

# Power Optimization of a Wind Turbine Using Genetic Algorithm



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**Abstract** Modeling and optimization of the wind turbine for better power and performance have become the demand in the development of renewable energy. Power coefficient ( $C_p$ ) is an important parameter which determines the efficiency of the wind turbine and it depends on the velocity of the wind, blade pitch angle, and tip speed ratio of the turbine. Selection of the appropriate value of these parameters while designing a wind turbine will provide the optimum value of coefficient of performance. In this paper, the optimum value of the power coefficient is obtained by using the genetic algorithm optimization technique. The optimum value of the power coefficient is found to be 0.46 which is increased by 0.05 than that of the value obtained from blade element momentum theory.

**Keywords** Blade element momentum · Power coefficient · Genetic algorithm

## 1 Introduction

Wind turbine is a device that converts the kinetic energy of wind into mechanical energy by rotation of shaft, which is then converted to electrical energy by the use of generator. Research on modeling and optimizing of various design parameters of wind turbine to obtain the optimum performance has been carried out a long time before. Sedaghat et al. [1] have performed analysis of compact blade element momentum theory to design blades of continuously varying speed horizontal axis wind turbine for optimum performance. Jain et al. [2] have presented a optimization technique based on genetic algorithm and estimated the optimum power of the wind

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turbine on the basis of parameters like blade rotating speed blade radius tip speed ratio, electrical power, etc. Mahmuddin [3] has developed a computational model based on blade element momentum theory by dividing the blade into several segments and analyzed different parameters required for optimal blade design process. In the analysis, tip and root losses are analyzed and the computational results are validated by comparing with the results obtained from QBlade software. Shen et al. [4] described an optimized model of horizontal axis wind turbine that is based on lifting surface method and genetic algorithm. In this model, chord length of airfoil and twist distribution of the blade is the decision variables that are analyzed by using micro-genetic algorithm in order to attain the best trade-off between the maximum annual energy production and minimum blade loads.

Designing of wind turbine blade using blade element momentum method and optimizing the model with the use of non-classical optimization techniques will allow the wind energy farms to produce the best energy under different aerodynamic and loading conditions. In this paper, first, a wind turbine model is designed using the blade element momentum theory, and the model is then optimized for better performance using genetic algorithm. The velocity data required for the operation of wind turbine is collected from a selected site, and other required parameters are determined to form blade element momentum theory analysis. The optimized parameters of the wind turbine presented in this study are the wind velocity and the radius of the turbine blade. The optimization of these parameters provides better power performance of the wind turbine.

## 2 Aerodynamic Design of Wind Turbine

The objective of an aerodynamic design of the wind turbine is to maximize the efficiency for given airfoil of the blade. Blade element momentum (BEM) also referred to as strip theory combines both momentum and element theory to provide useful relations for determining the parameters for wind turbine design [3].

### 2.1 Momentum Theory

In momentum theory, analysis of the forces acting at the blade is performed that is based on the conservation of linear and angular momentum. The momentum theory analysis of wind turbine can be observed inside a stream tube in which the wind turbine is placed inside the stream tube and the wind is allowed to flow through one end as shown in Fig. 1.

The thrust force acting on a wind turbine blade inside a stream tube as can be obtained as [5]:

$$dF_T = \rho v_1^2 [4a(1-a)] \pi r dr \quad (1)$$

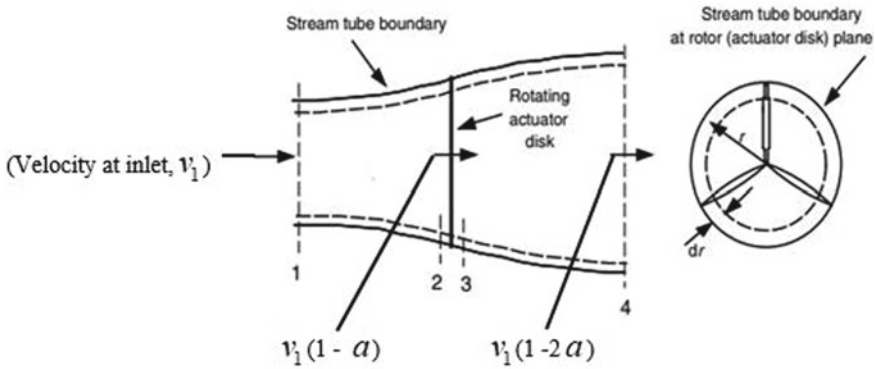


Fig. 1 Stream tube with rotating actuator disk [6]

