Effect of Blade Length on Maximum Extractable Wind Power and Efficiency

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***Abstract*—This paper analyzes the effect of the blade length of a contra-rotating wind turbine on a Horizontal Axis Wind Turbine. Implemented on the Dymola 2023x modeling and simulation tool, the contra-rotating wind turbine model utilizes the Dymola Wind Power library produced by Dassault Systèmes. The analysis is conducted using a sweep function which runs the simulation through wind speeds that constantly increase over 500 seconds. Each iteration of the sweep function increases the length of the contra-rotating wind turbine as well as its inertia. After the sweep completes a comparison metric variable, the rear rotor power coefficient, and maximum extractable power are compared.**

I. Introduction

Over the past three decades, wind electricity generation has experienced significant growth, becoming one of the fastest-growing sources of electricity worldwide. According to the US Energy Information Administration (EIA), wind power was responsible for the generation of 434.81 billion kilowatt hours of energy in the United States, approximately 10.25% of the total US power consumption in 2022[1]. Comparing the 2022 generation to the 2.79 billion kilowatt hours generated in 1990 (0.09% of the total US energy consumption in that year), wind power capacity has increased by an average of 23% annually, highlighting the growing importance of wind energy in the global energy mix.

Horizontal axis wind turbines (HAWTs) have undergone significant technological advancements, resulting in improved efficiency, reliability, and cost-effectiveness. These advancements include improvements in blade aerodynamics and materials, control systems to maximize extractable power from the wind, and gearboxes to increase the lifespan of components in the gearbox and drivetrain[2].

Moreover, variations in the overall design of HAWTs have the potential to significantly increase the efficiency and power output of wind turbines. Contra-rotating horizontal axis wind turbines (CR-HAWTs) are a type of wind turbine that uses two rotors mounted on the same axis, rotating in opposite directions. The front rotor turns in the same direction as the wind, while the rear rotor turns in the opposite direction. The rear rotor operates in the wake of the front rotor, resulting in reduced turbulence and increased wind flow, which can generate more electricity with greater efficiency from the available wind sources.

[1] "Electricity generation from wind," U.S. Energy Information Administration, 2021.

[2] "6 Advances in Wind Energy," ASME, [Online].

II. Related Work and Models

Limited research exists on CR-HAWTs; however, existing studies conducted on their performance suggest that they have the potential to significantly increase efficiency and power output compared to traditional HAWTs.

A study conducted by Hetyei and Szlivka proposes an optimization method for the design of CR-HAWTS using a multi-objective genetic algorithm. Various design parameters were analyzed such as radial and axial displacement of the rear rotor from the front rotor with the goal of maximizing power generation while minimizing structural loads[3].

Another study by Wu et al. investigated rear rotor configurations and their effects on aerodynamic performance. The study determined the optimal configuration of the rear rotor is dependent on the relative position and size of the front and rear rotors, but in general, a larger diameter and closer axial spacing between the front and rear rotors provides the best performance[4].

Additionally, the Dymola 2023x modeling and simulation tool contains a Wind Power library produced by Dassault Systèmes. The library includes a standard wind turbine model, a single rotor HAWT (SR-HAWT) rated for 2 MWH, which is modeled as a permanent magnet synchronous motor (PMSM) with a fixed stator. The library also includes data specifying constants and equations relevant to this type of wind turbine.

Simulation of the CR-HAWT will be like the provided sample simulation of the SR-HAWT, in which the provided wind speed will be varied over a specified interval of time. Control systems modeled in the wind turbine's subsystems alter the pitch angle of the wind turbine to maintain the rated output power. Most parameters will not need to be modified since the CR-HAWT simulation will use the same motor and power rating.

