Innovative Design of New Generation of Horizontal Axis Wind Turbines (HAWT)

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Abstract

A new innovative method for aerodynamic design of HAWT is introduced here. Aerodynamic design of horizontal axis wind turbines is presently obtained using the combined momentum and blade element theory (BEM). Further improvements were achieved by incorporating wake rotation, tip losses, and some off-design amendments. In all of these, no closed analytical solutions exist, drag coefficient is always taken to be zero when calculating axial and angular induction factors, and some cumbersome iterative numerical methods are employed to obtain wind turbine parameters. The iterative methods usually exhibit poor convergence and also sometimes lead to non-unique multiple solutions. In our new analytical approach, the mentioned theories are advanced into a new level of closed form unique solution in which all the effects of drag coefficient, wake rotation, and tip losses are incorporated for the design of new generation of HAWT. It is observed from this study that the classical optimum Glauert type wind turbines are not necessarily the best initial design; because some modification to the near root of HAWT blades introduced in our modelling can substantially enhance characteristics and performance of HAWTs particularly at high wind speeds.

Introduction

A closed mathematical method invented for the optimum design of the next generation of large HAWT. The classical method of designing optimum wind turbine rotor blade are expressed by Eggleston and Stoddard [1], Manwell et al. [2], Nelson [3], Hau [4], and Burton et al. [5]. This leads to requirement of a numerical iterative programme for obtaining the key parameters of the wind turbine blade, such as axial induction factor, angular induction factor, and the relative angle of wind. Using these, a number of computer programmes developed by Sedaghat et al. [6, 7, 8] for designing mid-class HAWTs. In general for the classical Glauert type optimum designs [1], the effects of drag coefficient are neglected in some stages for obtaining optimum design. Based on these, the performance of some conventional in operating wind turbines are given by some empirical relations [2]. The key feature of our new finding is the modification of the near root region of the HAWTs blade in comparison with classical Glauert type methods using a direct and non-iterative method.

Rotor design using BEM theory

The primitive blade shape is determined using an optimum shape blade considering wake rotating. Ultimate blade shape and its performance are specified with iterative relations and including drag, tip losses and ease of manufacturing. It is also worth emphasizing that with more accurate aerodynamic coefficients at high attack angles, the more accurate design and performance prediction can be obtained. But the aerodynamic coefficients of a rotating airfoil are different from the ones of a linear moving airfoil at stall conditions.

Considering the rotor as an actuator disk which its effects are a sudden drop in pressure and assuming constant speed at the rotor [2], the linear momentum theory is used for air flow through a one dimensional tube as shown in Fig. 4.

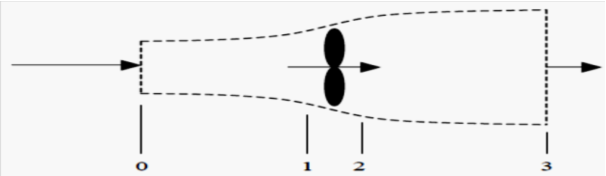

Fig. 1. Actuator disk modelling of a wind turbine in a stream tube

From Betz theory, an ideal wind turbine reduces wind speed to two third of the freestream value [2]. Since the wind turbine produces a useful torque for generating power, the conservation of moment of momentum must be satisfied by employing a wake rotation downstream of the wind turbine in some annular control volumes as shown in Fig. 2.

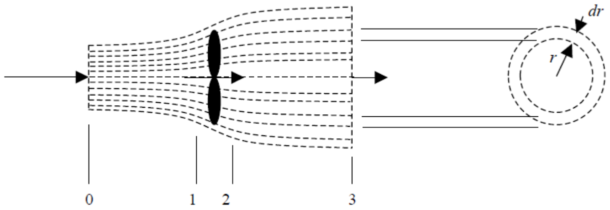

Fig. 2. Annular control volumes for calculating wake rotation.

