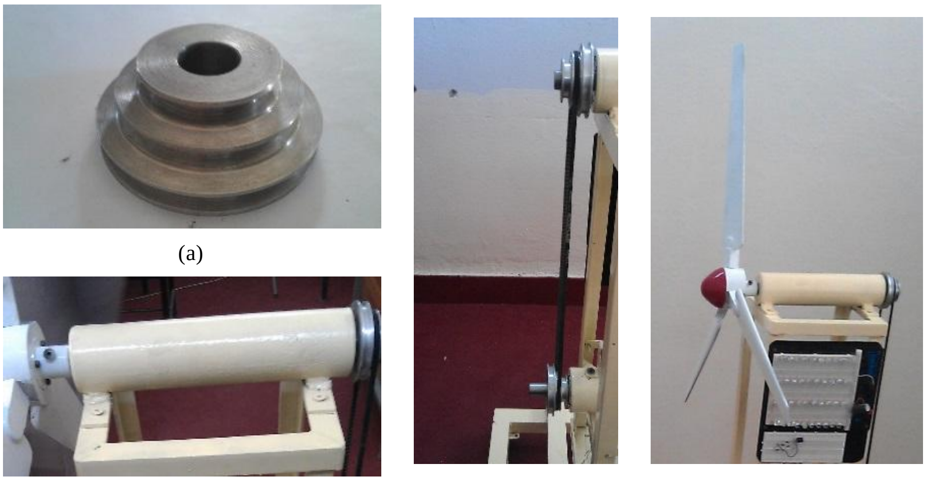
Parameter	Fabricated AFPMG Model	300 W RFPMG [1]
Power Density (W/kg)	113.82	73.2

3. Fabrication of Wind Energy System Model

After computing the design parameters, specifications and dimensions of wind turbine and AFPMG (Tables 1 and 3), the fabrication process of WES was started. First, the wooden pattern for blade of wind turbine has been prepared which is shown in Figure 4a. The three blades of wind turbine have been casted with aluminum material as shown in Figure 4b. The internal hub was manufactured and three identical blades have been attached at 120° apart to the hub. A provision is left for the propeller that three blades can be adjusted manually at specific angle of pitch. The propeller of wind turbine is shown in Figure 4c.

(a) (b) (c)

Figure 4. (a) Wooden blade pattern, (b) Aluminium casted blades, (c) Propeller of wind turbine.



(a) (b) (c) (d)

Figure 5. (a) Pulley; (b) Bearing housing (c) Pulley transmission system (d) Complete HAWT model.

The multi-stage pulley was designed instead of gear box which provides the provision for adjustment of shaft speed at three different speeds. The multi-stage pulley speed ratios are 1:2, 1:1, 2:1. The pulley is shown in Figure 5a. The propeller and pulley has been attached at both ends of shaft fitted with bearings at both ends of cylinder shown in Figure 5b. The transmission system consisting of multi-stage pulleys of wind turbine and AFPMG shaft along with belt is shown in Figure 5c. The complete HAWT model is shown in Figure 5d.

The AFPMG consists of one stator disc and two rotor discs. The 8 coils with computed specifications have been wound. One coil is shown in Figure 6a. The stator disc template has been prepared in which coils were placed for casting purpose as shown in Figure 6b. The Figure 6c shows the casting of stator disc with epoxy resin. After casting, the connections of coils have been completed. The complete stator disc is shown in Figure 6d.

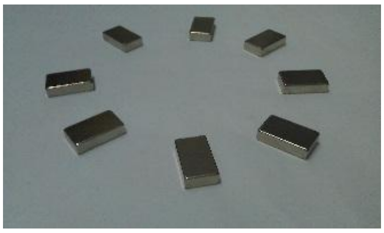
The rotor discs are composed of neodymium permanent magnets shown in Figure 7a. The rotor plates of required specifications alongwith shaft has been prepared as shown in Figure 7b. The two rotor discs are shown in Figure 7c. The complete AFPMG model fitted with one stator disc and two rotor discs has been assembled and shown in Figure 7d.

For operation of WES model at laboratory level, the main frame is fitted with pedestal fan as a source of wind in front of WES model. The pedestal fan behaves as wind tunnel and provides the wind with wind speed up to 10 m/sec. Thus complete WES model is shown in Figure 8.

(a)

(b) (c) (d)

Figure 6. (a) Coil (b) Stator disc template (c) Stator disc casting, (d) Stator disc.



(a)

(b) (c) (d)

Figure 7. Neodymium permanent magnets (b) Rotor plates (c) Rotor discs (d) Complete AFPMG model.