[3] C. Hetyei, F. Szlivka "Counter-rotating dual rotor wind turbine layout optimisation," Acta Polytechnica, vol. 60, no. 6, pp. 674-682, 2020

[4] Koehuan, Verdy & Kamal, Samsul & Sugiyono,. (2019). Numerical Analysis on Aerodynamic Performance of Counter-rotating Wind Turbine through Rear Rotor Configuration. Modern Applied Science. 13. 240. 10.5539/mas.v13n2p240.

III. Building the Model

From the Wind Power library, the following models and subsystems were duplicated and renamed:

- "WindPower.Examples.GeneratorSideControl"

Renamed: ContraRotating

- "WindPower.Turbines.Mechanical.Records.Data.cp_Polynomial.Demo1_2MW_withPitch"

Renamed: Contra_2MW_withPitch

- "WindPower.Turbines.Mechanical.Turbine_cp_Polynomial" (x2)

Renamed: TurbineIO, ContraTurbineIO

- "WindPower.Turbines.Mechanical.CoreElements.Turbine_cp_Polynomial" (x2)

Renamed: TurbineInnerIO, ContraTurbineInnerIO

- "WindPower.Turbines.Mechanical.CoreElements.Partial.Turbine_cp" (x2)

Renamed: PartialTurbine, PartialContraTurbine

- "WindPower.Turbines.Mechanical.CoreElements.Components.TurbineTorque" (x2)

Renamed: TurbineTorque, ContraTurbineTorque

- "WindPower.Common.Blocks.WindSource"

Renamed: WindSource

The model components were duplicated and placed in a new package. This new package allows the modification of various components to meet the specifications of the CR-HAWT model. *ContraRotating* represented the main body of the CR-HAWT; preliminary modifications to the model focused on the *linearPSM* component. Enabling the *useSupport* interface as shown below in Fig. 1 allows the stator of the PMSM to rotate, resulting in an additional port appearing on the motor component. Fig. 2 highlights what the *ContraRotating* model should look like after this modification.

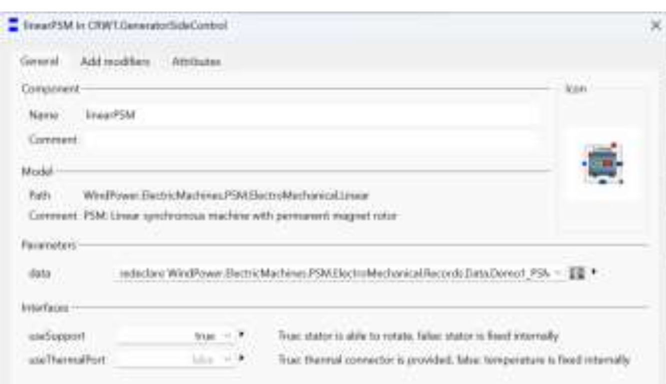


Fig. 1. Double clicking on the *linearPSM* component displays the settings for the motor. Changing the *useSupport* parameter under the *Interfaces* section to *true* enables a second port that additional components can be attached to.

