A numerical study of Vertical Axis Wind Turbine performances in twin-rotor configurations

M Guilbot¹, S Barre¹, G Balarac¹, C Bonamy¹ and N Guillaud²

¹ UGA, CNRS, Grenoble INP, LEGI, 38000 Grenoble, FR
² HydroQuest, 38240 Meylan, FR
E-mail: matthieu.guilbot@univ-grenoble-alpes.fr

Abstract. Placing two counter-rotating rotors of a Vertical Axis Wind Turbine (VAWT) can lead to a significant power enhancement and a faster wake resorption. This global power output is directly related to the spacing between both rotors permitting a mutual confinement effect. In addition, the relative direction of angular velocity of both rotors can strongly impact the overall performances of the machine. A range of two-dimensional (2D) Unsteady Reynolds Averaged Navier-Stokes (URANS) simulations has been managed in order to study the aerodynamic interactions occurring in a pair of VAWT. By comparing with a single-rotor of VAWT, it has been shown than the global power enhancement of a double-rotor VAWT is linked with an extension of the lift production range in one of the two first quartiles of the upwind path. Moreover, the region of the extra power generation seems to be dependant on the relative rotational directions of counter-rotating rotors. In all cases, the extent of lift generation can be associated with a suppression of the cross-stream velocity induced by the confinement of the neighbouring turbine. This local flow perturbation, closed to the inner region, leads to an augmentation of the incidence experienced by the blades in the upwind path, increasing the global lift and torque recovered by the turbine.

1. Introduction

1.1. Global context

With the increase of energy demand and global warming, renewable energies such as water or wind energies appear as durable and eco-friendly alternatives to fossil energies. In wind energy conversion, two main technologies of turbines co-exist and have its pros and cons: the Horizontal Axis Wind Turbines (HAWT) where the rotational turbine axis is aligned with the incoming flow and the Vertical Axis Wind Turbines (VAWT) where this axis remains perpendicular to the flow. Even if the first category is currently the most advanced and developed technology, recent reports underlined the numerous advantages of VAWT [1]. From a structural point of view, VAWT benefit of a lower center of gravity increasing the structure stability (for wind floating applications) and simplifying operating and maintenance operations. Moreover, VAWT can reduce some mechanical loads encountered by the blades: VAWT are not prone to fatigue effects due to gravity (for large-scale models). In terms of aerodynamics, VAWT also present some assets: no-sensitivity to the flow direction, a few drop of performances in high-turbulent flows and a faster wake resorption. This last point explains why several surveys pointed out the best power density (per unit of land area) of wind farms obtained with VAWT compared to HAWT with a substantial gain of performances by placing co-rotating turbines in close proximity.
However, a Single-Rotor Turbine (SRT) of a VAWT still suffer from a lower efficiency compared to an isolated rotor of a HAWT. Adding an additional rotor side-by-side to a SRT of a VAWT, creating then a Multi-Rotor Turbine (MRT), can improve the global performances of this turbine module. Furthermore, the resulting power enhancement of the double-rotor configurations can be observed for a large range of incoming wind directions [2], not requiring an additional expensive yaw-control mechanism.

