

## PERFORMANCE OF BATTERY-CHARGING WIND TURBINE DEVELOPED BY THE NERDC CENTRE

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**ABSTRACT:** A number of wind-turbine-generators installed in various parts of Sri Lanka have not been functioning at efficiency levels expected from them. This study was carried out to predict the performance of a wind turbine-generator, and to check whether the failures are really due to mismatch of the wind rotor and the generator. A two-bladed small-scale wind turbine-generator has been developed for battery-charging applications. For a wind-turbine-generator to maximise its energy output, the characteristic performance of the electric generator coupled to it should match with the characteristic performance of wind rotor. The performance of the wind-rotor developed for this study is theoretically predicted by considering the vortex system of the wind-rotor by using blade element theory and momentum theory, where the geometrical parameters ( $\beta$ ,  $C$ ) of the existing blade are used. According to the final results of this study, the performance of the wind-rotor is not properly matching with the permanent-magnet generator used with it. The performance curves of the wind-rotor and the generator were used in determining the curve of real power output of entire system at different wind speeds.

### 1. INTRODUCTION

In certain rural areas of Sri Lanka, battery-charging-wind-turbine has been identified as a viable off-grid power system, instead of costly electrification, for homes. In this context, National Engineering Research & Development Centre (NERDC) of Sri Lanka has developed a two-bladed, small-scale wind-turbine-generator for battery-charging applications.

This simple unit consists of a two-bladed wind-rotor directly coupled to a permanent-magnet generator. An inclined-hinged-tail vane is installed for both self-orientation of the wind-rotor to wind direction and for power control at wind speeds greater than the rated wind speed.

A number of wind-turbine-generators have been installed in the country, but most of them are not performing to the expectations. This study was carried out to predict the performance of a wind-turbine-generator, and to check whether the failures are due to their mismatch. To maximise energy output, the characteristic performance of the electric generator should be matched with that of the wind rotor.

### 2. CHARACTERISTICS OF THE WIND ROTOR

In the analysis of the characteristic performance of a wind-rotor, the main parameters are thrust force on the rotor, torque generated by the rotor, and rotational speed of the rotor. These parameters should be found at different values of wind speeds in order to analyse the characteristic performance of the wind-rotor. This is very important when it has to be coupled to an electric generator. A wind-rotor, in general, is designed so that optimum energy conditions are satisfied at a given specific tip-speed ratio. But in practise wind rotors do not always function at optimum conditions. It may run at various other tip-speed ratios.

Power output of this wind-turbine-generator was evaluated for different wind speeds. The main objective here is to theoretically find out the  $C_p$  values for different  $\lambda_0$  values of the NERDC wind-rotor. Geometrical parameters of the rotor are presented in table 1. Performance of the existing wind-rotor can

be analyzed by using the blade element theory (BET) and momentum theory (MT). This rotor consists of two blades with Profile NACA 4415<sup>[2]</sup>. The radius of the rotor is 1105 mm, and the hub radius is 105 mm.

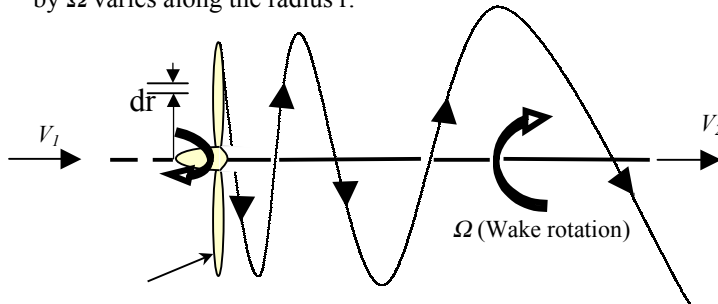
**Table 1: Geometrical parameters of 2-bladed wind rotor at NERDC**

Section	Radius (mm)	Chord length (mm)	Blade angle, $\beta$ (degrees)
1	155	189.2	22.0
2	255	177.7	19.5
3	355	166.2	17.1
4	455	154.7	14.7
5	555	143.2	12.3
6	655	131.7	9.8
7	755	120.2	7.4
8	855	108.7	5.0
9	955	97.2	2.6
10	1055	85.7	0.2

### 2.1 Blade Element Theorems and Momentum Theorem

Energy extracted from the wind is transmitted through the rotor in the form of torque, and the air is acted upon with a reactive torque that makes the wake to rotate opposite to the rotor motion. This implies that the downstream air consists of rotational kinetic energy, which is not included in the axial momentum theory. Indeed, this energy component represents a part of energy in air, which could not be absorbed by the rotor. Therefore, a more realistic value for  $C_{pmax}$  can be derived by the inclusion of wake-rotational effect<sup>[1]</sup>.

