A REVIEW ON COUNTER-ROTATING WIND TURBINES DEVELOPMENT

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Abstract - On a dynamic energy market characterized by the constant energy demand increase and economic as well as environmental constraints, the study and development of efficient conversion systems of wind's energy has been approached by a considerable number of researchers. Given the modern economic and environmental challenges regarding the energy production and consumption, an advance in the research of innovative or improved wind energy conversion solutions has been registered. The objective of this paper is to provide a comprehensive, but not exhaustive overview of research achievements in counter-rotating wind turbine systems development, characterization and use. The review presents the first theoretical results that led to the counter-rotating wind turbines development as well as the related methods used for investigating their performance. Valuable results have been found within various studies, which are carried out for different testing systems and conditions. Furthermore, there is still need of extensive studies, taking into account that the counter-rotating wind turbines have to prove their reliability in real operating conditions.

Keywords: wind energy, counter-rotation, wind turbine, performance.

1. INTRODUCTION

On a dynamic energy market characterized by the constant energy demand increase and economic as well as environmental constraints, the research on finding new or improved means of renewable energy sources conversion represents a suitable solution. The advance recorded in recent years for the energy produced by the conversion of renewables, especially wind, is reflected in the latest GWEC (Global Wind Energy Council) report. Across Europe, 13.805 GW of wind power was installed in 2015 [GWEC, 2016]. Romania installed in 2015 an additional 23 MW to the existing 2953 MW already installed by the end of 2014. In EU countries, there are currently installed 141.6 GW, out of the total cumulative capacity of 147.8 GW for all European countries. Furthermore, in 2015 the installed wind power exceeded the installed hydropower, becoming the third largest source of power generation in the EU [GWEC]. The world total of 432.883 GW of wind power is unevenly shared across the world (Fig. 1).

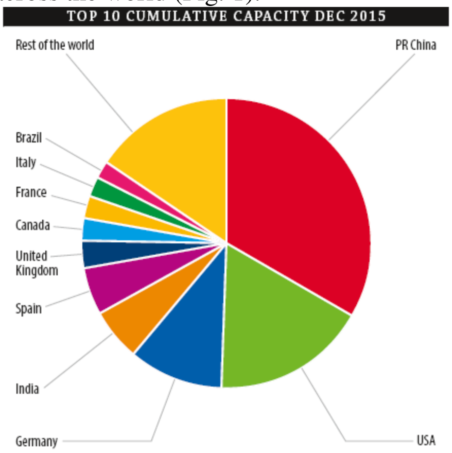

Fig. 1. Wind power across the world [1]

Given the modern economic and environmental challenges regarding the energy production and consumption, an advance in the research of innovative or improved wind energy conversion solutions has been registered. Therefore, the objective of this paper is to provide a comprehensive, but not exhaustive overview of research achievements in counter-rotating wind turbine systems (CRWT) development, characterization and use. A CRWT system consists of two rotors, one rotating clockwise, the other one counter-clockwise and either a unique generator adding-up the rotation of both wind rotors, or two independent electric generators, each of them connected to a rotor. The wind rotors can be placed in several positions: up-wind (in front of the generator), down-wind (in the rear of the generator) or at a certain distance, one up-wind and one down-wind. In the various existing studies in literature, the front rotor is called also main rotor or up-wind rotor; likewise, the rear rotor is called secondary rotor or down-wind rotor.

2. FIRST THEORETICAL RESULTS LEADING TO CRWT DEVELOPMENT

The starting point in the research and development of CRWT systems is represented by the results of the theoretical research performed by Newman in 1983 [2], who further analyzed and developed Betz's theory, which states that the wind turbine rotors reduce the wind velocity from the initial value v_1 (m/s), upstream the rotor, to $v_2 = v_1/3$ (m/s), downstream the rotor. Betz introduced the *power coefficient* C_P, which is a dimensionless parameter expressing a turbine's capacity to extract energy from wind.

$$C_P = \frac{P_{abs}}{0,5\rho v_1^3 A} \quad (1)$$

According to Betz's law, a wind turbine can theoretically capture approximately 59.3% from the airstream's energy. In real conditions, the power coefficient is lower than the theoretical value since the aerodynamic and mechanical losses of the turbine are considered. In equation (1), P_{abs} is the theoretical power absorbed by a wind turbine, ρ – air density in kg/m^3,A – the area swept by the turbine's rotor, perpendicular on wind's direction, in m^2.

By applying the actuator-disc theory to a vertical axis wind turbine, it was showed [2] that the theoretical maximum power coefficient of a wind turbine can be increased for a very high tip speed ratio from 59% to 64% if a second rotor with the same radius is placed downstream the first one (Fig. 2). This theoretical result led to various theoretical and experimental studies aiming to determine the conditions that ensure more power extraction from the wind.