1.2. Previous studies

Then, our study focuses on the optimization in terms of performances of different MRT configurations composed of two counter-rotating rotors. Previous experimental campaigns showed the beneficial energy exchange of two co-rotating pair of VAWT resulting in a significant power enhancement. For instance, the famous experimental survey conducted by Dabiri in the Antelope Valley open field in 2011 [2] underlined a power improvement of about 10% for the double-rotor configurations compared to a single one. Other experiments in wind channels [3–5] exhibited similar results with an increase of the global power output, comprised between 14% and 17% according to the considered MRT configuration, and wake losses reduction by using a doublet of counter-rotating VAWT. Numerical simulations had also been managed in order to identify the key flow mechanisms involved explaining this power output increase with twin-rotor configurations. Zanforlin [6] justified this performance gain by a change of the cross-stream velocity in the upwind path due to the presence of the neighboring turbine: the blades should encounter a more adapted relative flow leading to an extension of the lift generation range. Moreover, Zanforlin also evoked a “wake contraction” in the downwind path making a larger momentum flux available in the downwind region. Giorgetti [7] also linked this performance improvement with a “wake re-energization” process in the downwind path due to a central acceleration of the flow in the inner region between both rotors. More recently, Alexander [8] gave another interpretation of this power enhancement by stating that a double rotor of VAWT could reduce the “bypass flow” that goes outside of an isolated turbine. According to him, the leading flow mechanism should be the “interference” between the opposite cross-stream velocities of both rotors in the upwind path, resulting in a high pressure upstream central zone. Then, the flow should diverge from this central region and should be redirected through both rotors limiting the bypass flow. De Tavernier [9] supported than the power enhancement is due to a more favourable distribution of the angle of attack causing by two major flow phenomena: the flow in the central region of a double-rotor configuration is accelerated caused by the flow restriction induced by both co-rotating rotors itself; a wake contraction is observed due to the presence of the neighbouring turbine increasing the mass flow rate in the downstream region of the rotor.

1.3. Motivation of the study

Therefore, both numerical and experimental approaches demonstrate the same trends about the power enhancement of MRT by closing two counter-rotating rotors of VAWT compared to a SRT. However, this available bibliographic data highlights some controversy, particularly about which relative rotational direction of counter-rotating rotors offers the highest power improvement. The present work will focus on the possible synergy effects when placing two counter-rotating rotors side-to-side in order to create a turbine module. Then, a comparison with an isolated SRT will be first investigated. These aerodynamic effects of mutual confinement induced by both rotors will be studied and weighted with the inner rotor spacing. Indeed, the influence of the distance inter-axes between the two co-rotating rotors will be also examined. Finally, this study will pay specific attention to the effects of the relative opposite direction of rotor angular velocities on the overall performances of the MRT. This last point will be essential for this study as long as there is no consensus in the literature about this effect.
In that respect, the purpose of this paper is not to decide definitively whether the whole future of wind power should rest on VAWT twin-rotor machines, but simply to document the 2D aerodynamic effects of such an arrangement and nothing else.

2. Model set-up

2.1. Geometrical parameters

The present numerical study provides a complete performances’ analysis of 6 different MRT configurations composed of two co-rotating rotors and compares them to a SRT reference configuration. The considered turbine is a two-straight-bladed Darrieus turbine. This low-solidity VAWT conducts to an optimal Tip-Speed ratio \( \lambda_{opt} = \frac{D \omega_{opt}}{V_0} = 4.0 \) estimated numerically.

The geometrical characteristics of the isolated rotor are summarized in Table 1 whereas Table 2 precises the different MRT parameters.

| Table 1. Geometrical characteristics of the SRT reference case |
|---------------------------------------------------------------|
| **Blades number** | **Height** | **Diameter** | **Chord length** | **Solidity** | **Airfoil section** |
| \( N_b \) | \( H \) | \( D \) | \( c \) | \( \sigma = \frac{N_b c}{D} \) | NACA |
| 2 | 1m | 1m | 0.05m | 0.1 | 0018 |

| Table 2. Geometrical details of the 6 MRT configurations |
|-----------------------------------------------------------|
| **MRT configuration** | **MRT 1** | **MRT 2** | **MRT 3** | **MRT 4** | **MRT 5** | **MRT 6** |
| **Rotor spacing** \( e \) | 1.05D | 1.05D | 1.50D | 1.50D | 1.50D | 1.50D |
| **Rotational direction** \( \omega \) | + | - | + | - | + | - |
| **Mast** | no | no | no | no | yes | yes |