It should be noted that the wake-rotational effect is the main case for low  $C_p$  values in low-speed wind-rotors. These rotors impart higher reactive torques on the wind, than high-speed rotors, which result in higher wake-rotations leading to higher losses. Figure 1 shows the basic configuration of the flow through a wind-rotor with wake-rotation. The rotor speed is denoted by  $\omega$ , and rotational speed of the wake given by  $\Omega$  varies along the radius  $r$ .



**Wind rotor**

Figure 1: Flow behind the rotor with wake-rotational effect

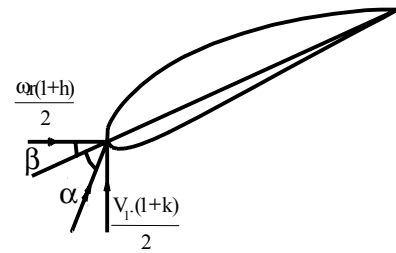


Figure 2: Velocity diagram of a blade element

As seen from figure 1:

Downstream of the rotor, the rotational speed of the wind flow is  $\Omega$ .

$$\text{Hence, } \Omega = h\omega,$$

The axial speed through the rotor can be derived.

$$\text{Let, } V_2 = k V_1$$

where,  $V_1$  - wind speed,  $h$  - radial flow interference factor and  $k$  - axial flow interference factor.

As seen from figure 2:

$$\phi = \alpha + \beta \quad (1)$$

$$\cot \phi = \frac{U}{V} = \frac{\omega.r.(1+h)}{V_1.(1+k)} \quad (2)$$

$$= (\omega.r/V). (1+h)/(1+k) \\ = \lambda. (1+h)/(1+k) \quad (3)$$

## 2.2 Aerodynamic Performance

The performance of the wind rotor is theoretically predicted by considering the wake-rotation of the wind-rotor by using blade element theory and momentum theory, where the geometrical parameters ( $\beta$  - blade angles,  $l$  - chord lengths of each blade elements) of the existing blade are used. The characteristic performance of a wind-rotor is usually given by the variation of power coefficient ( $C_p$ ) with respect to tip-speed ratio ( $\lambda_0$ ).

Calculation of axial thrust and torque:

Considering the blade element theory, axial thrust  $dF$  is given by:

$$dF = b.d.F_v = \frac{1/2 \cdot \rho.l.W^2.b.C_l.\cos(\phi - \varepsilon).dr}{\cos \varepsilon} \quad (4)$$

Aerodynamic torque,  $dM$ , is given by:

$$dM = r.b.dF_u = \frac{1/2 \cdot \rho.l.r.W^2.C_l.\sin(\phi - \varepsilon).dr}{\cos \varepsilon} \quad (5)$$

where,

$C_l$  - coefficient of lift,  $C_d$  - coefficient of drag,  $\tan \varepsilon = C_d/C_l$

$\rho$  - air density,  $b$  - number of blades of wind rotor

and  $W$  - wind speed relative to the wind rotor,  $l$  - chord length of blade element

The above two values,  $dF$  and  $dM$ , can be determined by the general dynamics theory. Consider the axial momentum of the flow through the annulus:

Thrust = (rate of mass flow,  $m$ , through the element) x (change in the axial velocity).

Then, axial thrust,  $dF = \rho. \pi.r.dr.V_1^2.(1-k^2)$  (6)

Aerodynamic torque,

$$dM = \rho.\pi.r^2.dr.V_1.(1+k)\Omega \\ = \rho.\pi.r^3.dr.\omega.V_1.(1+k).(h-1) \quad (7)$$

Comparing the expression for  $dF$  derived by blade elementary theory with that derived by momentum consideration given in equations (4) and (6) leads to, after substituting for  $W$ ,

$$C_l.b.l = \frac{2\pi.r.V_1^2.(1-k^2).\cos \varepsilon}{W^2.\cos(\phi - \varepsilon)} = \frac{8\pi.r.(1-k).\cos \varepsilon.\sin^2 \phi}{(1-k).\cos(\phi - \varepsilon)}$$