where ‘ $v_1$ ’ is the downstream wind velocity, ‘ $\rho$ ’ is the air density, ‘ $r$ ’ is the distance of the element from hub, and ‘ $a$ ’ is the axial induction factor which could be written as:

$$a = \frac{v_1 - v_2}{v_1} \tag{2}$$

If a rotating stream tube is introduced, then the torque that acts on the blade is given by:

$$dT = 4a'(1 - a)\rho v_1 \Omega r^3 \pi dr \tag{3}$$

where ‘ $w$ ’ is angular velocity, ‘ $\Omega$ ’ is the blade rotation speed, and ‘ $a'$ ’ is angular induction factor and is given by:

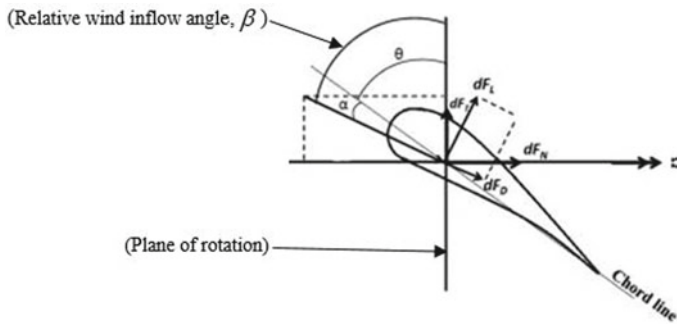
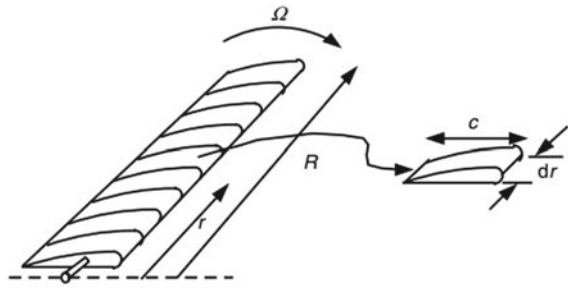
$$a' = \frac{w}{2\Omega} \tag{4}$$

### 2.2 Blade Element Theory

The forces on the blades of a wind turbine can also be expressed as a function of lift and drag coefficients and the angle of attack. For blade element theory analysis, the whole blade is divided into smaller elements of infinitesimal thickness and assumed that there is no aerodynamic interactions between different blade elements as shown in Fig. 2.

The geometry of the blade along with different forces acting on the blade profile is shown in Fig. 3. The forces that act on the blade elements can be determined by the lift and drag coefficients as given in the equations below [5]:

**Fig. 2** Schematic of blade elements with various design parameters [6]



**Fig. 3** Forces acting on blade profile [6]

$$dF_T = \frac{1}{2} B \rho W^2 (C_L \sin \beta + C_D \cos \beta) c dr \tag{5}$$

$$dT = \frac{1}{2} B \rho W^2 (C_L \sin \beta - C_D \cos \beta) c r dr \tag{6}$$

where ‘ $C_L$ ’ is the lift coefficient, ‘ $C_D$ ’ is the drag coefficient, ‘ $B$ ’ is the number of blades, ‘ $\beta$ ’ is the relative inflow angle, ‘ $c$ ’ is the chord length of an airfoil, and ‘ $W$ ’ is the resultant velocity. The relative angle ‘ $\beta$ ’ and chord length ‘ $c$ ’ of the airfoil at different sections of the blade can be calculated as:

$$\beta = \frac{2}{3} \tan^{-1} \left( \frac{1}{\lambda_r} \right) \tag{7}$$

$$c = \frac{8\pi r}{B C_L} (1 - \cos \beta) \tag{8}$$

$$\text{Resultant velocity, } W = \frac{(1 - a)}{\cos \beta} \tag{9}$$

### 2.3 Blade Element Momentum Theory

Blade element momentum theory combines both the momentum and blade element theory to derive the equations that is very useful to design the wind turbine. The thrust force and the torque obtained from the blade element momentum theory can be expressed in equations shown below [5]:

$$dF_T = \sigma' \pi \rho v^2 \frac{(1 - a)^2}{\cos^2 \beta} (C_L \cos \beta + C_D \sin \beta) r dr \tag{10}$$