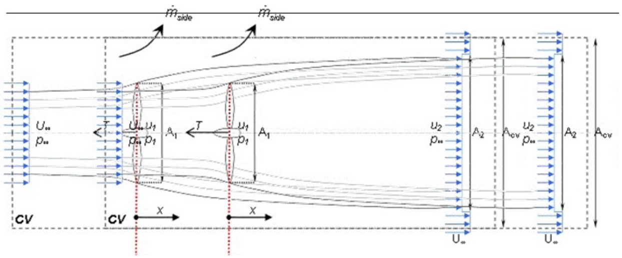

Fig. 2. Stream tubes and parameters in Newman's theory, retrieved from [4]

Furthermore, in [3], it was theoretically showed/demonstrated that in the case of multiple rotors with the same radius, the ideal power coefficient can be further increased, approximately by 13% compared to the single rotor case. The limitations of this theory were determined by flow visualization that showed inaccurate results beginning from a distance equal to a half of a disc diameter. A theoretical model aimed to improve the power extraction from wind is proposed in [4], which considers two co-axial rotors (Fig. 3), the second rotor being smaller than the front rotor (Fig. 4) and placed approximately in the inner bladeless region of the front rotor. The central part of the upstream rotor (76.2% of the rotor diameter) doesn't extract wind's energy since it has no blades. After further calculation, it was shown that the theoretical power coefficient depends on the induction velocities a and c. For the analyzed case, the maximum power coefficient of 0.814 was obtained for a = 0 and c = 0.418, meaning that the velocity doesn't modify (does not decrease) when crossing the front rotor due to the absence of the blades.

The study and development of CRWT prototypes of 500 W ÷ 50 kW [5] intensified starting with early 2000's. Thus, in 2003, a 6kW prototype was tested in California (USA) [6] over a period of 4 months, for various meteorological conditions. It was found that the system is more efficient at low rotational speeds (16-60 rpm), the energy extracted from wind can increase with up to 40% compared with the single rotor case and the bending stress over the tower is lower.

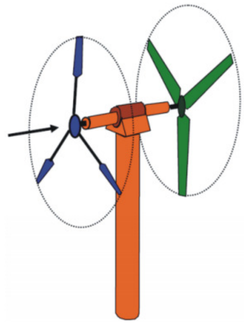

Fig. 3. Design of counter rotating horizontal axis wind turbine system proposed in [4]

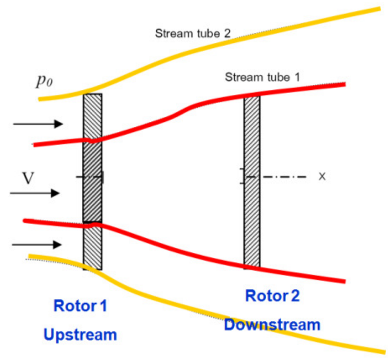

Fig. 4. Stream tubes of the rotors considered in [4], retrieved from the presentation

3. PARAMETERS AFFECTING THE TURBINE EFFICIENCY

The power extracted by a wind turbine from wind depends on the geometrical parameters, aerodynamic parameters and operating conditions. Thus, the size and number of blades, the airfoil type, the method the rotation is transmitted to the electrical generator etc. are parameters affecting the overall efficiency of a turbine.

The performance of a wind turbine is described by the variation of the power coefficient C_P and the torque coefficient C_m with the rapidity of the turbine: $C_P = C_P(\lambda)$ and $C_m = C_m(\lambda)$.

The torque coefficient is given by:

$$C_m = \frac{M}{0,5\rho v_1^2 AR} \quad (2)$$

with M [Nm] the aerodynamic torque of the rotor and R [m] – turbine's radius.

The tip-speed ratio of the turbine is a dimensionless coefficient given by the ratio of linear velocity at blade's tip, u [m/s], to the wind velocity, V_∞:

$$\lambda = \frac{u}{V_\infty} = \frac{\omega R}{V_\infty} \quad (3)$$

with R [m] the radius of the rotor and ω [rad/s] the rotational speed.

Considering the wind velocity V_∞ as being the velocity at the entrance of the rotor v_1 and using $P = \omega \cdot M$, it results:

$$C_p = \lambda \cdot C_m \tag{4}$$

Another dimensionless parameter on which depend the characteristics of a wind turbine is *solidity* (σ); it represents the ratio between the area of the blades, A_p, and the area swept by the blades, A, at one spin of the rotor:

$$\sigma = \frac{A_p}{A} \cdot \tag{5}$$

The rapid the turbine is ($\lambda > 4$), the lower the solidity; thus, the lift area of the blades is decreasing.

Besides the parameters above, the efficiency of a CRWT system depends also on other parameters such as the diameter ratio of the two rotors and on which rotor (larger or smaller) is placed in front, the distance the rotors are placed one to each other.