Similarly, comparing  $dM$  given in equations (5) and (7),

$$C_l.b.l = \frac{2\pi.r.V_1.(1+k).(h-1).\cos \varepsilon}{W^2.\sin^2(\phi - \varepsilon)} = \frac{4\pi.r.(h-1).\sin 2\phi.\cos \varepsilon}{(h+1).\sin(\phi - \varepsilon)}$$

After rearrangement to get the following:

$$\frac{1-k}{1+k} = \frac{C_l.b.l.\cos(\phi - \varepsilon)}{8\pi.r.\cos \varepsilon.\sin^2 \phi} \quad (8)$$

$$\frac{h-1}{1+h} = \frac{C_l.b.l.\sin(\phi - \varepsilon)}{4\pi.r.\sin 2\phi.\cos \varepsilon} \quad (9)$$

The wind rotor is divided into equal 10 sections and  $C_p$  value for each section was calculated by using the iterative procedure. The curve of coefficient of lift ( $C_l$ ) and of coefficient of drag ( $C_d$ ) versus the angle

of attack ( $\alpha$ ) of the blade profile NACA 4415 was used for this calculation [2]. Then, coefficient of performance of the wind rotor segment at radius  $r$  ( $C_{Pr}$ ) with respect to different tip speed ratios ( $\lambda_0$ ) was calculated.

$$C_{Pr} = \frac{dP_u}{\rho \pi r dr V^3} = \lambda^2 \cdot (1 + k) \cdot (h - 1) \quad (10)$$

$$P = \int_r^R C_{Pr} \rho \pi r dr V^3 = \frac{1}{2} C_p \rho \pi R^2 V^3 \quad (11)$$

Then, coefficient of performance of the wind rotor ( $C_p$ ) is given by,

$$C_p = \frac{2}{R^2} \int_r^R C_{Pr} r dr \quad (12)$$

Coefficient of momentum of rotor ( $C_m$ ) is defined by,

$$C_m = \frac{C_p}{\lambda_0} \quad (13)$$

Table 2: Theoretically calculated performance of the wind rotor

Tip-Speed Ratio ( $\lambda_0$ )	$C_p$	$C_m$
0	0.00	
1	0.04	0.04
2	0.12	0.06
3	0.21	0.07
4	0.30	0.08
5	0.37	0.07
6	0.40	0.07
7	0.39	0.06
8	0.34	0.04
9	0.25	0.03
10	0.13	0.01
11	0.00	0.00

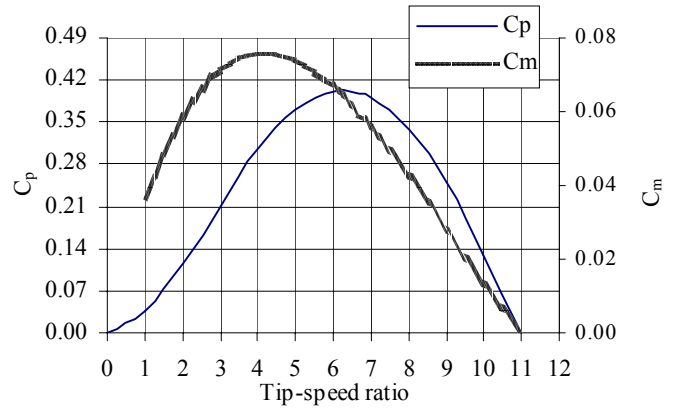


Figure 3: Performance curve of the existing NERDC wind-rotor

### 3. CHARACTERISTICS OF PERMANENT MAGNET GENERATOR

In this wind-turbine-battery-charging unit, the wind-rotor is directly coupled to the permanent magnet generator. Power absorption by the permanent magnet generator at different rotational speed is found by using a torque meter. The load for the generator is a bank of 12V-batteries and the prime mover is an induction motor driven by a variable-frequency inverter. Characteristic performance of the permanent magnet generator is presented in table 3 and figure 4 [3].

Table 3: Characteristic performance of permanent-magnet generator (PMG) with 12V battery bank

Speed (rev/min)	Torque(N.m)	Power input (W)	Power output (W)	Efficiency %
200	2.59	52.1	0.6	1.2
225	2.7	63.9	3.8	5.9
250	3.2	82.9	10.2	12.2
275	3.4	97.7	19.7	20.2
300	4.0	127.9	35.2	27.5
325	4.5	154.0	42.6	27.6
350	4.7	174.1	55.8	32.0
375	4.9	195.5	67.4	34.5
400	5.6	236.9	82.1	34.6
425	6.5	292.0	92.6	31.7
450	6.8	319.8	106.2	33.2
475	7.0	348.9	118.5	33.9
500	7.5	390.9	129.5	33.1
525	7.9	435.7	140.2	32.3
550	8.4	482.2	149.4	30.9
575	8.6	517.7	162.2	31.3
600	8.6	540.2	169.3	31.3