$$dT = \sigma' \pi \rho v^2 \frac{(1 - a)^2}{\cos^2 \beta} (C_L \cos \beta - C_D \sin \beta) r^2 dr \tag{11}$$

where ‘ $\sigma'$ ’ is the local solidity and is given as:

$$\sigma' = \frac{Bc}{2\pi r} \tag{12}$$

### 2.4 Tip Loss Correction

In the wind turbine, there occur some losses in the tip of the turbine blade which is to be accounted in blade element momentum theory as a correction factor. Correction factor indicates the loss reduction of forces along the blades and its value varies from 0 to 1 given as [5]:

$$Q = \frac{2}{\pi} \cos^{-1} \left( \exp \left( -\frac{B}{2} \left( \frac{R - r}{r \sin \beta} \right) \right) \right) \tag{13}$$

where ‘ $R$ ’ is the maximum radius of the rotor. The force and the torque equation after accounting the tip loss factor can be expressed as:

$$\frac{a}{1 - a} = \frac{\sigma' (C_L \sin \beta + C_D \cos \beta)}{4Q \cos^2 \beta} \tag{14}$$

$$\frac{a}{1 - a'} = \frac{\sigma' (C_L \cos \beta + C_D \sin \beta)}{4Q \lambda_r \cos^2 \beta} \tag{15}$$

where ‘ $\lambda_r$ ’ is the local tip speed ratio and is given as:

$$\lambda_r = \frac{\Omega r}{v} \tag{16}$$

## 2.5 Power Output

The total power output that can be obtained from the rotor is a function of parameters like velocity of wind, density of air, radius of the rotor, and coefficient of performance. The total power of the rotor can be expressed as:

$$P = \int_{r_h}^R \Omega dT dr \quad (17)$$

The coefficient of performance is an important parameter that is used to determine power and its maximum value is given by Betz's limit to be 0.59. The expression to calculate coefficient of performance is:

$$C_p = \frac{P}{P_{wind}} \quad (18)$$

where ' $P_{wind}$ ' is the power contained in the wind and is given as:

$$P_{wind} = \frac{1}{2} \rho \pi R^2 v^3 \quad (19)$$

On solving the above three equations, we can obtain the  $C_p$  as a function of various parameters required the design of wind turbine as [5]:

$$C_p = \left( \frac{8}{\lambda^2} \right) \int_{\lambda_h}^{\lambda} Q \lambda_r^3 a' (1 - a) \left[ 1 - \frac{C_D}{C_L} \tan \beta \right] d\lambda_r \quad (20)$$

where ' $\lambda_r$ ' is tip speed ratio and is defined as the ratio between the tangential speed of the tip of a blade and the actual speed of the wind. Tip speed ratio is expressed as:

$$\lambda = \frac{\Omega R}{v} \quad (21)$$

## 3 Genetic Algorithm

Genetic algorithm is a random search and optimization technique which works on the principle of genetics and natural selection. Genetic algorithm requires initialization and representation of the population and appropriate fitness function. The need of appropriate fitness function is to lead the algorithm to provide optimal solution.

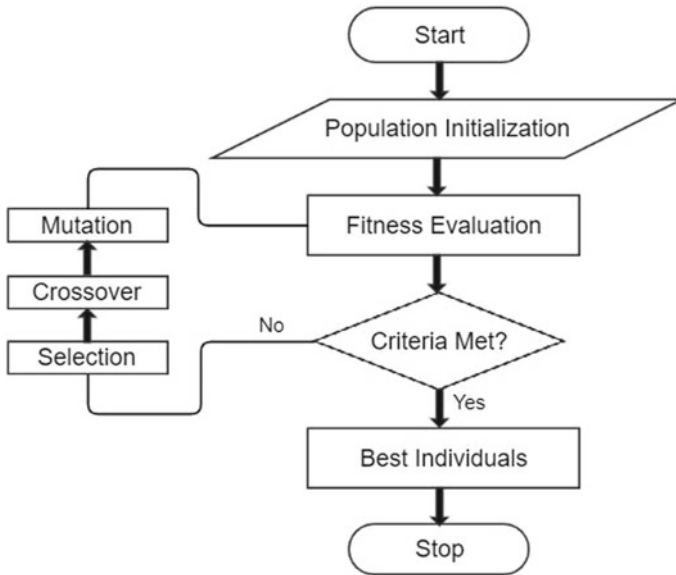


Fig. 4 Genetic algorithm flow diagram

The selection operator usually selects or reproduces the individuals that have better fitness values as that of parents. The crossover operator creates the new population by combining genes of the parents that is in the current population. The mutation operator creates the entirely new population by changing the genes of individual parents. At every step, the algorithm uses individuals of current generation to generate new population, and fitness evaluation is carried out until the best population is determined. The genetic algorithm can be stopped to achieve the desired value by defining the limit of generation required for iteration. The flow diagram of genetic algorithm showing different steps is shown in Fig. 4.