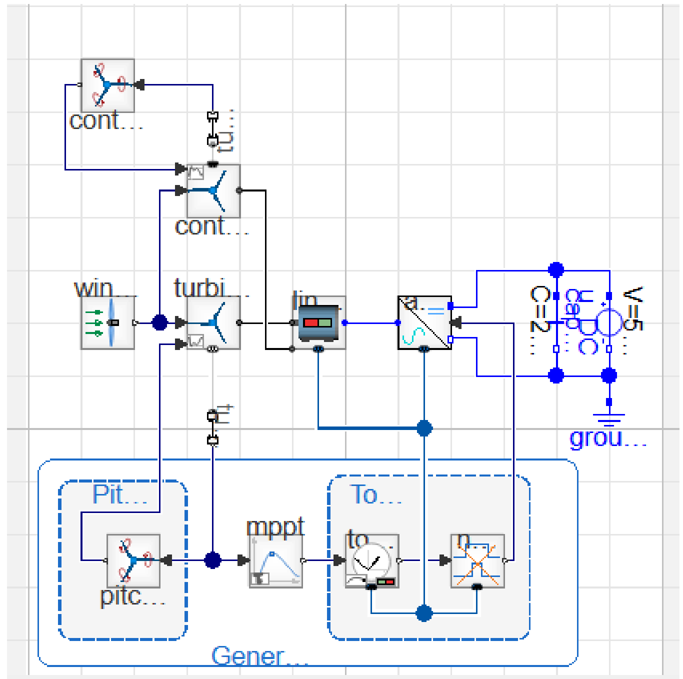


Fig. 2. Enabling the *useSupport* parameter modifies the rotor so that the stator is not fixed. The purpose of changing this parameter is so the motor is also affected by the second wind turbine which will be added to this port.

Once the second port is enabled on the PMSM, the *pitchControl* and the *turbine* were duplicated inside the model and renamed *contraPitchControl* and *contraTurbine* respectively. They were then attached to the new PMSM port (Fig. 2). Finally, the *Contra_2MW_withPitch* component into the *ContraRotating* model and was redeclared to the aforementioned data component name. This configuration allowed for independent adjustments of the rear rotor parameters from those of the front rotor. It is important to note that both turbines will use the same wind speed for the simulation, and the wake effects of the front turbine will not be considered.

Analysis of the efficiency and power output of different variations of the rear rotor length in the CR-HAWT model suggests a need for easy access to the power variables *P_w* and *P_t*. The power variable used in the comparison, *P_t*, represents the maximum extractable wind power, and is calculated from *P_w*, the wind power. The relationship between the two variables is as follows:

$$P\_w = 0.5*\rho*\pi*R^2*V^3$$
$$P\_t = P\_w*powerCoefficient$$

In the above equations, ρ represents the air density, R represents the radius of the wind turbine blades, and V represents the wind speed. To ensure that the values of both variables were easily accessible in the top layer of the model, *RealOutputs* were added to the lower layers of the model to propagate *P_w* and *P_t* upwards to the top layer of the model. Modifying these variables at the top layer directly will not influence the model since these values are calculated at the lowest turbine layer using values propagated downward from the top layer.

CR-HAWTs are designed to have the blades rotating in opposite directions to increase electricity generation efficiency. Simulating rotation in the opposite direction simply requires a change in sign in the *ContraTurbineTorque* model's *tau_t* parameter in the equation section of the model:

```
equation
  tau_t = flange_a.tau; //<-- Originally
-flange_a.tau
  w_t = der(flange_a.phi);

  P_w = 1/2 * rho * r_t^2 * Modelica.Constants
.pi * windSpeed^3;
  P_t = P_w*powerCoefficient;
  tau_t = WindPower.Functions.divNoZero(P_t, w
_t);
  Pw=P_w;
  Pt=P_t;
```

This change records the rotational data in the opposite direction relative to the original turbine. With this change, both turbines should be using the modified turbine models with *P_w* and *P_t* propagated. Next, the turbine power output components were added using Add blocks. Fig. 3 shows the successful propagation of the power variables and their addition.

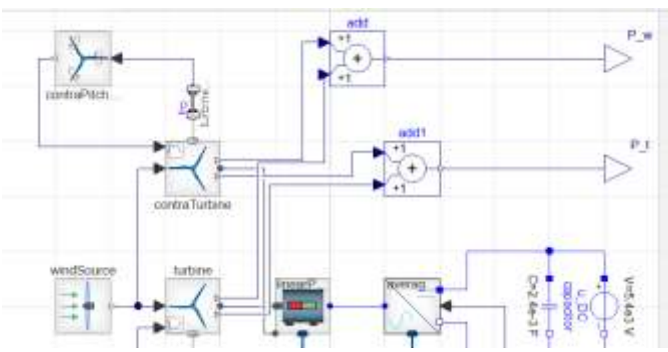


Fig. 3. Variables *P_w* and *P_t* are propagated upwards to the top layer of the model. The values from the *contraTurbine* and *turbine* components are added together to provide a value for the overall *P_w* and *P_t*.