(a) (b)

Figure 8. Complete micro WES model.

Figure 9. Operational micro WES model in lab.

Table 5. Definitions of parameters for case studies.

No.	Parameter	Symbol
1	Wind Speed (m/sec)	V_w
2	Shaft Speed of Wind Turbine (rpm)	n
3	Shaft Speed of AFPMG (rpm)	N
4	No-Load DC Voltage of AFPMG (volt)	V_N
5	Load DC Voltage of AFPMG (volt)	V_L
6	Electrical Load (watt)	EL
7	Frequency of AFPMG (Hz)	f
8	Pulley Ratio	PR
9	Blade Pitch of Wind Turbine (deg)	B
10	Voltage Regulation	VR

The output AC voltage of AFPMG has been rectified to DC voltage and a 50 led panel has been connected as load for AFPMG. The operating WES model is shown in Figure 9.

4. Experimentation on WES Model

The different case studies have been conducted while performing different experiments on WES model. First of all, the parameters considered while experimentation is to be specified and these parameters are listed in Table 5.

4.1 Case Study # 1 – Demonstration of Variable Wind Speed Parameter

In this case study, the effect of variable wind speed parameter on WES model is demonstrated at rated parameters of blade pitch, pulley ratio and electrical load. The variable wind speed is obtained by varying the fan speed which behaves as wind tunnel. The observations against variable wind speeds from 5 m/sec to 9 m/sec are recorded in Table 6.

Table 6. WES model results on variable V_w

Rated Parameters		V_w	-	B	20°
		PR	1:2	EL	25 W
V_w (V)	n (rpm)	N (rpm)	f (Hz)	V_N (V)	V_L (V)
5	110	220	14.6	4.4	3.7
6	240	480	32.0	9.6	8.0
7	350	700	46.6	14.0	11.7
8	375	750	50.0	15.0	12.5
9	395	790	52.6	15.8	13.2

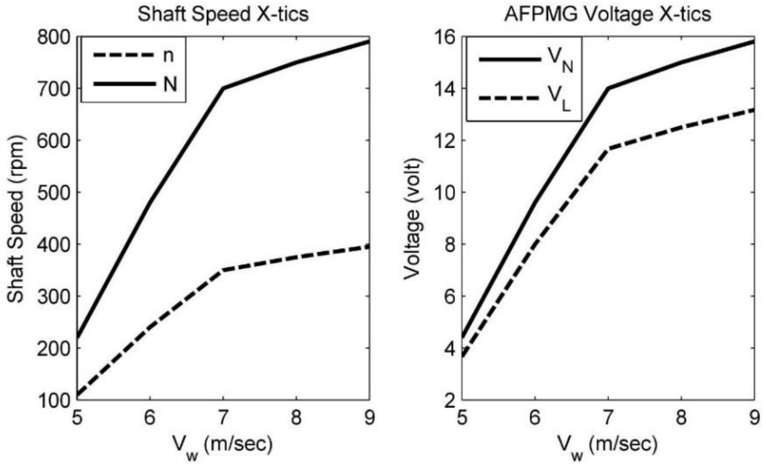


Figure 10. WES model results on variable V_w

Table 7. WES model results on variable B.

Rated Parameters		V_w	8 m/sec	B	-
		PR	1:2	EL	25 W
B (deg)	n (rpm)	N (rpm)	f (Hz)	V_N (V)	V_L (V)
15°	350	700	46.6	14.0	11.7
20°	375	750	50.0	15.0	12.5
25°	390	780	52.0	15.6	13.0
30°	400	800	53.3	16.0	13.3
35°	380	760	50.7	15.2	12.7

The obtained results from the case study can also be analyzed graphically. Figure 10 shows the shaft speed and AFPMG DC voltage characteristics against variable wind speed parameter.

4.2 *Case Study # 2 – Demonstration of Variable Blade Pitch Parameter*

In this case study, the effect of variable blade pitch parameter on WES model is demonstrated at rated parameters of wind speed, pulley ratio and electrical load. The blade pitch angle of wind turbine blades is adjusted manually at specified value. The observations against variable blade pitch angles from 15° to 35° are recorded in Table 7.

The obtained results from the case study can also be analyzed graphically. Figure 11 shows the shaft speed and AFPMG DC voltage characteristics against variable blade pitch parameter.