4. VARIOUS METHODS FOR INVESTIGATING THE PERFORMANCE OF CRWT

The research and development of counter rotating wind turbines focussed on the investigation of different issues, like the method the movement is transmitted from the rotors to the electric generator, blade type and solidity, diameter ratio between the front and rear rotor, the distance between the two rotors etc. Thus, one of the issues encountered in the development of CRWT systems is represented by the type of movement transmission, namely the generator or generators. Several approaches are found in literature: one generator for each rotor [7], one generator coupled to the rotors through a differential planetary system in [8] and one single permanent magnets generator, with kinematic coupling of the rotors [9].

Most of the research reported within the literature approached the study of CRWT systems both theoretically (especially CFD) and experimentally, either by performing own tests or by comparing the theoretical results with experimental results reported in other works.

The study of counter-rotating wind turbines optimization using blade element momentum theory (BEMT) is developed in [10]. The pitch angles, radius ratios and rotation speeds were chosen as design values and were used in the investigation of the power and thrust coefficients. Also, the torque balance was considered in the design process, considering in the case of one generator with kinematic coupling to the two rotors that the shaft torque is the same for both front and rear rotor. This assumption is also used in [11]. By using BEMT for the front rotor, the induction factor and angular induction factors were determined and, consequently, the power and thrust coefficients. The aerodynamic performance of the rear rotor was predicted by considering as input data the flow field developed downstream the front rotor, namely assuming that the rear rotor is placed in the fully developed stream tube of the first rotor. The study was performed for a fix distance between the two rotors: 0.33*D*, where *D*is the diameter of the front rotor. Therefore, since this assumption couldn't be proved in their study (not having exactly the information regarding the distance associated to this fully developed flow), the authors addressed this issue by Vortex Lattice Method (VLM). The optimization was performed by using a genetic algorithm. A shorter length of the front rotor than the one of the rear rotor was found. Also, for the optimized case, it was found that the power coefficient of the front rotor is superior to the one of the second rotor.

The free-wake vortex lattice method [12] considers simultaneously the interaction between the two rotors by not imposing any constraint to the inflow velocity of the rear rotor. The study is performed by considering that the two rotors have the same radius, *R*, the same solidity as a wind turbine having a single rotor and are placed at the distance d/R=0.25, 0.5, 0.75, 1. The maximum power coefficient for zero pitch angles showed little changes among the 4 analysed distances. Even if the power coefficient of the front rotor increases along with the distance, in the same time, the power coefficient of the rear rotor decreases, so the overall efficiency is almost constant. The results obtained by this study were compared with the experimental ones resulted from the research performed in [13] and in [14] in order to validate the numerical model. The theoretical reduced axial velocity behind the front rotor showed a good agreement with the one experimentally obtained in [13]. By comparing the axial induction factor for the rear rotor obtained by VLC and by BEMT, it was found that BEMT can be applied in limited cases, since the difference between the values increases with the distance *d*.

In [15], the aerodynamic performance of the front and rear rotors was numerically investigated aiming to extract the maximum energy from wind, both by the front and rear rotor. By CFD simulations, the performance of each rotor was separately determined and by parametric study the optimum axial distance between them was determined. The CRWT system consisting of two rotors with 3 blades each was also compared wind a single 3 bladed wind turbine. The performed computations showed an increase of about 35% of the CRWT thrust over the single turbine thrust, namely 545N versus 350 N for 10m/s wind velocity. The results of the CFD simulations were compared and validated with experimental data from literature, reported in [8]. The maximum computed torque was identified: 4770 Nm for 14 m/s wind velocity. Also, this wind velocity is associated with the maximum power output of 90 kW. The optimum axial distance between the two rotors was calculated at 0.65*d*, where *d* is the diameter of the up-wind rotor, leading to a maximum power increase of 9.67%. A good correlation between the CFD results and the measurements was identified. Still, in some conditions, the predictions were slightly larger than the measured values. In the single rotor case, the results of the CFD simulations were slightly lower than the experimental values reported in [8]. In [16], there are presented theoretical investigations through CFD methods (k-ω shear stress transport turbulence and moving reference frame for the second rotor) compared with experimental results reported in [8] and with own experimental results obtained in a wind tunnel on a 1:20 scale model of the 30 kW CRWT system reported in [8].

