Analysis of Wind Energy Potential and Optimum Wind Blade Design for Jamshoro Wind Corridor

SYED UMAID ALI*, RAFIULLAH KHAN**, AND SYED ATHAR MASOOD**

ABSTRACT

Pakistan is facing energy crisis since last decade. This crisis can be effectively handled by utilizing alternative energy resources. Pakistan has a huge wind energy potential of about 50,000MW. The contribution of costal area of Sindh, Pakistan in the total wind energy potential is about 43000MW. The Jamshoro wind corridor has the highest wind potential of all coastal areas of Sindh. In this paper a wind blade design has been developed and optimized for Jamshoro wind corridor. The theoretical blade design include the airfoil selection, appropriate chord length selection and optimization of twist angle. The designed blade has been analyzed using Q-blade. Considering the Jamshorowind conditions, blade of around 43 meters have been designed and optimized theoretically. Then the theoretical design is also been checked and verified in Q-blade. Theoretical optimization includes using different combinations of NACA profiles and using exhaustive iterative method to get optimized twist angle. This ensures the design with maximum power output with respect to wind speed of Jamshoro. For low wind speeds, theoretical results and simulated results in Q-blade were almost same but for high wind speeds, results were significantly different due to limitation of iterations in theoretical design.

Key Words: Wind Blade, Blade Element Theory, Q-Blade, Wind Energy Potential.

1.   INTRODUCTION

The shortfall of Pakistan energy has reached a level of 4406 MW [1]. This shortfall can be covered by using renewable resources including wind, solar, hydel, biofuel and geothermal energies. The estimated wind energy potential of Pakistan is 50,000MW [2]. Alone from the coastal areas of Pakistan, 43,000 MW electricity can be produced [3].It was further estimated that of the total coastal area of Sindh, about 9700 Km² area can be used to generate 11,000 MW electricity through wind turbines. This much electricity can not only end the power crisis of Pakistan but also reduces the generation cost of electricity in Pakistan but unfortunately this potential has never been exploited before.

The monthly wind speed as well as wind power density for different stations in Sindh has been plotted in Fig. 1(a-b) [3]. Amongst those stations, Jamshoro having the mean wind speed of 8.5m/s and wind power density of 770W/m²can be classified as excellent site for wind power generation according to classification of Pak Metrological Department [3].

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The main focus of this paper is to design an optimum wind blade for the Jamshoro wind corridor that can produce maximum power output and this can only be achieved when it can harness maximum wind energy. Fig. 2 shows steps to design an optimum wind blade. Equations used for optimization of twist angle and chord length distributions are have been deduced from BEM (Blade Element Momentum) theory[4]. Different blade profiles have been analyzed and then combination of best blade profiles have been used and then verified in Q-blade.
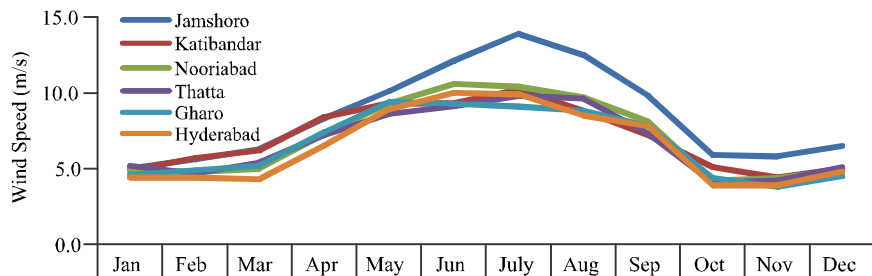
2. BLADE DESIGN PROCEDURE

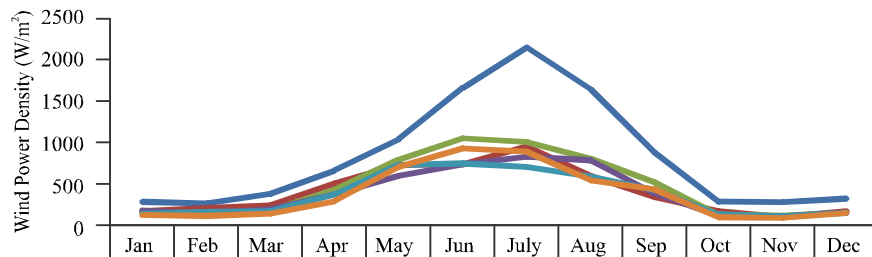Following are the steps for designing the wind turbine blade [5]:

(1)   Power output from wind turbine can be calculated as follows:

$$P = C_p \eta \, 0.5 \rho \pi R^2 V^3 \qquad (1)$$

Where P is the power output, C_p is performance coefficient, η is the mechanical and electrical efficiencies, R is the tip radius, V is the wind velocity.