### 4 Computational Model

The computational model used for the study is an airfoil of NACA 4412 and the airfoil that is obtained from the QBlade software is shown in Fig. 5. The graph between  $C_L$

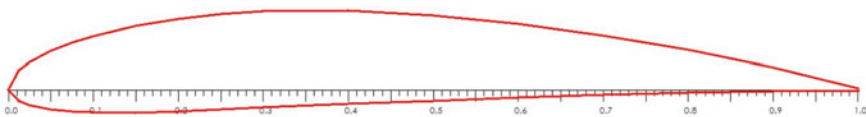


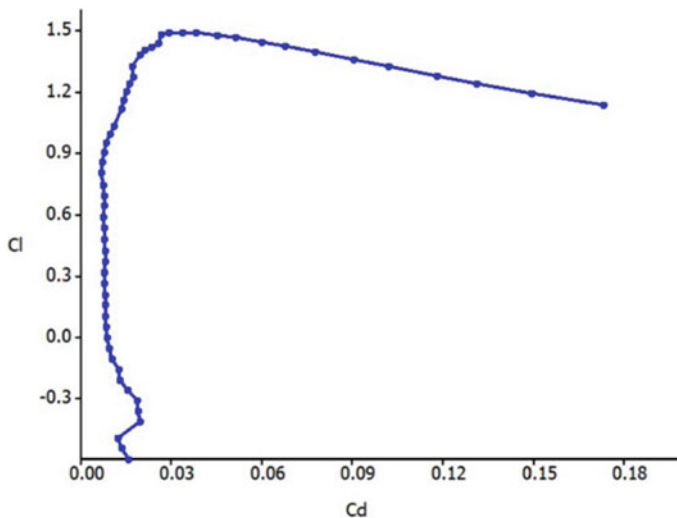
Fig. 5 NACA 4412 airfoil obtained from QBlade

versus  $C_D$  and  $C_L$  versus  $\alpha$  is also obtained from the QBlade software as shown in Figs. 6 and 7, respectively. The QBlade results shown below in the graph are quite similar to the results obtained from the computational study of NACA 2415 [3]. From the graph, it is seen that the value of  $C_D$  and  $C_L$  are 0.01 and 1, respectively. These values of  $C_D$  and  $C_L$  are used for the calculation of coefficient of performance of the wind turbine model presented in this study.

The different steps that are involved in the design of wind turbine blade using blade element momentum theory are listed below.

1. Determine the radius of rotor for 4 KW power using other known parameters such as velocity of wind and density of air.
2. Choose the design tip speed ratio value and number of blades for wind turbine.
3. Select the type of airfoil used in blade design (NACA 4412) and obtain the lift and drag coefficients value using angle of attack.
4. Divide the blade into 10 elements and calculate the chord length, blade solidity, axial and angular induction factors, and relative inflow angle for each sections.
5. Recompute the values of chord length, blade solidity, axial, and angular induction factors, and relative inflow angle and compare the values obtained from the previous iteration.
6. Continue the iteration until the values get converged.
7. Calculate the tip loss correction factor.
8. Compute the value of coefficient of performance.

The velocity data of wind required for this study is collected from a site, and the moving average of the collected data is taken. Different input parameters that are required to design the wind turbine model for this study are listed in Table 1.