In order to determine or predict the performance of the CRWT systems, several studies were performed [6], [8], [17-21]. For example, using the quasi-steady strip theory and a wake model resulted from the data obtained by carrying out experiments on a scale model in a wind tunnel, the aerodynamic performance of a 30 kW CRWT system was predicted in [8]. The CRWT system had two rotors, each of them with 3 blades (NACA 4415 airfoil for the front and NACA 0012 for the rear rotor), the front rotor having a 5.5 m diameter and the rear rotor an11 m diameter. The front rotor had a rotational speed of 150 rpm, while the rear rotor rotated at 300 rpm. A differential planetary system connected the rotors to the electric generator. The rotors were placed at different distances, in the range of 0.125...0.5 from the diameter of the front rotor. In order to compare the results of the proposed theoretical method to the wind tunnel data, the analysis was performed by considering a uniform flow field for the front rotor and no aerodynamic interference between the two rotors. The relative size and the optimum placement of the rotors were obtained by parametric investigation. The size of the rear rotor was considered as increasing from zero to the size of the front rotor. The best performance of the 30 kW CRWT system was identified at approximately 0.5 of the front rotor's diameter. Also, field measurements were performed for a period of 9 and a half hour. Each of the measured data was averaged over a period of 10 minutes [22]. A relatively good agreement of the field data and theoretical data was obtained. Moreover, the CRWT data were compared to the single rotor case and an increase of about 21% was found at a rated speed of 10.6 m/s. The total maximum power coefficient of 0.5 of the CRWT system was determined.

In [7], an increase of 43.5% of the annual energy that can be produced by a CRWT having two 500 kW rotors compared with a single turbine of the same type, when operating at 10 m/s wind velocity was predicted. The numerical prediction was achieved by using the *actuator line technique* which combines the Navier-Stokes solver with the technique described in [23], which was validated with the experimental results of a 50kW Nordtank turbine. The numerical investigation was performed in EllipSys3D code.

Using a modified blade element momentum theory, the influence on the performance of CRWT system of different parameters (pitch angles, rotating speed, and blades radii) was studied in [21], by assuming that the rear rotor operates inside the fully developed stream tube of the front rotor. It was found that, for a maximum extracted power of the system, the rotors have to share the total extracted power (not when the front rotor extracts the maximum power from wind), the pitch of the rear rotor has to be lower than the one of the front rotor and the rotating speed of the rear rotor is lower than the one of the front rotor.

Based on solidity effect, a numerical investigation of single wind rotors and of a CRWT system was performed in [18]. The results were compared to the experiments obtained on a 10 m diameter wind rotor. A 30% increase in the maximum power coefficient was found for the case of CRWT when compared to a single rotor of half solidity and 5% decrease when the single rotor has the same solidity.

The majority of the CRWT systems reported in literature are provided with a front rotor smaller than the rear rotor. Despite this fact, in [24-26], the Intelligent Wind Turbine Generator (a system having the front rotor larger than the second rotor), is presented while being found in tandem operation. Both rotors are placed either in front of the generator (up-wind), or after the generator (down-wind), having both inner and outer rotational armatures.

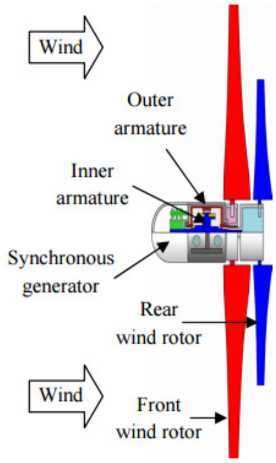

Fig. 5. Down-wind turbine system [26]

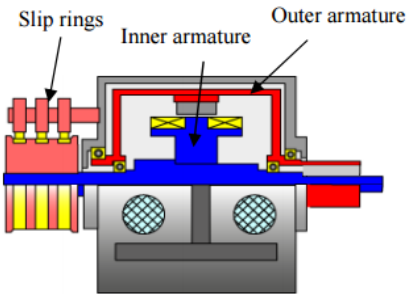

Fig. 6. Double rotational armatures synchronous generator [26]

The system was tested in a wind tunnel and the influence of different parameters on the performance of the system was analyzed. The front rotor has 2 m diameter, and the rear rotor 1.33 m diameter. The power of the electric synchronous generator with mobile armatures is of 1 kW. In order to simulate the wind velocity, the system was tested by placing it on a vehicle driven at different speeds, the acceleration and deceleration periods being removed from the measured data sets. It was determined that the system's performance varies significantly along with the blade setting angles as well as with the applied load.

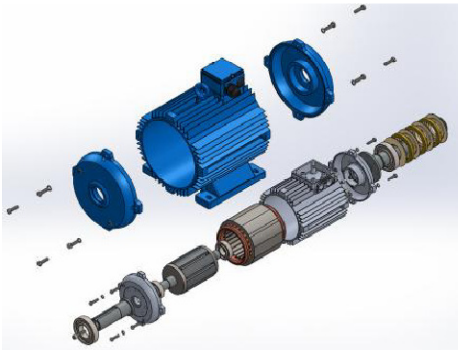

Fig. 7. Double rotational armatures synchronous generator [11]

Priyono et al. [27] designed, optimized and studied the characteristics of an Intelligent Wind Turbine (IWT) by means of BEM and CFD simulations. The optimized IWT consists of two rotors having 3 blades each, of NACA 6412 profiles. The diameter ratio is 1:1, each blade with 600 mm diameter. It was shown that both rotors are counter-rotating at low wind velocities (4-6 m/s), but for higher wind velocities, the rear rotor is entrained by the front rotor, so it rotates in the same direction with the first rotor. Thus, starting with the velocity of 7 m/s, the rotational speed of the rear rotor begins to decrease. At higher wind velocities of 11.5 m/s, the rear rotor is co-rotating with the front rotor.