(a) MONTHLY AVERAGE WIND SPEEDS (M/S) FOR DIFFERENT STATIONS IN SINDH AT 50M [3]

(b) MONTHLY AVERAGE WIND POWER DENSITY (WATT/M²) FOR DIFFERENT STATIONS IN SINDH [3]

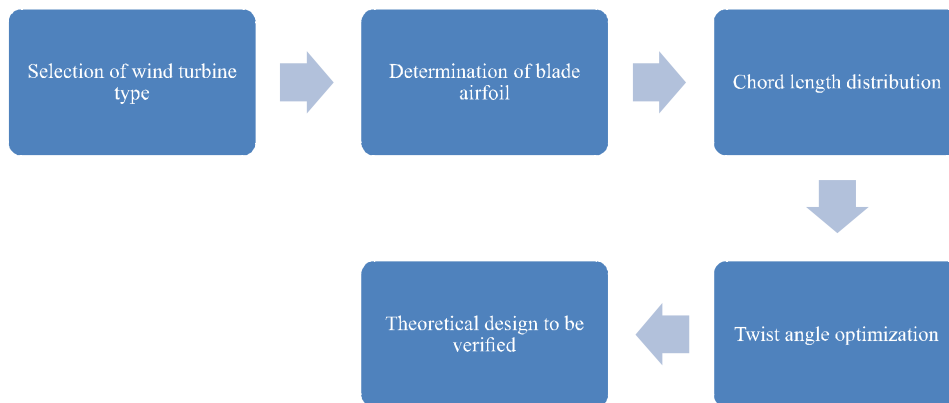*FIG. 1. MONTHLY AVERAGE WIND DATA FOR DIFFERENT STATIONS IN SINDH*

FIG. 2. STEPS FOR DESIGNING OF AN OPTIMUM WIND TURBINE BLADE

(2) The value of Power Coefficient (C_p) is being set by Betz limit which sets an upper limit of 0.59 of the theoretically achievable energy from the available wind energy. Normally power coefficient (C_p) = 0.4 [6-7].

(3) η can be assumed around 0.9 because it accounts to losses occurred in mechanical components e.g. generator, gearbox etc. of wind turbine [8].

(4) Tip speed ratio (η) is normally selected from 6-9 as it has vital role in converting kinetic energy into electrical energy [9-10].

(5) Number of blades is to be selected from Table 1 [11]. It has the vital role in maintaining the geometrical stability of the blade.

(6) After selecting number of blades, optimum airfoil is to be chosen. Optimum airfoil should have high lift to drag ratio as well as it ensures stability of the blade. That's the reason thick airfoils are being used near hub and thin airfoils are used near tip.

(7) After selecting airfoils, aerodynamic conditions for each airfoil will be selected. It is common to consider 80% of the C_L (airfoil lift coefficient)for calculating optimized twist angle for each section [12].

(8) After selecting airfoil aerodynamic conditions, blade is divided into 10-20 sections [13]. Each section has got its own airfoil so individual section can be optimized.

(9) Chord width, twist angle and Reynolds number are calculated according to following equations.

(i) Chord Width

$$C = \left(\frac{16\,\pi r}{BC_L}\right)\sin^2\left(\frac{1}{3\tan^{-1}\left(R/\lambda r\right)}\right) \tag{2}$$

(ii) The Reynolds Number is given as:

$$Re = \frac{\rho \dfrac{V^2}{L}}{\mu \dfrac{V}{L^2}} = \rho VL/\mu \tag{3}$$

(iii) The Twist Angle is:

$$\beta = 90^{\circ} - \frac{2}{3}\tan^{-1}\left(1/\lambda\right) \tag{4}$$

$$a = \left(1 + \frac{4\cos^2\beta}{C_L\sin\beta}\right)^{-1} \tag{5}$$

$$a' = \left(\frac{1-3a}{4a-1}\right) \tag{6}$$

$$a' = \left[\frac{\sigma' CL}{4\lambda\cos\beta}\right]\left(1-a\right) \tag{7}$$

(10) Iterative process is being adopted for twist angle. Following are the steps.