**Fig. 6**  $C_L$  versus  $C_D$



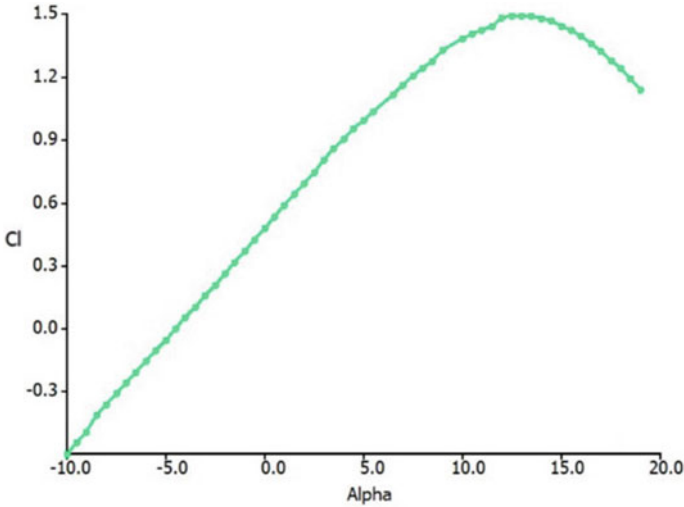


Fig. 7  $C_L$  versus alpha

Table 1 Input parameters of turbine blade

Input parameters	Value
Wind velocity	6.8 m/s
Radius of blade	4.3 m
Number of blades	3
Rotational speed	11.75 rad/s
Density of air	1.233 kg/m <sup>3</sup>
Lift coefficient	1
Drag coefficient	0.01

### 5 Optimization Problem Formulation

Optimization calculations are performed in genetic algorithm code developed in MATLAB. The objective function used for optimization in this study is the power coefficient ( $C_p$ ) which is maximized in order to determine the value of velocity of wind and radius of the turbine blade. The objective function is defined as:

$$\text{Objective function: } C_p = \left( \frac{8\Omega^2}{v^2 R^2} \right) \int_{\lambda_h}^{\lambda} Qr^4 a'(1 - a) \left[ 1 - \frac{C_D}{C_L} \tan \beta \right] dr \quad (22)$$

$$(5 \leq v \leq 15) \text{ m/s, } (3 \leq R \leq 6) \text{ m/s}$$

The control parameters that are required in genetic algorithm are chosen as:

- Population size: 50
- Number of generations: 300
- Crossover fraction: 0.8
- Elite count: 2
- Pareto fraction: 0.035
- Penalty factor: 100
- Migration interval: 20
- Migration fraction: 0.2.

The genetic algorithm is terminated if any of the below specified criteria are met.

- Number of generations limit: 300
- Stall generations limit: 100
- Function tolerance: 1e-50
- Constraint tolerance: 1e-12.

## 6 Results and Discussion

The input parameters mentioned in Table 1 are used to calculate other important parameters using the concept of blade element momentum theory mentioned in Sect. 3. The blade is divide into 10 elements and the local tip speed ratio ' $\lambda_r$ ', relative inflow angle ' $\beta$ ', and the chord length ' $c$ ' at different sections of the blade are calculated using MATLAB and tabulated in Table 2.

Tip loss correction factor is calculated to be 0.98. All the parameters obtained are used to calculate the coefficient of performance ' $C_p$ ' value as 0.41 in MATLAB. The plot obtained by plotting different functions in genetic algorithm code is shown in Fig. 8. The plot consists of the subplots of best individual, score diversity, stopping, and selection function. It can be seen that algorithm is converged to the best functional value at 0.45 at radius of the blade 4.05 m and velocity of wind 6.6 m/s shown by

**Table 2** Design parameters of blade

$R$ (m)	$\lambda_r$	$\beta$	$C$ (m)
0.405	0.7	36.67°	0.6715
0.81	1.4	23.69°	0.5718
1.215	2.1	16.97°	0.4432
1.62	2.8	13.10°	0.3532
2.025	3.5	10.63°	0.2911
2.43	4.2	8.93°	0.2467
2.835	4.9	7.69°	0.2136
3.24	5.6	6.75°	0.1881
3.645	6.3	6.01°	0.1678
4.05	7	5.42°	0.1517