A CRWT model having the rotor's diameter of 0.8 m, same (mirrored) blade types and independent generators was investigated in [28], both numerically and experimentally. Each of the rotors was separately tested in a wind tunnel and afterwards, the operation of the counter-rotating system was tested. In order to get a correlation between the operation of the CRWT system in a free stream and its operation in a wind tunnel, the blockage effects in the wind tunnel were investigated using both a CFD model and measurement of the drag coefficient. An increase of 9% of the maximum extracted power was found in comparison to the single rotor case. The results were used to predict the dynamic behaviour of the system for the case of a single generator coupled to the rotors by a differential planetary gearing. In the case of 0.8m diameter rotors, it was found that the front rotor extracts 74% power while the rear rotor only 26%. Therefore, it was concluded that the diameter of the front rotor should be smaller than the one of the rear rotor.

In [29], a 10 kW CRWT system with horizontal axis, same diameter for the rotors and NREL airfoils was investigated. The diameter of the rotors for the investigated system is 7.16 m and the distance between the two rotors is 6 m. The CFD modelling revealed that while the power coefficient for the single rotor case is 37%, at 6 tip speed ratio (TSR), the one for the system counter-rotation case is 39%, obtained for 5 TSR.

In [11], there was investigated a CRWT system of 1kW rated power at 10 m/s, having the front rotor diameter of 1.23 m and the rear rotor diameter of 1.33 m as well as a single generator, with double rotational armatures. The wind tunnel tests revealed an output power increase in the range of 37%÷45.2% (varying with the wind velocity) compared to the single rotor case, the front rotor being considered as reference. The unique generator of the system is subject to a patent request [30] and has some advantages such as reduced size, increased rotational speed and no losses due to movement transmission. Subsequently, the 1kW CRWT system was tested in field conditions [31]; 3 levels of electrical loads proportional to the wind intensity were used: 300 W for wind velocities in the range of 3 ÷ 6 m/s, 600 W for the range of 6 ÷ 8 m/s and 900 W for the range of 8 ÷ 10 m/s. A good agreement between the results of the field tests and the results of the wind tunnel tests was found. Still, due to the short testing period of the system and to weather conditions, the results can be considered as being preliminary. The CRWT system used in the research reported in [11] and [31] was achieved within a research project [32].

Fig. 8. 1kW CRWT system operating in situ [31]

Given the fact that the second rotor operates inside the wake of the first rotor, an important issue to be considered in the design of the counter-rotating wind turbine systems is the *wake aerodynamics*. This issue was investigated in several research works [33-38], which studied the wake aerodynamics of the rotor and/or the tower. For example, model wind turbines of 0.9m diameter were used in some studies: in [36] there were performed investigations regarding wake aerodynamics on wind turbines placed at a distance of 3 and 5 rotor diameters by measuring the axial velocity component; in [38] there were performed experiments in a wind tunnel both for the single rotor case and for two counter-rotating rotors case for turbines with 0.9m diameter and investigated near and far the wake fields.

Since the counter-rotating systems require special types of electric generators, some patents have been developed regarding the wind turbines with rotors in counter rotation and/or the related generator [7], [9], [30]. The patent in [7] refers to a system consisting of two separate conversion units, formed by a rotor and a generator. The regulation of the rotational speed between the two rotors, counter-rotating independently, is performed by a power electronic system which controls the electric current produced by the two rotors. With the modification of the wind velocity, the rotational speeds are regulated at a value that optimizes the power produced by the system (operating at maximum power coefficient). In a range of wind velocities over a reference period, the contribution of each rotor to the overall power produced by the system is the same. The patent application in [30] refers to a generator having both armatures mobile, suitable to be used both for wind and hydro counter rotating turbines.

5. COMPLEMENTARY STUDIES TO THE CRWT RESEARCH FIELD

Lately, the promising results obtained by the theoretical and experimental investigation of some developed CRWT systems led to studies aiming to analyze the benefit of the effects brought by a second rotor in the case of wind power plants. This approach has its reasons mainly due to smaller turbine spacing, especially for onshore applications but not only. An example is represented by the research reported in [39], consisting in an experimental study for some models of stand-alone co-rotating wind turbines and stand-alone counter-rotating wind turbines of the same diameter and having horizontal axis. By performing tests both in counter and co-rotation cases, for a constant wind velocity and for a spacing of 0.7*d* (with *d* the diameter of the rotor) between the turbines, it was determined that the overall power is 17% larger in the case of counter rotation. The analysis was made for different spacing and showed that better results can be obtained when the rotors of the turbines in a wind farm are operating in counter rotation. Thus, for spacing lower than 2*d* and counter-rotation, the second turbine, placed in the rear of the first one produces at least 10% more power than in the case of co-rotation operation; for 5*d* spacing this benefit reduces to about 4%.