The computational domain of the reference SRT case and the MRT configurations ones are identical. The length of the domain is equal to \( L = 50D \) with the turbine position at \( x = 20D \) from the inlet of the domain. These streamwise dimensions seem to be sufficient to establish the turbine wake according to our flow visualizations. The width of the channel is fixed to \( W = 20D \). Some tests have been managed in order to quantify the blockage effect due to the proximity of lateral boundaries. Even if a small blockage effect persists with \( W = 20D \), estimated to +3.6% for the SRT and more than +7% for the MRT configurations according to Blackwell formula [10], the next conclusions seems independent to the lateral confinement. Indeed, a similar numerical study with a narrower domain, with \( W = 2.5D \), leads to similar observations and conclusions (not presented here). For the MRT configurations, a 2\(^{nd}\) counter-rotating rotor has just been added side-to-side to the first one. The distance between the two rotors axis, conventionally named \textit{rotor spacing} distance, is represented by the parameter \( e \). The relative rotational direction \( \omega \) of the two counter-rotating rotors can take two values: \( \omega^+ \) when the two rotors \textit{suck} the fluid and \( \omega^- \) when they \textit{push} the fluid to flow back. For two MRT configurations, a central mast with an elliptic shape \((a = 0.2D \text{ and } b = 0.1D)\) has been added as displayed on Figure 6,(b). Figure 1.(a) displays the computational domain and its relative dimensions for the specific MRT 3 configuration. Figure 1.(b) defines the two possible relative directions of
angular velocity between the Counter-Clockwise (CW) and the Anti-Counter-Clockwise (ACW) rotors. The considered fluid is air at ambient temperature $T = 25^\circ C$ (with a kinematic viscosity

$$\nu = 15.6 \times 10^{-6} m^2.s^{-1}$$

and leads to moderate Reynolds numbers $Re_c$ in the range of 100 000. The free-stream velocity is assumed to be uniform and co-linear to the $x$-axis with a magnitude $V_0 = 8 m.s^{-1}$.

2.2. Numerical parameters
Concerning the numerical approach, Unsteady Reynolds Averaged Navier-Stokes (URANS) simulations have been conducted with the open source software OpenFOAM [11]. The one-equation Spalart-Allmaras turbulent model is used due to its good capacity to predict boundary layer separation and turbulent flow reattachment [12], adapted to predict with precision the cross-flow turbine performances [13]. 2nd order implicit schemes are employed for both spatial and temporal discretizations. A final time step corresponding to a rotation increment of $d\theta = 0.25^\circ$ is employed for the last 5 revolutions. The implicit time integration is used to speed-up the simulation by permitting to reach high Courant numbers with $CFL >> 1$. To simulate the rotating part, a sliding mesh technique is employed with fields interpolations between the fixed domain and the rotating regions. 15 revolutions have been simulated in order to reach a periodic behaviour of the forces and moments on the turbine. The time-averaging $< . >$ is realized between the 13th and the 15th revolutions:

$$< X(\theta) > = \frac{1}{6\pi} \int_{24\pi}^{30\pi} X(\theta) d\theta$$

Unstructured meshes have been generated via the software NUMECA-Hexpress with a structured part around the blades: 20 layers composed of hexahedrons have been created in the boundary layer region. These grids include a fine resolution close to the blades with $y+ = 1$. The chosen low–$Re$ approach for the near-wall treatment permits to accurately predict the flow dynamics inside the boundary layers. Our grid generation strategy leads to a final mesh of 326 000 cells for the SRT reference case. For the MRT configurations, the mesh of the 2nd rotor is generated just by duplicating the initial single rotor with a $(xOz)$-symmetry plane. An overview of the final mesh of the rotor region is given in Figure 2. For all these MRT configurations, a local
mesh refinement in the inner region has been achieved in order to see the mutual confinement of both rotors. It conducts to final meshes of about 620,000 cells for the MRT configurations. In terms of boundary conditions, classical conditions for external incompressible flow are used \cite{14}: a uniform velocity profile is imposed at the inlet (with a fixedValue \( V_{in} = V_0 = 8 m.s^{-1} \) associated with a zeroGradient on the pressure) while a constant pressure condition is set at the outlet (with a fixedValue \( P_{out} = 0 Pa \) associated with a zeroGradient on the velocity). No-slip conditions are imposed on the rotating blades and symmetryPlane conditions are assumed on the lateral walls. These boundary conditions are also represented in Figure 1.(a).

The validation part of this numerical study was done by realizing a series of numerical tests to ensure the accuracy of the present results. The influence of the final time step \( dt = d\theta/\omega \), the number \( N \) of simulated turbine revolutions and a grid sensitivity analysis were notably investigated (see Appendix).