(11) Make an initial guess of axial induction factor (a) and a'.

TABLE 1. TSR AND NUMBER OF BLADES

TSR	1	2	3	4	>4
No. of Blades	8-24	6-12	3-6	3-4	1-3

(a)   Calculate solidity (σ') and β.

(b)   Choose appropriate C_L and C_D for the angle of incidence.

(c)   Calculate a and a' again until Δa and $\Delta a'$ converges.

3.   WIND TURBINE BLADE DESIGN FOR JAMSHORO

The input parameters for the blade design for Jamshoro are presented in the following section. These parameters will be used to compute theoretical design. Later, simulations in Q-blade will be performed to validate the design.

3.1   Input Parameters

In July Jamshoro has got the highest wind speed of 13.9m/s and in January lowest wind speed of 5m/s. keeping in view the above conditions, following parameters were selected for the design:

(1)   Power Coefficient (C_p) = 0.4 [14-15].

(2)   Efficiency (η)= 0.9 [16-17].

(3)   Tip speed ratio (λ) =7 [18-19].

(4)   3 blades have been chosen as per Table 1.

(5)   After analyzing their aerodynamic characteristics i.e. lift coefficients and lift to drag ratio, three NACA profiles i.e. NACA 4412, 4415 and 4418 have been selected with their lift coefficients as 1.45, 1.45 and 1.48, respectively.

(6)   Each section has its own airfoil. Normally 80% of the airfoil lift coefficients is used to calculate blade twist. In our case for NACA 4418 it is 1.184 and for NACA 4415 and NACA 4412 it is 1.16 [20].

(7)   Blade consists of 17 sections[21].

(8)   Total blade tip radius is 43.25 for wind speed of Jamshoro ranging from 5-13.9m/s, to get maximum power output. If small radius such as 3 or 5 meter is selected then there is no power output at wind speed of 5/m/s which is unacceptable due to the fact that there will be no power output for 6months (January, February, March, October, November and December). But if radius is 43.25 meter then we get good power output of 162KW from one wind turbine.

3.2   Theoretical Design of Blade

Power output of the blade was calculated using equation1 by substituting Cp = 0.4, η = 0.9, R = 43m. For wind speed of 5 m/s, the power output was 161.9 KW. For wind speed of 13.9m/s, the power output was 3.48MW. The design Table 2 summarizes the results of the theoretical blade design.

First four sections are just used for strengthening the blade. The calculation for 5th section is presented in **Appendix-I**. Calculation results for all sections are summarized in Table 3.

4.   THEORETICAL DESIGN VERIFICATION USING Q-BLADE

While simulating the blade design in Q-Blade software, first of all NACA profiles were declared as shown in **Fi**g. 3. In the second step the section wise blade profile was created. After that the C_L/C_D versus angle of Attack graphs of each section of blade was simulated. Fig. 4 shows the C_L/C_D versus Angle of Attack graphs for 5th section of blade. The maximum value of Cl/Cd occurred for 5th section and it was equal to 140 at α=6^0. For other section this value was decreased and minimum value occurred for 17th section and it was equal to 100 at α=6^0. The power coefficient versus tip speed ratio graph was obtained by

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Q-blade simulation and is shown in Fig. 5. Power vs Wind Speed graph in Q-blade simulation is shown in Fig. 6.