Since the research reported in literature is based mainly on theoretical studies and on the investigation of experimental models and since the positive effects brought by the second turbine is doubtless, rules or laws for scaling up the models are necessary in order to deploy CRWT systems in situ. Therefore, even if not representing the main goal of this paper, there is mentioned some research [40-43] that approached the study of some similarity parameters necessary in the wind turbines scaling-up process and/or for predicting the turbines behaviour in different operating conditions. In [40] are reported some results obtained during the UpWind research project. Theoretical, technical and economic issues involved in the wind turbine's scaling up process were approached especially in order to determine if a superior power leads to a lower cost of the obtained energy. On the other hand, in order to predict the behaviour and long term performance of some offshore turbines by laboratory investigations on reduced scale models, the study of some scaling laws for achieving 1:100 models is approached in [41]. The laboratory tests are aimed at determining the long term performance, especially as regards the dynamic interaction between soil and structure.

6. CONCLUSION

Several studies have been performed, focussed either on determining the influence of a limited number of parameters on the performance of a counter rotating wind turbine or on a larger number of parameters. Summarizing some of the analyzed research on CRWT systems, Table 1 shows few details about the type of investigation and applied methods.

Table 1. Types of investigation and applied methods in the study of CRWT systems

Reference	Method of investigation, short details
[28]	Theoretical and experimental study of CRWT system with 0.8 m diameter rotors
[13]	Experimental study in wind tunnel
[11]	Experimental study in wind tunnel of 1kW CRWT system
[12]	Numerical study (free VLM) compared to experiments from [13] and to BEMT; same rotor diameters, different distances d=0.25;0.5;0.75;1
[10]	Theoretical study (BEMT and genetic algorithm for optimization) of a CRWT system with rotors placed at 0.33diameter of the front rotor
[16]	Theoretical study (CFD using k-ω coupled with Moving Reference Frame technique) compared to experimental results obtained on a 1:20 scale model of the CRWT from [8] and to experimental results reported in [8]
[8]	Theoretical study compared to own field experiments for 30 kW CRWT system
[15]	Theoretical (CFD) study compared to experimental results reported in [8]
[17]	Numerical performance prediction of a CRWT system consisting of two 500 kW turbines
[24], [25]	Experimental study of Intelligent Wind Turbine Generator system, design of blades and generator
[27]	Design and theoretical optimization study
[6]	Design of a 6kW CRWT prototype and field tests
[21]	Theoretical study using modified BEMT
[18]	Numerical investigation compared to experiments on a 10 m diameter rotor
[31]	Experimental study of 1kW CRWT model - field tests compared to wind tunnel tests reported in [11]
[36]	Theoretical and experimental study of wake aerodynamics on wind turbines placed at a distance of 3 and 5 rotor diameters
[38]	Experimental study on wake measurements in a wind tunnel - near and far wake field both for single rotor and for counter-rotating rotors

Despite the valuable results found within the studies, since the performance of the turbine system depends on multiple parameters (such as blade type, solidity of the two rotors, area swept by the blades, diameter ratio of the front and rear rotor, distance between the two rotors, movement transmission system), there is still need of extensive studies of this type of wind kinetic energy conversion system. Also, the counter rotating wind turbines have to prove their reliability in real operating conditions. However, the studies performed during the last two decades, proved the advantages of these systems. Thus, the additional energy converted by the second rotor, either smaller or larger than the first one, it is certain, even if its additional input to the overall efficiency of the CRWT system varies from one study to another.

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REFERENCES

[1]. Global Wind Energy Council, Global wind report. Annual market update 2015, www.gwec.net

[2]. Newman, B.G., Actuator-disc theory for vertical-axis wind turbines, in J. Wind Eng. Ind. Aerodyn., vol. 15, 1983, pg. 347–355.

[3]. Newman, B.G., Multiple actuator-disc theory for wind turbines, in J. of Wind Engineering and Industrial Aerodynamics, vol. 34, issue 3, 1986, pg. 215-225.

[4]. Chantharasenawong, C., Suwantragul, B., Ruangwiset, A., Axial Momentum Theory for Turbines with Co-axial Counter Rotating Rotors, Commemorative International Conference of the Occasion of the 4th Cycle Anniversary of KMUTT Sustainable Development to Save the Earth: Technologies and Strategies Vision 2050: (SDSE2008) 11-13 December 2008, Bangkok, Thailand.