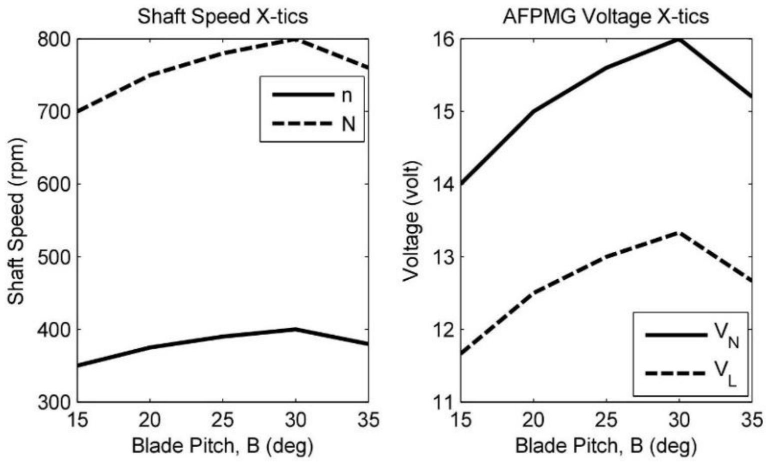


Figure 11. WES model results on variable B.

Table 8. WES model results on variable PR.

Rated Parameters		V_w	8 m/sec	B	20°
		PR	-	EL	25 W
PR	**n (rpm)**	**N (rpm)**	**f (Hz)**	**V_N (V)**	**V_L (V)**
1:2 (0.5)	375	750	50.0	15.0	12.5
1:1 (1)	398	398	26.5	8.0	6.6
2:1 (2)	460	230	15.3	4.6	3.8

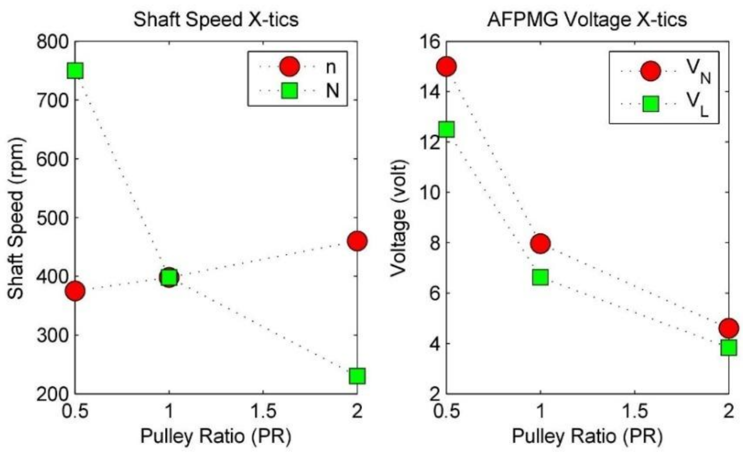


Figure 12. WES model results on variable PR

4.3 Case Study # 3 – Demonstration of Variable Pulley Ratio Parameter

In this case study, the effect of variable pulley ratio parameter on WES model is demonstrated at rated parameters of wind speed, blade pitch and electrical load. The pulley ratio of transmission system of WES model is varied by changing the belt position at multi-stage pulley. The observations against variable pulley ratios of 1:2, 1:1 and 2:1 are recorded in Table 8.

The obtained results from the case study can also be analyzed graphically. Figure 12 shows the shaft speed and AFPMG DC voltage characteristics against variable pulley ratio parameter.

Table 9. WES model results on variable EL.

Rated Parameters		V_w	8 m/sec	B	20°
		PR	1:2	EL	-
EL (watt)	n (rpm)	N (rpm)	f (Hz)	V_N (V)	V_L (V)
0	490	980	65.3	19.6	16.3
5	465	930	62.0	18.6	15.5
10	440	880	58.7	17.6	14.7
15	415	830	55.3	16.6	13.8
20	392	784	52.3	15.7	13.1
25	375	750	50.0	15.0	12.5

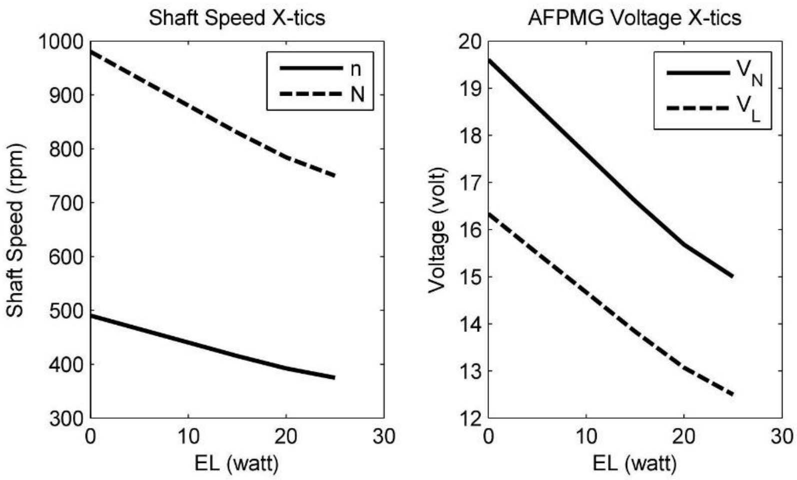


Figure 13. WES model results on variable EL.