3. Results
In order to quantify the performances of each configuration, we define the global Power Coefficient \( C_P \) as follows:

\[
C_P = \frac{M_z \omega}{\frac{1}{2} \rho DH V_0^3} \quad \text{with} \quad M_z = \left[ \iint_S \left( \vec{OM} \wedge (-P\vec{n} + \vec{t} : \vec{n}) \right) dS \right] \cdot \vec{e}_z
\]  

(2)

where \( M_z \) is the axial "drive" torque (i.e. the projection along the \( z \)-axis of the moment of pressure and viscous surface loads) recovered by a single rotor.

For the MRT configurations, the torque \( M_z \) refers to the total torque recovered by the double-rotor configuration i.e. the sum of both co-rotating rotors contributions. In that case, Equation (2) can be rewritten as:

\[
C_P = \frac{M_{tot} \omega}{\frac{1}{2} \rho 2 DH V_0^3} \quad \text{with} \quad M_{tot} = |M_z(\text{rotor}_{ACW})| + |M_z(\text{rotor}_{CW})|
\]  

(3)

Figure 3 presents the time-average Power Coefficient \( < C_P > \), with the blockage correction from \cite{10}, displayed versus Tip-Speed ratio \( \lambda \) for the SRT reference case and for all tested MRT configurations (i.e. for different rotor spacing \( e \), for both rotational directions \( \omega^+ \) and \( \omega^- \) and with/without a central mast). As long as our study deals with the optimization of aerodynamic performances, we will focus on the optimal Tip-Speed ratio \( \lambda_{opt} \) for which one the average Power Coefficient \( < C_P >_{opt} \) is maximal. Table 3 presents these optimal values of \( < C_P >_{opt} \) on \( \lambda_{opt} \) respectively for each MRT and SRT configurations.

3.1. Influence of the twin-rotor effect
The first result of the present study is that, placing the two counter-rotating rotors in closed proximity with the MRT configurations increases slightly the global power output compared to a
Figure 3. Average Power Coefficient $<C_P>$ versus Tip-Speed ratio $\lambda$

Table 3. Time-average Coefficients for different VAWT configurations

| Configuration | SRT | MRT 1 | MRT 2 | MRT 3 | MRT 4 | MRT 5 | MRT 6 |
|---------------|-----|-------|-------|-------|-------|-------|-------|
| $<C_P>_{opt}$ | 0.400 | 0.419 | 0.438 | 0.416 | 0.427 | 0.426 | 0.439 |

SRT. The SRT reference case gives an optimal Power Coefficient $<C_P>_{opt} = 0.400$ at $\lambda_{opt} = 4.0$. Globally, all the MRT configurations experience higher Power Coefficients for every considered Tip-Speed ratios as displayed on Figure 3. Moreover, we observe that the power enhancement of the "$\omega-$" MRT configurations is accompanied by an increase of the optimal Tip-Speed ratio with $\lambda_{opt} = 4.2$ (cf Figure 3 with the "$\omega-$" MRT represented in solid lines). The MRT configuration for $e = 1.50D$ shows respectively $<C_P>_{opt} = 0.416$ for $\omega+$ and $<C_P>_{opt} = 0.427$ for $\omega-$corresponding to a power enhancement of about +4% and +7% compared to the SRT case, in accordance with the 10% maximal value found in the literature studies for this rotor spacing [6–8]. The double-rotor effect of the MRT configurations, resulting in an higher Power Coefficient $<C_P>_{opt}$, is intensified when the rotors are placing closer and closer i.e. when the rotor spacing $e$ is decreased, once again in good agreement with the literature findings [7; 9].