[5]. Infinite Wind Energy, Technology and Product Brochure, Increasing Energy Efficiency for Residential & Commercial. Wind Applications http://www.infinitewindenergyllc.com/IWE_Small2.pdf.

[6]. Appa, K., Energy Innovations Small Grant (EISG) Program (Counter Rotating Wind Turbine System), EISG Final Report, (California, US) 2002, http://www.eai.in/ref/invent/upload/00-09%2520FAR%2520Appendix%2520A.pdf.

[7]. Debleser, Y., Jeumont Industrie, Wind turbine with counter rotating rotors, US Patent No. 6504260, 2003.

[8]. Jung, S.N., No, T.-S., Ryu, K.-W., Aerodynamic performance prediction of a 30 kW counter-rotating wind turbine system, in Renewable Energy 30, 2005, pg. 631–644.

[9]. Shinn, C.,Kowintec, Over–drive gear device, US Patent No. 5222924, 1993.

[10]. Hwang, B., Lee, S., Lee, S., Optimization of a counter-rotating wind turbine using the blade element and momentum theory, in J. of Renewable and Sustainable Energy, 5, 2013, pg. 052013-1–052013-10, doi: 10.1063/1.4826940.

[11]. Mituleţ L.A., Oprina, G., Chihaia, R.A., Nicolaie, S., Nedelcu, A., Popescu, M., Wind tunnel testing for a new experimental model of counter-rotating wind turbine, in Procedia Engineering, vol. 100, 2015, pg. 1141-1149.

[12]. Lee, S., Son, E., Lee, S., Velocity interference in the rear rotor of a counter-rotating wind turbine, in Renewable Energy 59, 2012, pg. 235-240.

[13]. Schepers, J.G., Boorsma, K., Bon, A., Kim, C., Cho, T., Results from Mexnext: analysis of detailed aerodynamic measurements on a 4.5m diameter rotor placed in the large German Dutch wind tunnel DNW, Brussels, Belgium: EWEA, 14-17 March 2011.

[14]. Schepers, J.G., Snel, H., Model experiments in controlled conditions - final report, ECN-E--07-042, ECN 2007, available at http://www.ecn.nl/docs/library/report/2007/e07042.pdf

[15]. Kumar, P.S., Bensingh, R.J., Abraham, A., Computational analysis of 30 kW contra rotor wind turbine, in ISRN Renewable Energy, article ID 939878, doi:10.5402/2012/939878, 2012, 5 pages.

[16]. Kumar, P.S., Abraham, A., Bensingh, R.J., Ilangovan, S., Computational and experimental analysis of a counter-rotating wind turbine system, in J. of Scientific & Industrial Research 72, 2013, pg. 300-306.

[17]. Shen, W.Z., Zakkam, V.A.K., Sorensen, J.N., Appa, K., Analysis of counter-rotating wind turbines, IOP Publishing, J Phys, Conference series, 2007, vol. 75, doi:10.1088/1742-6596/75/1/012003.

[18]. Lee, S., Kim, H., Lee, S., Analysis of aerodynamic characteristics on a counter-rotating wind turbine, in Current Applied Physics, vol. 10, 2010, pg. S339-S342.

[19]. Liu, S., Janajreh, I., Development and application of an improved blade element momentum method model on horizontal axis wind turbines, in Int. J. of Energy and Environmental Engineering 2012, 3: 30.

[20]. Habash, R.W.Y., Groza, V., Yang, Y., Blouin, C., Guillemette, P., Performance of contrarotating wind energy converter, in ISRN Mechanical Engineering, vol. 2011, article ID828739, 10 p., doi: 10.5402/2011/828739.

[21]. Lee, S., Kim, H., Son, E., Lee, S., Effects of design parameters on aerodynamic performance of a counter-rotating wind turbine, in Renewable Energy, vol. 42, 2012, pg 140-144.

[22]. ***IEC 61400-12, Wind turbine generator systems–part 12: wind turbine power performance testing. IEC, 1998.

[23]. Sørensen, J. N., Shen, W.Z., Numerical Modeling of Wind Turbine Wakes, in. J. of Fluids Engineering, 124 (2), 2002, pg. 393-399.

[24]. Kanemoto, T., Galal, A.M., Development of Intelligent Wind Turbine Generator with Tandem wind Rotors and Double Rotational Armatures* (1st Report, Superior operation of tandem wind rotors), in JSME Int. J., series B, vol. 49, no. 2, 2006, pg. 450-457

[25]. Kubo, K., Kanemoto, T., Development of Intelligent Wind Turbine Generator with Tandem Wind Rotor and Double Rotational Armatures (Second report, Characteristics of tandem wind rotors), in J. of Fluid Science and Technology, vol. 3, no. 3, 2008, pg. 370-378.