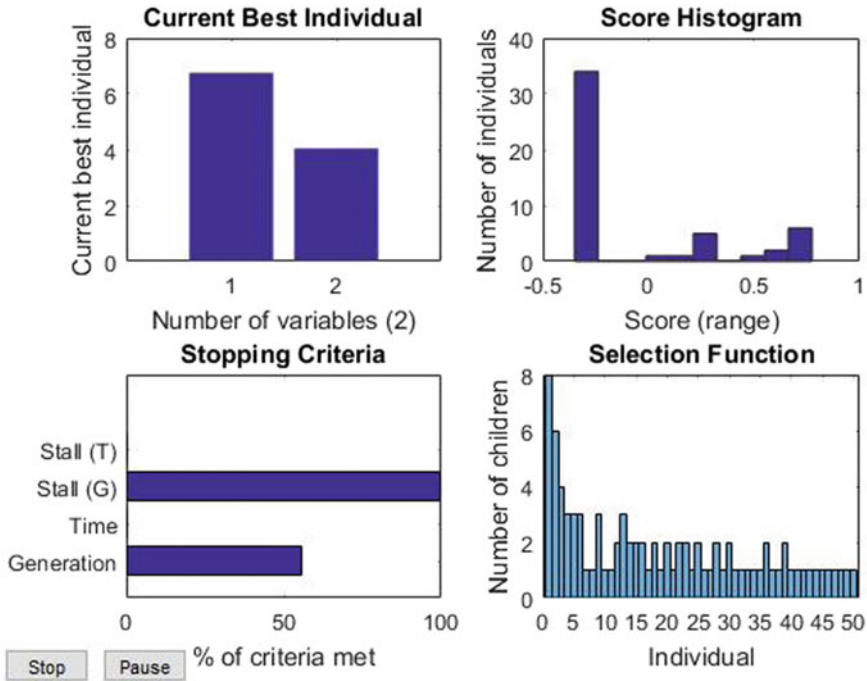


Fig. 8 Convergence plot of genetic algorithm

the current best individual subplot. The score histogram shows the score value of individuals at each generation, whereas the selection histogram shows the parents chosen for each generation. The optimization process is terminated because average change in the fitness value is less than that of defined function tolerance value. The number of generations used is 111 and the number of function evaluation is 5600.

The plots of  $C_p$  with design variables show the increase in power coefficient for the optimized blade by 0.05. The graph between power produced by the wind turbine and radius of the blade in Fig. 11 shows the increase in power by 0.49 KW. Power versus wind speed curve also shows the increase in power produced of the optimized blade by 0.5 KW (Figs. 9, 10, and 12).

## 7 Conclusion

Wind energy is a very important source of renewable energy and proper modeling of wind turbine is required for generating optimum power under various conditions. Genetic algorithm is an important optimization tool that can be used to design an appropriate wind turbine for specific site. The algorithm developed in the MATLAB is based on different assumptions in which iterations are carried out until the desired