The theoretical calculation revealed a power output value of 161.9 KW at 5m/s wind speed. The Q-blade simulation results give slightly higher power output of 163KW. Also simulated power output for 13.9m/s wind speed is 4MW but theoretical power output is 3.48MW. The power difference between theoretical and simulated design is small for minimum wind speed of 5m/s. On the other hand, the power difference between theoretical and simulated design is significant for maximum wind

TABLE 2. WIND BLADE PROFILE DESIGN FOR DIFFERENT SECTIONS OF THE BLADE

No.	Pos (m)	Twist Angle	Chord Width (m)	Aerofoil	Reynold Number (million)
1.	0	6.4	2.5	Circular Foil	D=1.2
2.	1.5	6.4	3	Circular Foil	D=1.2
3.	3.5	6.4	4	Circular Foil	D=1.2
4.	6.5	6.4	5	Circular Foil	D=1.2
5.	8	6.4	5.21	NACA-4418	0.172
6.	11	6.5	4.4	NACA-4418	1.45
7.	14	6.65	3.7	NACA-4418	1.22
8.	17	5.95	3.21	NACA-4418	1.06
9.	20	5.48	2.81	NACA-4418	0.92
10.	23	5.9	2.55	NACA-4415	0.84
11.	26	4.8	2.29	NACA-4415	0.75
12.	29	3.8	2.08	NACA-4415	0.68
13.	32	2.7	1.9	NACA-4412	0.62
14.	35	2.1	1.75	NACA-4412	0.57
15.	38	1.7	1.62	NACA-4412	0.53
16.	41	1	1.51	NACA-4412	0.49
17.	43.25	0.5	1.43	NACA-4412	0.47

TABLE 3. TWIST ANGLE CALCULATION FOR WIND BLADE DESIGN

No.	Pos (m)	Twist	No.	Pos (m)	Twist
5.	8	6.4	12.	29	3.8
6.	11	6.5	13.	32	2.7
7.	14	6.65	14.	35	2.1
8.	17	5.95	15.	38	1.7
9.	20	5.48	16.	41	1
10.	23	5.9	17.	43.25	0.5
11.	26	4.8			

speed of 13.9m/s, this is due to the fact that for simulated design, the Q-blade software uses BEM theory for optimization of the wind blade which changes power coefficient to 0.47. Theoretical and simulated power outputs during different months of the year have been compared in Fig. 7.

The blade designed for the Jamshoro wind corridor has been optimized according to the wind speed data presented in Fig. 1. However, if the wind speed become higher than the maximum observed speed of 13.9 m/s, the corresponding Reynolds number will be higher. In such case the blade should be redesigned. The Reynolds number is given by Equation (3). This equation implies that for higher Reynolds number the cord length should by decreased accordingly, resulting in dull blade. The variation of chord length with wind energy is illustrated in Fig. 8. It has been shown that chord length decrease linearly with wind velocity.

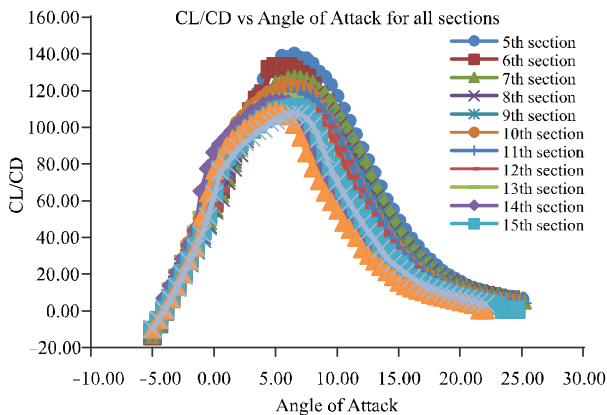*FIG. 3. SHOWING WIND BLADE IN Q-BLADE HAVING 17 SECTIONS*

FIG. 4. C_L/C_D VS. ANGLE OF ATTACK FOR DIFFERENT SECTIONS
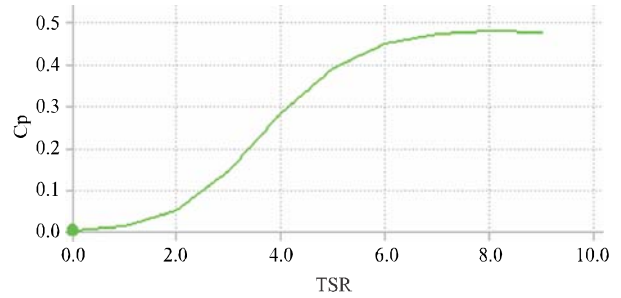
FIG. 5. POWER COEFFICIENT VS TSR GRAPH