3.2. Influence of the rotational direction

However, this power enhancement must be pondered with the considered relative rotational direction: with the direction $\omega-$, an increase of +2.5% on the optimal Power Coefficient is found by decreasing $e$ from $1.50D$ to $1.05D$ compared to less than +0.7% with the direction $\omega+$. Therefore, it has been shown that, independently of this distance $e$, the rotational direction $\omega-$ leads to higher performances compared to a SRT: a gain of +4.5% for $e = 1.05D$ and +2.6% for $e = 1.50D$. 
3.3. Influence of the central mast

Finally, a configuration with a central mast confirms these previous conclusions: the rotational direction $\omega^-$ always denotes higher performances. Besides, adding a mast reinforces this beneficial energy exchange between the co-rotating rotors with an increase of the maximal Power Coefficient $<C_P>_\text{opt}$ of more or less $+2.7\%$ compared to the same MRT configuration without mast with $e = 1.50D$.

4. Discussion

4.1. Analysis of local power extraction

In order to explain these global performances’ differences, a more detailed analysis has been done by focusing on instantaneous quantities. For instance, the Figure 4 displays the temporal evolution of the instantaneous Power Coefficient recovered by one blade during an entire turbine revolution. The angular position $\theta$ is defined as follows: $\theta = 0^\circ$ when the turbine is aligned with the $y$-axis and defined positive in the counter-clockwise direction. The optimal Tip-Speed ratio $\lambda_{\text{opt}}(\text{MRT}) = 4.2$ for all MRT configurations is considered (even if it is not exactly the same $\lambda_{\text{opt}}(\text{SRT})$, the following conclusions remain the same). To localize the performances differences, we can split the blade revolution into 4 equal-quartiles: $\theta \in [0^\circ : 90^\circ], [90^\circ : 180^\circ], [180^\circ : 270^\circ], [270^\circ : 360^\circ]$ in which ones power coefficients have been computed and averaged on each intervall (but not reported here). The first two quartiles for $\theta \in [0^\circ : 180^\circ]$ correspond to the upwind path whereas the last two quartiles with $\theta \in [180^\circ : 360^\circ]$ describe the downwind path.

A plenty of observations can be done thanks to this graph:

- The upwind path contributes to the major part of energy extraction (more or less $75\%$ of the total $<C_P>$) for all configurations and it can be explained by the low-solidity employed.
- The maximal peak of $C_P$ is reached for different angular positions depending on the configuration: the isolated rotor seems to present a maximal production peak around $\theta_{\text{max}} = 94^\circ$ whereas the different MRT configurations let appear a slight “shift” of this $\theta_{\text{max}}$, respectively to a lower value for the “$\omega^-$” configurations (solid lines) and to an higher value for the “$\omega^+$” configurations (dotted lines).
- In the upwind path, the balance of power production is quiet different according to the considered rotational direction $\omega$: for the “$\omega^-$” configurations, the first quartile seems to be more beneficial with an increase of $C_P$ of about $+30\%$ whereas for the “$\omega^+$” configurations, rather the second quartile presents higher values of $C_P$ of about $+15\%$ compared to the SRT.
- In the downwind path, all the MRT configurations recover much more power than the SRT reference case: about $+20\%$ for the “$\omega^+$” configurations and $+30\%$ for the “$\omega^-$” configurations. But these important power enhancements must be pondered by the low energy extraction of the downwind region situated in the wake of the upstream blade.

4.2. Analysis of averaged velocity fields

To give some physical explanations to this power enhancement, we can focus on averaged velocity fields around the blades. Indeed, two leading flow mechanisms can be responsible for an extra lift generation: a local increase of the flow rate passing through the rotor or an increase of the relative incidence on the blades. Figure 5 shows the averaged streamwise $\bar{V}_x$ and cross-stream $\bar{V}_y$ velocity components along a $y$-line situated at exactly one chord $c$ in front of the ACW rotor (please refer to Figure 1.(b) to see this $y$-line plotted with a black dashed arrow). Two principal conclusions can be driven to this figure:

- Both counter-rotating rotors of MRT configurations experience lower flow rates compared to the single rotor. The streamwise velocity $\bar{V}_x$ seems to be only increased in the inner
Figure 4. Instantaneous Power Coefficient $C_p$ versus angular position $\theta$ for $\lambda = 4.2$

![Instantaneous Power Coefficient $C_p$ versus angular position $\theta$ for $\lambda = 4.2$.](image)

Figure 5. Evolution of averaged streamwise $\tilde{V}_x$ and cross-stream $\tilde{V}_y$ velocities along a $y$-line just in front of the anti-clockwise rotor

![Evolution of averaged streamwise $\tilde{V}_x$ and cross-stream $\tilde{V}_y$ velocities along a $y$-line just in front of the anti-clockwise rotor.](image)

part of the double-rotor configurations as displayed on Figure 6.(b). This observation is opposed to the explanation of the power enhancement with the "reduction of the by-pass
flow” passing outside the single rotor given by Alexander [8].