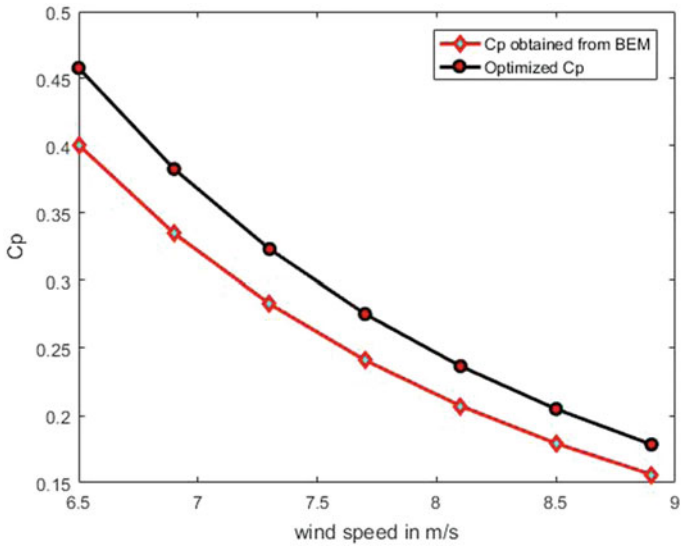


Fig. 9  $C_p$  versus wind speed curve

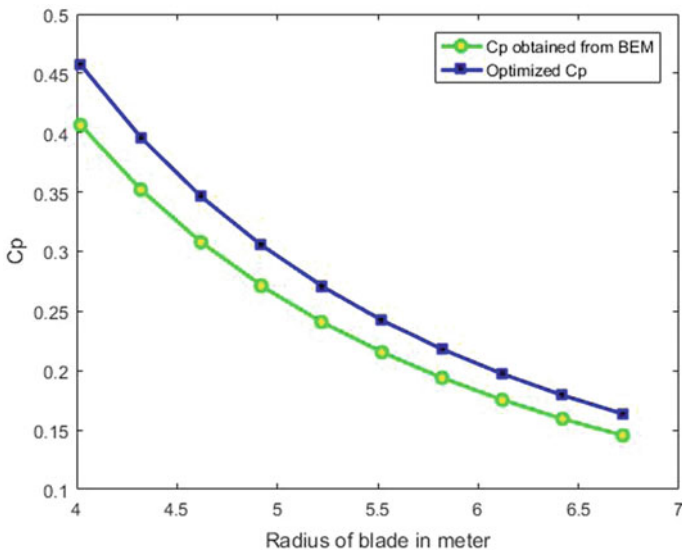


Fig. 10  $C_p$  versus radius curve

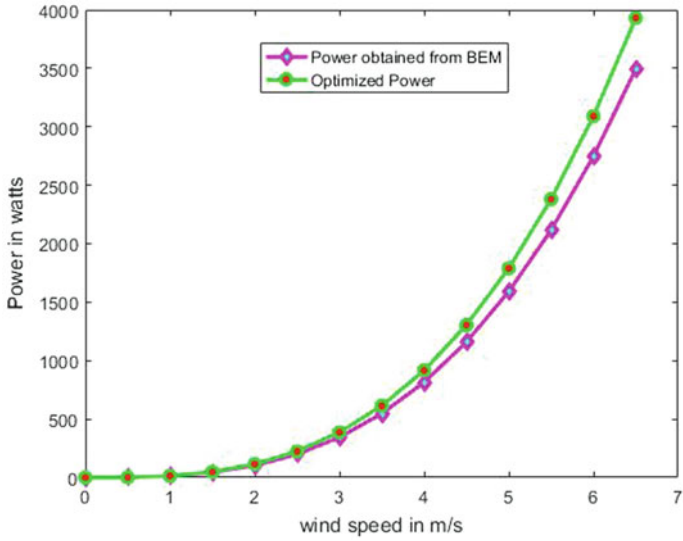


Fig. 11 Power versus wind speed curve

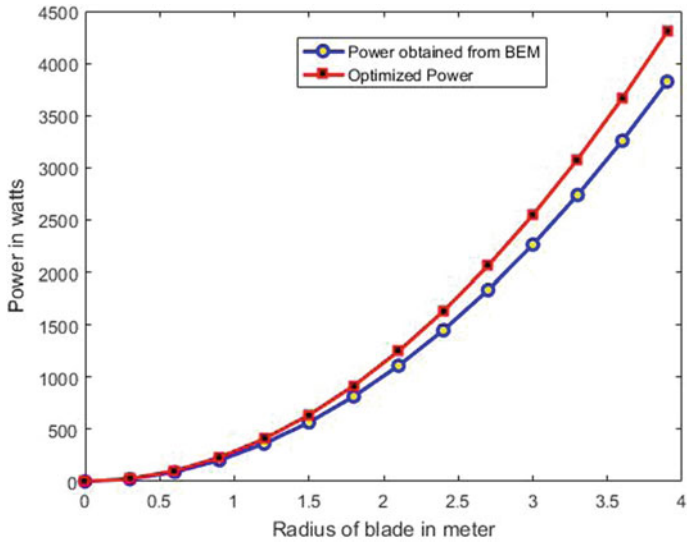


Fig. 12 Power versus radius curve

result is not achieved. The present study is based on blade element momentum theory and various wind parameters are analyzed to provide an optimum solution to the problem. The optimized power is 500 W more than that is obtained from blade element momentum theory calculations. Prediction of appropriate wind speed and radius of the turbine blade gives the best performance of the wind turbine. We can implement this design to promote the wind energy for best turbine efficiency in areas where it is difficult to predict the parameters required to design wind turbine.

## References

1. Sedaghat A (2014) Aerodynamics performance of continuously variable speed horizontal axis wind turbine with optimal blades. *Energy J* 1–8
2. Jain P (2012) Optimization of the wind power generation unit using genetic algorithm. *Int J Eng Sci Technol (IJEST)* 4(11):4592–4597
3. Mahmuddin F (2016) Rotor blade performance analysis with blade element momentum theory. In: *The 8th international conference on applied energy—ICAE2016, energy procedia*, vol 105, pp 1123–1129
4. Shen X (2011) Optimization of wind turbine blades using lifting surface method and genetic algorithm. In: *Proceedings of ASME Turbo Expo 2011*, pp 1–7, GT2011, Vancouver, British Columbia, Canada
5. Jureczko M (2005) Optimization of wind turbine blades. *J Mater Process Technol* 167:463–471
6. Manwell JF, McGowan JG, Rogers AL (2009) *Wind energy explained theory, design and application*, 2nd edn. Wiley, Hoboken (2009)