In actuator disk theory, friction drag is ignored which is not realistic. In order to modify this shortcoming [2], blade element theory is considered to incorporate the effects of drag force exerted on each elemental constitution of blade as shown in Fig. 3. The design with wake rotation took into account the generation of rotational kinetic energy in the wake, which resulted in less energy extraction by the rotor than it would be expected without wake rotation.

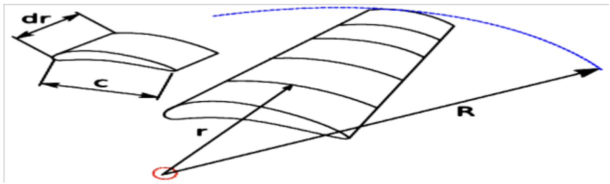

Figure 3. Annular control volumes for calculating wake rotation.

Adopting the procedure discussed in Manwell [2], one may calculate the power coefficient through an iterative method to the following form:

$$C_P = 8/\lambda^2 \int_{\lambda_h}^{\lambda} F \lambda_r^3 \acute{a} \, (1-a)[1-(C_d/C_l)\cot\varphi] d\lambda_r$$

F is tip loss correction factor, a is axial induction factor, $\acute{a}$ is angular induction factor, $\lambda_r = r\Omega/U$ is the local speed ratio for an element of blade at radial distance of r. The element dimension is c as the local chord length and dr as the width of element. The drag to lift ratio (C_d/C_l) corresponds to the local airfoil section.

Results of the New Method

A closed mathematical method invented for the optimum design of HAWT in this work and the results of this method is compared with the classical Glauert optimum design and an empirical performance characteristics of some conventional in operating wind turbines. The key feature of our finding is in modification of the near root region of the blade of HAWTs in comparison with classical Glauert type methods. The results of this innovative design are merely presented in this short communication.

The variation of the angular induction factor, $\acute{a}$, as the function of the local speed ratio, λ_r, for different values of the drag to lift ratio, $\varepsilon = \frac{C_d}{C_l}$, is shown in Fig. 4 for present method also is compared with the Glauert optimum rotor design. The results indicate that the angular induction factor variation against the local speed ratio for our optimum design is independent to the drag to lift ratio and compares well with the Glauert optimum design.

Figure 5 shows the interesting phenomena that the proposed model in this paper has always generated the optimum value for the axial induction factor, a=1/3, for the most practical ranges of drag to lift ratio for wind turbine rotors in operation today. For the high drag to lift value of cd/cl=0.04, the axial induction factor reduces for the local speed ratios higher than 8 near tip of blade rather than the root! The axial induction factor from the classical Glauert optimum rotor deviated from the optimum value near the root of the blade. This clearly shows the advantage of present modelling compared with classical methods to maintain the optimum axial induction factor throughout the rotor.

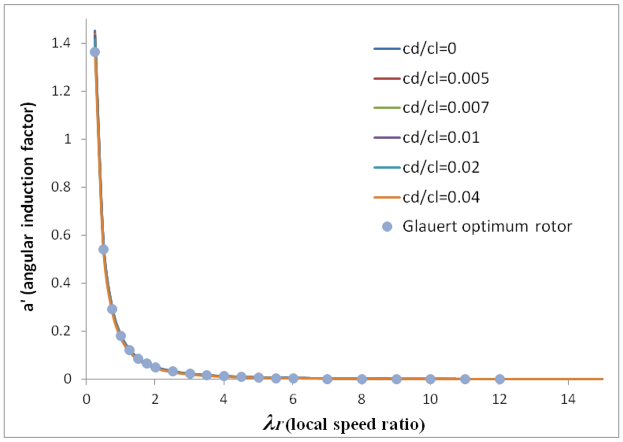

Fig. 4. The variation of the angular induction factor against the local speed ratio for different values of drag to lift ratios