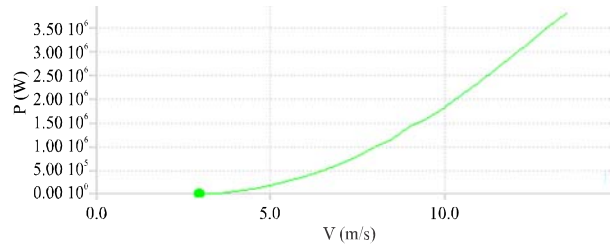*FIG. 6. COMPARISION POWER VS. WIND SPEED GRAPH OBTAINED FROM Q-BLADE SIMULATION*
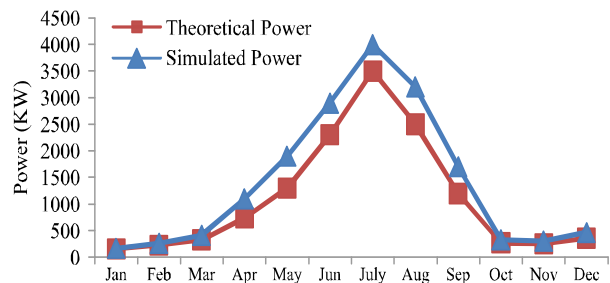
FIG. 7. MONTH WISE THEORETICAL AND SIMULATED POWER OUTPUTS

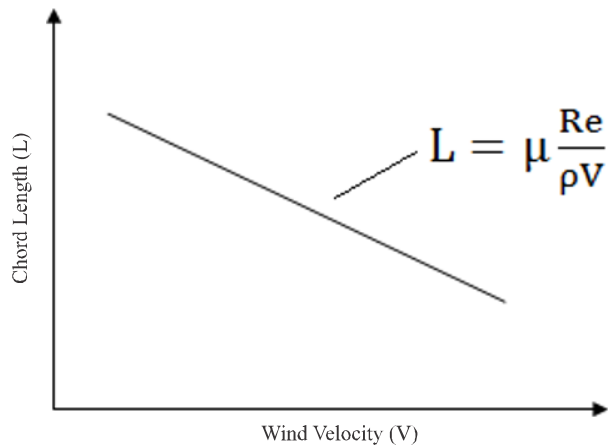$$L = \mu \frac{Re}{\rho V}$$

FIG. 8. ILLUSTRATION OF THE VARIATION OF CHORD LENGTH WITH RESPECT WIND VELOCITY

Mehran University Research Journal of Engineering & Technology, Volume 36, No. 4, October, 2017 [p-ISSN: 0254-7821, e-ISSN: 2413-7219]
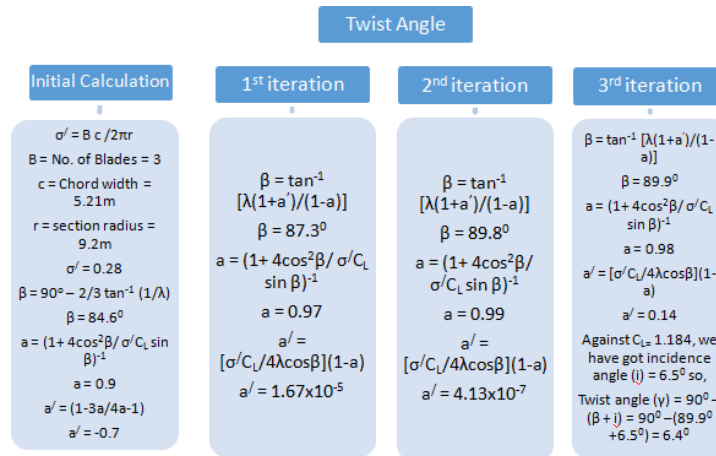
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5. CONCLUSION