[26]. Galal, A.M., Kanemoto, T., Field tests of wind turbine unit with tandem wind rotors and double rotational armatures, in J. of Fluid Science and Technology, vol. 3, no. 3, 2008, pg. 359-369.

[27]. Priyono S., Deny Bayu S., Design and Blade Optimization of Contra Rotation Double Rotor Wind Turbine, in Int. J. of Mechanical & Mecatronics Engineering IJMME-IJENS, vol. 11, no. 1, 2011, pg. 17-26.

[28]. Herzog, R., Schaffarczyk, A.P., Wacinski, A., Zürcher, O., Performance and stability of a counter–rotating windmill using a planetary gearing: Measurements and Simulation, European Wind Energy Conference & Exhibition 2010, Warsaw, Poland, 20 - 23 April 2010.

[29]. Hoang, A.D., Yang, C.J., An evaluation of the performance of 10kw counter-rotating wind turbine using CFD simulation, EWEA 2013, Vienna, Austria.

[30]. Mihaiescu, G.M., Popescu, M., Nicolaie, S., Oprina, G., Chirita, I., Tanase, N., Chihaia, R., Mitulet, A., Hydro power unit used for hydraulic energy conversion extracted from water streams, patent application no. A/00865/23.11.2012.

[31]. Oprina, G., Mitulet, A., Nicolaie, S., Cirnaru, R., Cuciureanu, D., Comparative Analysis of a Counter

Rotating Wind Turbine Testing Results, DOI: 10.5593/SGEM2015/B41/S17.015, SGEM2015 Conference Proceedings, ISBN 978-619-7105-38-4 / ISSN 1314-2704, June 18-24, 2015, Book4, pg. 115-122.
[32]. ***Power Generation System which Uses a Double - Effect Wind Turbine in Order to Ensure the Energy Autonomy in Specific Applications, Joint Applied Research Projects, contract no. 39/2012.
[33]. Smith, D., Taylor, G.J., Further analysis of turbine wake development and interaction data, Proceedings of the 13th BWEA Wind Energy Conference, Swansea, UK, 1991, pg. 325.
[34]. Vermeer, L.J., Sørensen, J.N., Crespo, A., Wind turbine wake aerodynamics, in Progress in Aerospace Sciences, vol. 39, 2003, pg. 467-510.
[35]. Maeda, T., Yokota, T., Shimizu, Y., Adaki, K., Wind tunnel study of the interaction between two horizontal axis wind turbines, in Wind Engineering, vol. 28, issue 2, 2004, pg. 197-212.
[36]. Bartl, J., Pierella, F., Sætran, L., Wake measurements behind an array of two model wind turbines, in Energy Procedia, vol. 24, 2012, pg. 305-312.
[37]. Blomhoff, H.P., An experimental investigation of wind turbine wakes, Master thesis, Norwegian University of Science and Technology, 2012, available at https://www.diva-portal.org/smash/get/diva2:565906/FULLTEXT01.pdf
[38]. Schümann, H., Pierella, F., Sætran, L., Experimental investigation of wind turbine wakes in the wind tunnel, in Energy Procedia 35, 2013, pg. 285-296.
[39]. Yuan, W., Tian, W., Ozbay, A., Hu, H., An experimental study on the effects of relative rotation direction on the wake interferences among tandem wind turbines, in Sci China-Phys Mech Astron 57, 5, doi: 10.1007/s11433-014-5429-x, May 2014, pg. 935-949.
[40]. Sieros, G., Chaviaropoulos, P., Sørensen, J.D., Bulder, B.D., Jamieson, P., Upscaling wind turbines: theoretical and practical aspects and their impact on the cost of energy, in Wind energ. 2012, 15:3-17, published online in Wiley Online Library, DOI: 10.1002/we.527
[41]. Bhattacharya, S., Muir Wood, D., Lombardi, D., Similitude relationships for physical modelling of monopile-supported offshore wind turbines, in Int. J. of Physical Modelling in Geotechnics, vol. 11, issue 2, 2011, pg. 58-68, doi: 10.1680/ijpmg.2011.11.2.58
[42]. Hernandez, W.D.S., Donadon, M.V., Montero, O.J.V., Camacho, R.G.R., Similarity laws for aerodynamic performance evaluation of wind turbines, 22nd Int. Congress of Mechanical Eng., November 3-7, 2013, COBEM 2013, pg. 1071-1082.
[43]. Snamina, J., Martynowicz, P., Prediction of characteristics of wind turbine's tower-nacelle system from investigations of its scaled model, Conference paper, July 2014, available at https://www.researchgate.net/publication/279208490_Prediction_of_Characteristics_of_Wind_Turbine's_Tower-Nacelle_System_from_Investigations_of_its_Scaled_Model