Table 10. Rated parameters for WES€

Rated Parameters	V_w	8 m/sec	B	20°
	PR	1:2	EL	25 W
	N, n	Variable		

4.4 *Case Study # 4 – Demonstration of Variable Electrical Load Parameter*

In this case study, the effect of variable electrical load parameter on WES model is demonstrated at rated parameters of wind speed, blade pitch and pulley ratio. The electrical load on AFPMG terminals is varied in terms of LEDs on LED load panel. The observations against variable electrical load from 5 W to 25 W are recorded in Table 9.

The obtained results from the case study can also be analyzed graphically. Figure 13 shows the shaft speed and AFPMG DC voltage characteristics against variable electrical load parameter.

4.5 *Case Study # 5 – Demonstration of Voltage Regulation Parameter*

In this case study, the effect of variable shaft speeds of HAWT and AFPMG on WES model is demonstrated at rated parameters of wind speed, blade pitch, electrical load and pulley ratio. The rated parameters of case study are given in Table 10.

From observations, no-load and load DC voltage of AFPMG are recorded. The voltage regulation of AFPMG is computed at various shaft speeds of AFPMG. The results are shown graphically in Figure 14.

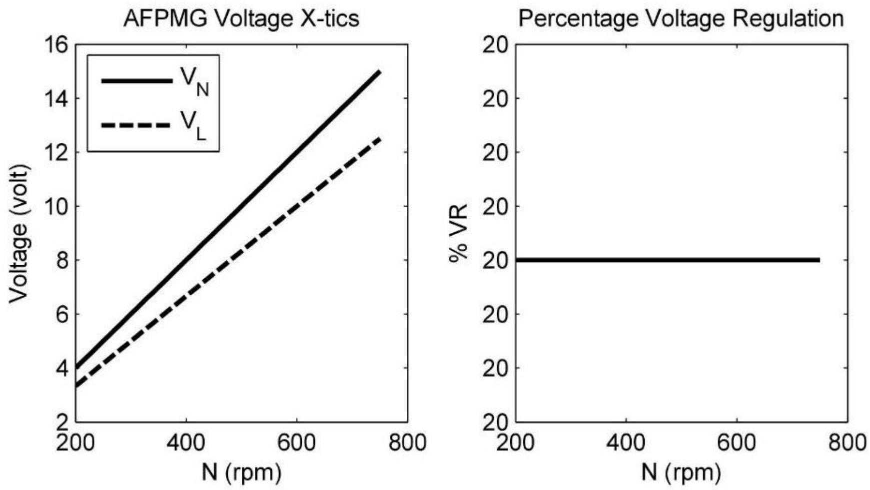


Figure 14. Voltage regulation of AFPMG.

Table 11. Runaway speed test.

Case	Shaft Speed of HAWT (n)
Shaft speed of HAWT with AFPMG	390 rpm
Shaft speed of HAWT without AFPMG	562 rpm

4.6 *Case Study # 6 – Runaway Speed Test of HAWT*

In this case study, the HAWT is run in front of wind tunnel with AFPMG coupled and decoupled forms at wind speed of 8 m/sec. Table 11concludes the results in terms of shaft speeds at either of the cases.

4.7 *Case Study # 7 – Peripheral Speed Test of AFPMG Rotor Discs*

The peripheral speed is defined as the relative speed between stationary coils and rotating magnets [17]. High peripheral speed enhances the terminal voltage of generator but with coil heating and centrifugal force constraints. The expression for peripheral speed is given by [17].

$$\upsilon = \pi D_r n_s \tag{10}$$

where

D_r = Rotor disc diameter (m)

n_s = Maximum shaft speed of AFPMG (rps)

The value of peripheral speed for the AFPMG is computed which comes out to be 5.64 m/sec.

5. Conclusion

In this research paper, a micro WES has been designed, fabricated and tested for different experiments. The presented WES has been designed in such a way that it operates within the premises of laboratory. The experiments related to wind power (power generation) are conducted on this prototype model. Thus proposed micro WES model is well suited for undergraduate students to get concepts of wind power generation system and laboratory. The design of automatic blade pitch control system is the horizon for future work.

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