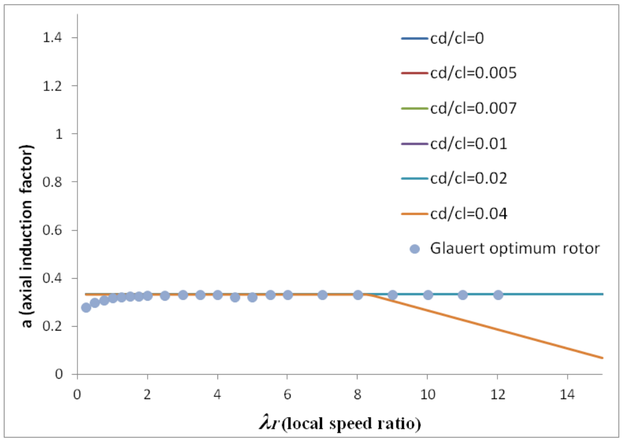

Fig. 5.The variation of the axial induction factor against the local speed ratio for different values of drag to lift ratios

Similarly as shown in Fig. 6, it is observed that the relative wind angle compares well with the Glauert classical distribution and the effect of drag to lift ratio is merely appears for large drag to lift ratio of cd/cl=0.04 near the tip of the blade. It is however interesting to note that the relative wind angle near the root is slightly lower than the value obtained from the classical Glauert solution and therefore enhances the wind turbine performance near the root. For instance for cd/cl=0.005, the relative wind angle from our model at $\lambda_r = 0.25$ is calculated $\varphi = 47.5\, deg$ whilst for the Glauert rotor this value is $\varphi = 50.6\, deg$. For the dual's point optimisation of cC_l, the multiplier of the chord length, c, by the cross section aerofoil lift coefficient, C_l, a blade element parameter (BEP) in the form of $\frac{cC_lB\Omega}{2\pi U} = \frac{4a}{1-a}F\lambda_r\frac{sin\varphi}{(cot\varphi+\varepsilon)}$ is introduced and the variation of this parameter is demonstrated in Fig.7.

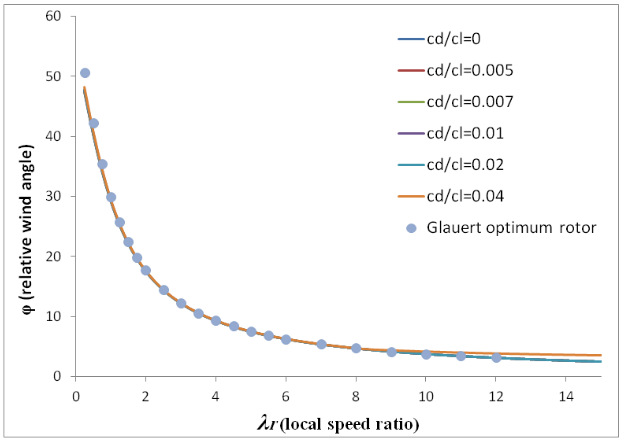

Fig. 6. The variation of the relative wind angle against the local speed ratio for different values of drag to lift ratios

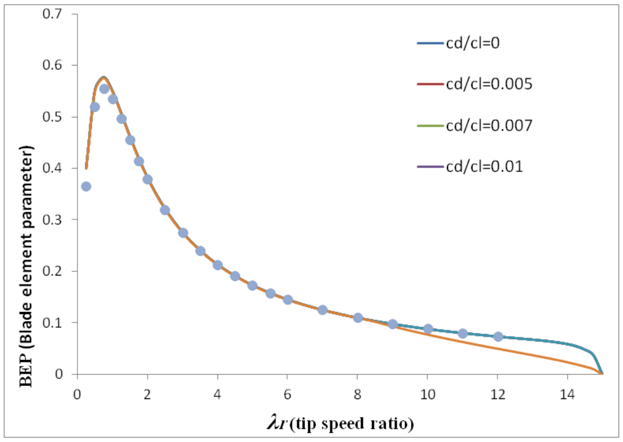

Fig. 7. The variation of the blade element parameter against the local speed ratio for different values of drag to lift ratios

This again clearly shows some enhancement in design of the blade near root. The BEP value is higher near the root compared with the classical design; therefore, more power may be obtained from the region near the root of the blade using our modelling. In a similar fashion a solidity parameter is defined as $\sigma C_l = \frac{4a}{1-a}F\frac{sin\varphi}{(cot\varphi+\varepsilon)}$ and its variation is shown in Fig. 8. This figure shows that the solidity parameter is insensitive to the drag to lift ratio. However, the solidity parameter near the root is higher than the Glauert design. For instance for cd/cl=0.005, the solidity parameter from our model at $\lambda_r = 0.25$ is calculated $SP = 1.6$ whilst for the Glauert rotor this value is $SP = 1.46$.