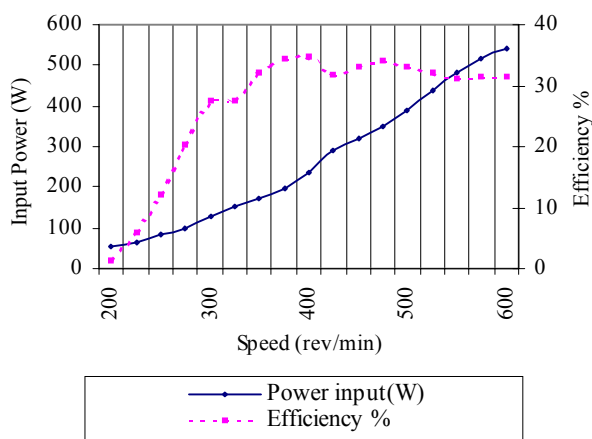


Figure 4: Characteristic performance of permanent-magnet generator



Figure 5: NERDC permanent magnet generator

#### 4. COMBINED PERFORMANCE OF THE WIND ROTOR AND THE PERMANENT MAGNET GENERATOR

By considering the curve of  $C_p$  versus  $\lambda_0$  of the wind rotor, the power output of the wind rotor corresponding to each wind speed can be found out. Then, the generator and the rotor performance curves of the wind turbine-generator system can be plotted, as shown in Figure 6.

$$\lambda_0 = \frac{\omega \cdot r}{V_1} \quad (13)$$

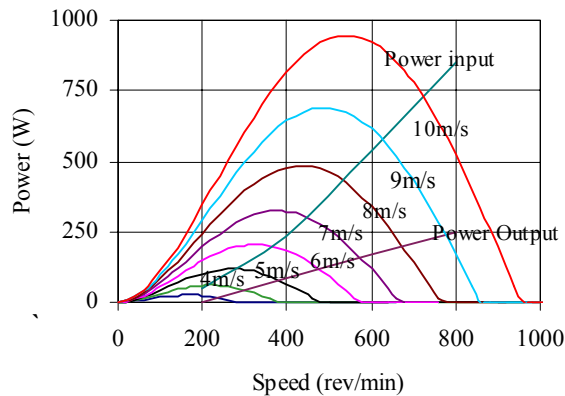


Figure 6: Generator and rotor performance curves of NERDC wind-turbine generator

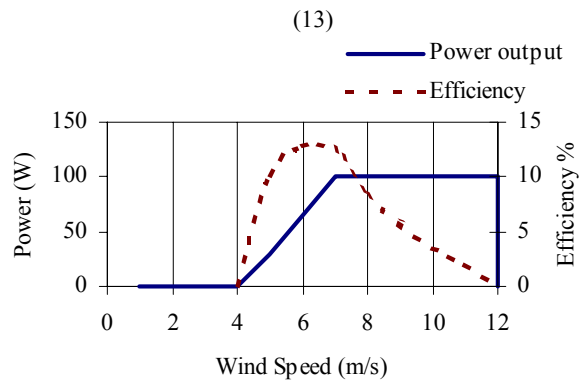


Figure 7: Output power characteristics and efficiency of NERDC wind turbine

The curve of power output versus rotational speed of the wind rotor at each wind speed and the curve of power input versus rotational speed of the generator is plotted in the same graph. The generator power input curve should pass through the maximum points of the power output curves of wind-rotor at each wind speed, if they properly match.

#### 5. CONCLUSION

By considering the combined characteristic graphs (Figure 6), it is evident that generator power input curve is not passing through the maximum points of the wind rotor characteristics curves. It means that the wind turbine-generator is not performing at the optimum condition. To match the wind-rotor and generator, these two should be coupled by using a suitable speed-increasing gearbox or the wind rotor or generator characteristic performance should be modified to tally each other. Power output characteristics of the wind turbine with this type of passive controlling design at wind speeds higher than the rated value are complex. The prediction of such characteristics is not a part of the present study. Therefore, it is assumed that the inclined-hinge tail-vane with side-vane mechanism works ideally such that the power output above the rated wind speed remains at 100W until the cut-off wind speed is reached. Variations of overall efficiency of the system together with the effect of power modulation can be observed in Figure 7.

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