- According to the rotational direction, the absolute value of the cross-stream velocity $|V_y|$ is reduced to 0 when the blades pass close to the inner accelerated flow region matching perfectly with the power increase regions; respectively for $y \in [0.5:1]$ or $\theta \in [0^\circ:90^\circ]$ for the ”ω−” configurations and for $y \in [0:0.5]$ or $\theta \in [90^\circ:180^\circ]$ for the ”ω+” ones. Then, the explanation of the power improvement could rather be associated to the “cancellation” of the cross-stream velocity component $V_y$. This observation had already been given by Zanforlin [6] who claimed that ”the change of lateral velocity in the upwind path” can make the incoming flow more favourable generating more lift and torque.

4.3. Analysis of local flow incidence

To evaluate the relative incidence seen by the blades, we can define the angle of incidence $\alpha$ as follows and simplify this expression for the specific angular position $\theta = 90^\circ$:

$$\alpha = \frac{\dot{V} \cdot \dot{t}}{\dot{W} \cdot \dot{n}} \Rightarrow \alpha(\theta = 90^\circ) = \frac{V_x}{V_y + R\omega}$$

where $\dot{V}$ and $\dot{W}$ are respectively the absolute and relative velocities. Figure 6.(a) presents the evolution of the angle of incidence $\alpha(\theta = 90^\circ)$ along an arbitrary $y_1$-line defined on Figure 6.(b) with a black solid arrow. The net power enhancement of the “ω−” MRT cases compared to the “ω+” MRT configurations at $\theta = 90^\circ$ (cf Figure 4) can be explained by an higher incidence on the blades increasing the tangential component of the lift responsible of the “driving” torque. Some additional visualizations of the incident flow at $\theta = 60^\circ$ and $\theta = 120^\circ$ (not presented in this paper) confirmed this power enhancement explanation with the increase of angle of incidence $\alpha$.

As long as the flow incidence varies with $\lambda$, the turbine solidity $\sigma$ should have an important influence on the most favourable rotational direction ”ω” of a twin-rotor configuration, as already observed by De Tavernier [9]. Indeed, increasing $\sigma$ conducts to smaller operating Tip-Speed ratios with higher angles of incidence on blades, leading possibly to dynamic stall [15], and could completely modify the previous conclusions about the optimal ”ω” direction. Next simulations will be investigated on high-solidity turbines in order to deeply analysis this solidity effect on a pair of counter-rotating VAWT, particularly on the change of incidence related to the considered rotational direction.

5. Conclusion

A series of 2D URANS simulations was conducted on a counter-rotating doublet of VAWT using the OpenFOAM finite-volume code with the Spalart-Allmaras turbulence model. A specific attention has been taken to obtain accurate simulations in order to arbitrate the antagonistic results found in the literature, in particular concerning the influence of the relative rotational direction on the global performances. At present, the results obtained show that the performance improvement by closing two rotors denotes a lower degree of importance than reversing the rotational direction of the rotors. Indeed, there is a significant power output enhancement by using the ”ω−” rotational direction for all MRT configurations. The addition of a central mast increases this power enhancement in every case but it does not change the optimal rotational direction. The global power enhancement should be related to an increase of the relative incidence on the blades particularly favourable with the ”ω−” configurations. However, this better energy extraction is directly linked to the turbine solidity: in our study, the low-solidity employed allows us to increase the relative small angles of attack experienced by the blades without deep stall and then expand the lift generation range. Increasing the solidity could increase the incidence on the blades beyond the dynamic stall angle and lead to total flow detachment on the blades with no more lift generation. Therefore, the conclusions about the
Figure 6. (a) Evolution of the angle of incidence \( \alpha \) along a \( y_1 \)-line at \( \theta = 90^\circ \) (left); (b) Velocity fields for MRT 1 & 2 (middle) and MRT 5 & 6 (right) configurations.