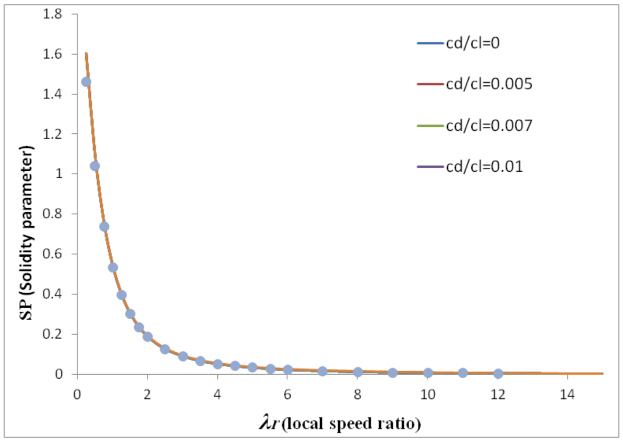

Fig. 8. The variation of the solidity parameter against the local speed ratio for different values of drag to lift ratios

Moreover, the most significant outcome of this work is presented in Figs. 9 to 11. In Fig. 9, the local power coefficient is shown across the blade radius for different drag to lift ratios. It is observe that the present modelling not only has significantly improved the rotor design of HAWT in comparison with Glaert model but also demonstrates the performance and characteristics of the new generation of optimum HAWTs. A significant power gain can now be obtained just near the root of the blade in comparison with the classical optimum design particularly at high speeds. The available empirical results for the conventional wind turbines presented in Manwell (2002) [2] as

$$C_{p,\max} = \left(\frac{16}{27}\right)\lambda\,[\lambda + \frac{1.32 + \left(\frac{\lambda - 8}{20}\right)^2}{B^{2/3}}]^{-1} \quad - \frac{0.57\varepsilon\lambda^2}{\left(\lambda + \frac{1}{2B}\right)}$$

In the above relation, *B* is the number of blades, which is taken equals to 3 for the most conventional HAWTs.

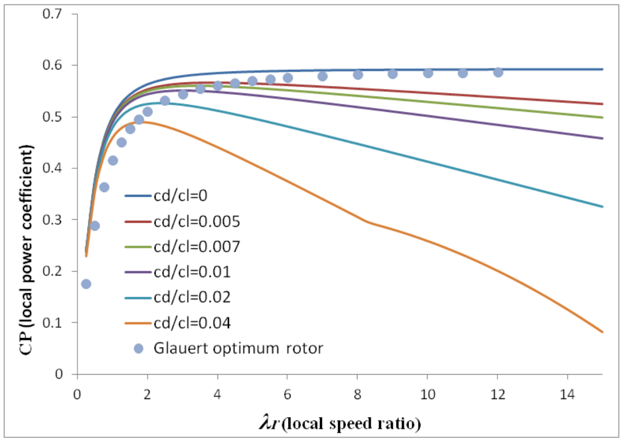

Fig. 9. The variation of the local power coefficient against the local speed ratio for different values of drag to lift ratios

As shown in Fig. 10 for the local power coefficient, far better power generation is observed by using the new generation of the wind turbine blades in comparison with empirical relation for the conventional commercial wind turbines. This was not seen in all previous figures and for all previous parameters such as angular induction factor or chord and twist angle distribution but has shown their undiscovered sensitive effects in the power coefficient.