Wind blade was designed in accordance with BEM theory for wind conditions of Jamshoro. Also basic parameters for wind blade design were identified and analyzed and then using those parameters, theoretical design was prepared and then verified with Q-blade. The theoretical results reveal that for minimum wind speed equal to 5m/s (in January), the power is equal to 161.9KW. For the high wind speed equal to 13.9m/s (in July) the power is 3.48MW. The Q-blade analysis showed that for minimum wind speed of 5m/s power is 163KW. For high wind speed equal to 13.9m/s, the power is 4MW. The power difference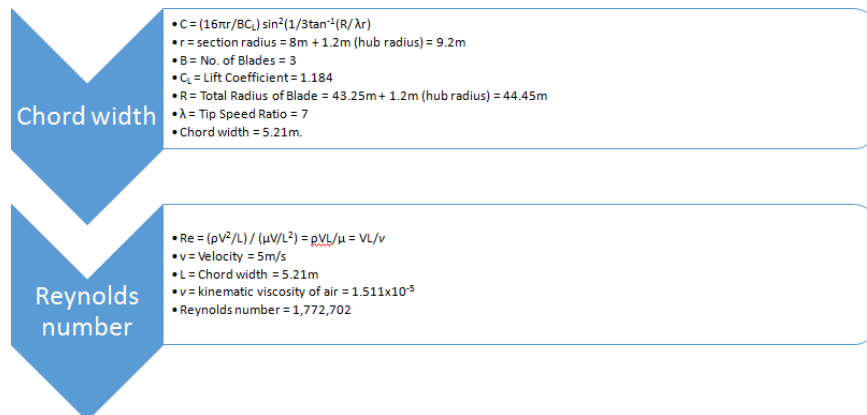 between theoretical and simulated design is small for minimum wind speed of 5m/s, In case of maximum wind speed, the difference between theoretical and simulated design is more because Q-blade uses BEM theory for optimization of the wind blade. It has changed the power coefficient to 0.47 that results in higher coefficients.

The design presented in this paper can be validated with HARP which is a MATLAB optimization toolbox. Similarly the optimization can be performed with respect to efficiency using optimization function and optimization algorithms for achieving maximum efficiency. However the efficiency optimization should be performed such that the cost of design is unaffected.

APPENDIX-I. 5TH SECTION ITERATION PROCESS

Twist Angle

Initial Calculation

$\sigma' = B c /2\pi r$
B = No. of Blades = 3
c = Chord width = 5.21m
r = section radius = 9.2m
$\sigma' = 0.28$
$\beta = 90° - 2/3 \tan^{-1}(1/\lambda)$
$\beta = 84.6°$
$a = (1+ 4\cos^2\beta/\sigma'C_L \sin\beta)^{-1}$
$a = 0.9$
$a' = (1-3a/4a-1)$
$a' = -0.7$

1st iteration

$\beta = \tan^{-1}[\lambda(1+a')/(1-a)]$
$\beta = 87.3°$
$a = (1+ 4\cos^2\beta/ \sigma'C_L \sin\beta)^{-1}$
$a = 0.97$
$a' = [\sigma'C_L/4\lambda\cos\beta](1-a)$
$a' = 1.67\times10^{-5}$

2nd iteration

$\beta = \tan^{-1}[\lambda(1+a')/(1-a)]$
$\beta = 89.8°$
$a = (1+ 4\cos^2\beta/\sigma'C_L \sin\beta)^{-1}$
$a = 0.99$
$a' = [\sigma'C_L/4\lambda\cos\beta](1-a)$
$a' = 4.13\times10^{-7}$

3rd iteration

$\beta = \tan^{-1}[\lambda(1+a')/(1-a)]$
$\beta = 89.9°$
$a = (1+ 4\cos^2\beta/\sigma'C_L \sin\beta)^{-1}$
$a = 0.98$
$a' = [\sigma'C_L/4\lambda\cos\beta](1-a)$
$a' = 0.14$
Against $C_L = 1.184$, we have got incidence angle (i) = 6.5° so,
Twist angle (γ) = 90° − (β + i) = 90° −(89.9° +6.5°) = 6.4°

Theoretical Calculation

Chord width

- $C = (16\pi r/BC_L) \sin^2(1/3\tan^{-1}(R/\lambda r)$
- r = section radius = 8m + 1.2m (hub radius) = 9.2m
- B = No. of Blades = 3
- C_L = Lift Coefficient = 1.184
- R = Total Radius of Blade = 43.25m + 1.2m (hub radius) = 44.45m
- λ = Tip Speed Ratio = 7
- Chord width = 5.21m.

Reynolds number

- $Re = (\rho V^2/L) / (\mu V/L^2) = \rho VL/\mu = VL/v$
- v = Velocity = 5m/s
- L = Chord width = 5.21m
- v = kinematic viscosity of air = 1.511×10^{-5}
- Reynolds number = 1,772,702

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