relative rotational direction could be reversed by considering high-solidity turbines. In addition, the influence of 3D effects have not been considered in this 2D numerical study: for some VAWT designed with a very low blade-to-chord ratio, high turbulent 3D flows can strongly impact the relative incoming flow seen by the blades. By this way, the previous conclusions could be modified for realistic 3D cases.

Appendix

A precise study focused on the influence of numerical parameters was done in order to obtain numerical results as accurate as possible. For these numerical tests, the "convergence criterion" proposed here is the invariance of the average Power Coefficient \( <C_P> \) between two incremental \( (i) \) and \( (i+1) \) values: 

\[
\epsilon = \frac{<C_P(i+1)> - <C_P(i)>}{<C_P(i)>} \times 100% < 1.0\%
\]

Figure A1 illustrates and quantifies the impact on the average Power Coefficient \( <C_P> \) of three numerical variables. The first graph represents the instantaneous Power Coefficient \( C_P \) for four different final time steps \( dt_{\text{final}} = \theta_{\text{final}}/\omega \) with the associated average values \( <C_P> \) detailed in the first table: \( \theta_{\text{final}} = 0.25^\circ \) shows no more big impact on \( <C_P> \). The second graph illustrates the convergence of \( <C_P> \) according to the considered \( N^{th} \) turbine revolution: after \( N = 12 \) revolutions (i.e from the 13\( ^{th} \) revolution) \( <C_P> \) does not vary a lot. Finally, the third graph shows a relative small grid sensitivity on \( C_P \) for three grids with different refinement levels (its mesh characteristics are presented in the last table): the Mesh X2 has been chosen for the current study.
Figure A1. Variation of average Power Coefficient $< C_P >$ for $\lambda = 4.2$ of the SRT reference case with different numerical parameters: $dt_{final}$ (top); $N$ (middle) and grid refinement (bottom).
References
[1] Borg M, Shires A and Collu M 2014 *Renewable and Sustainable Energy Reviews* 39 1214–1225
[2] Dabiri J O 2011 *Journal of Renewable and Sustainable Energy* 3 043104
[3] Kinzel M, Mulligan Q and Dabiri J 2012 *Journal of Turbulence* 13 38
[4] Brownstein I, Wei N and Dabiri J 2019 *Energies* 12 2724
[5] Vergaerde A, De Troyer T, Kluczewska-Bordier J, Parneix N, Silvert F and Runacres M 2020 *Renewable Energy* 146 181 – 187
[6] Zanforlin S and Nishino T 2016 *Renewable Energy* 99 1213–1226
[7] Giorgetti S, Pellegrini G and Zanforlin S 2015 *Energy Procedia* 81 227–239
[8] Alexander A and Santhanakrishnan A 2020 *Renewable Energy* 148 600 – 610
[9] De Tavernier D, Ferreira C, Li A, Paulsen U and Madsen H 2018 *Journal of Physics: Conference Series* 1037 022015
[10] Blackwell B F, Sheldahl R E and Feltz L V 1976 Wind tunnel performance data for the Darrieus wind turbine with NACA 0012 blades. Tech. Rep. SAND76-0130
[11] Weller H G, Tabor G, Jasak H and Fureby C 1998 *Computers in Physics* 12 620–631
[12] Crivellini A and D’Alessandro V 2014 *International Journal of Heat and Fluid Flow* 47 70–83
[13] Bachant P and Wosnik M 2016 *Journal of Renewable and Sustainable Energy* 8 053311
[14] Balduzzi F, Bianchini A, Maleci R, Ferrara G and Ferrari L 2016 *Renewable Energy* 85 419–435
[15] Guillaud N, Balarac G, Goncalves E and Zanette J 2020 *Renewable Energy* 147 473–486