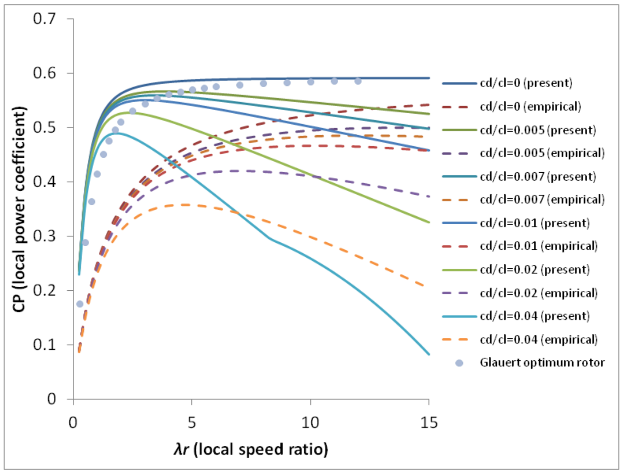

Fig. 10. Comparison of the local power coefficient against tip speed ratio for different values of drag to lift ratios for present new design (solid lines), conventional rotor design (dashed lines), and the Glauert optimum rotor

In Fig. 11 the total power coefficient is shown which indicate that at higher wind speeds (for lower values of tip speed ratios) the power gain of the innovative designed rotor can be much higher than the classical rotors.

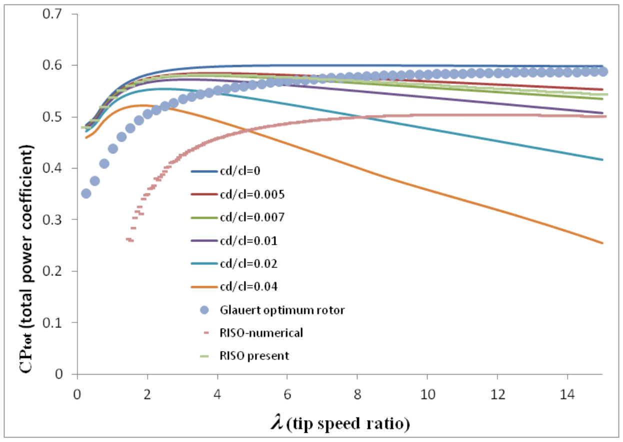

Fig. 11. The variation of the total power coefficient against tip speed ratio for different values of drag to lift ratios

In Burton et al. [5], for the optimal blade design for constant-speed operation which is common for grid connected turbines, we see that the tip speed ratio is continuously changing and no simple technique is yet introduced for the optimal design of a blade operating at constant rotational speed. Burton et al. [5] have shown the results for the maximum power coefficients for a range of design tip speed ratios and several lift/drag ratios using a non-linear programming method as shown in Fig. 12. This confirms that our unique innovative method do the same without limitation of using any non-linear programming while maintaining the maximum power for the full blade length.

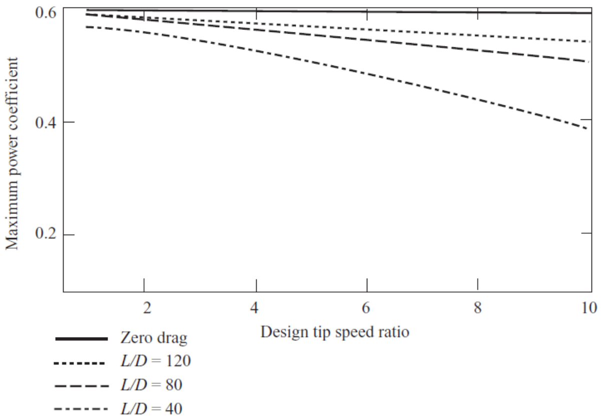

Fig. 11. The variation of maximum power coefficient with design tip speed ratio for various lift/drag ratios [5]

Conclusions

New generation of HAWT can substantially benefit from the outcome of this study which needs more financial and supports from the major organisation and institutions in Iran to support our study to elaborate in full all aspects of manufacturing and tests of the new innovative design of HAWT blades. We strongly believe that the finding of our research can considerably contribute in cost reduction of the wind turbines, increase in the net power gain from the wind energy, and cost reduction in electricity produced by the new generation of large horizontal axis wind turbines.

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