Consistency across simulations is a priority since the results of the simulation need to be replicable. Accomplishing this requires the elimination of randomness in the simulation; the only source of which came from the *windSource* component. This component was modified to remove random noise, leaving the ramp function which linearly increased the wind speed over time. The unrandomized *windSource* subsystem replaced the original component, and the parameter declarations for *rand_min* and *rand_max* were removed to ensure that the new *windSource* component does not introduce randomness.

The final modification to the model was adding a comparison metric to the top layer of the model. A comparison metric is necessary for the comparison of models with different parameters because each turbine has its own efficiency and performs differently when at different lengths. For this simulation, the formula used to evaluate performance incorporated the maximum extractable wind energy and inertia of the wind turbines as follows:

```
compMetric = (turbine.P_t + contraTurbine.P_t)
 / (turbine.coreElement.J_t + contraTurbine.
coreElement.J_t);
```

Running preliminary tests of the CR-HAWT model against the example SR-HAWT model confirmed the modifications worked as expected. Fig. 4 below shows the simulation results of various parameters over a 500 second interval.

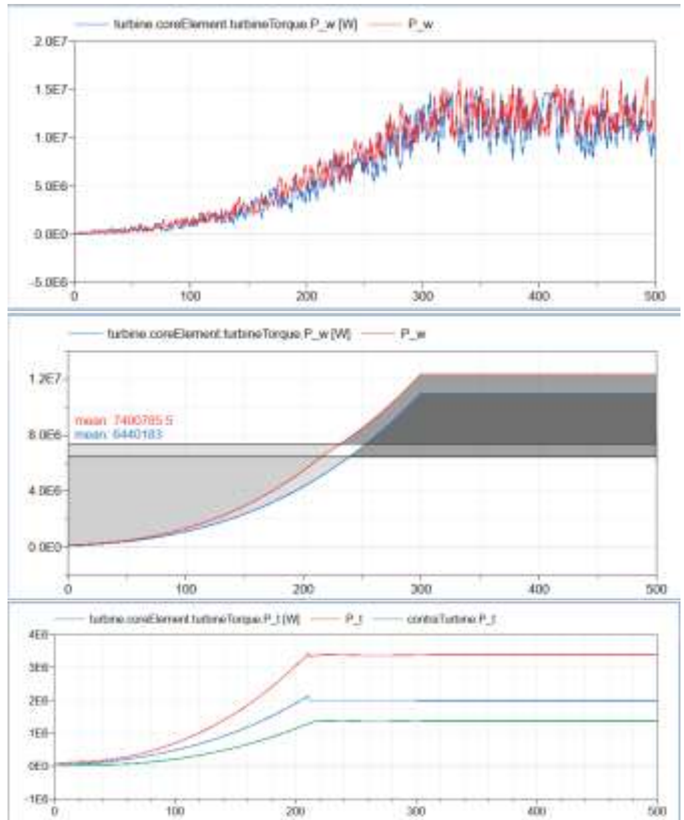


Fig. 4. Variables *P_w* and *P_t* are shown over 500 seconds. The red line represents the CR-HAWT while the blue line represents the example SR-HAWT.

Randomness in the wind source (top) produces very large fluctuations in power output, reducing the reliability of simulation results. Eliminating the randomness in the wind source (middle) produced results that are both more reliable and reproducible. The unrandomized results confirm the CR-HAWT wind power is higher than the SR-HAWT. Plotting the overall *P_t* against the maximum extractable wind power from each wind turbine (bottom) confirmed the CR-HAWT model successfully combines the power output of the two wind turbines to produce a greater maximum extractable wind power than the SR-HAWT. Fig. 5 shows the completed top layer of the model after verification of the modifications.

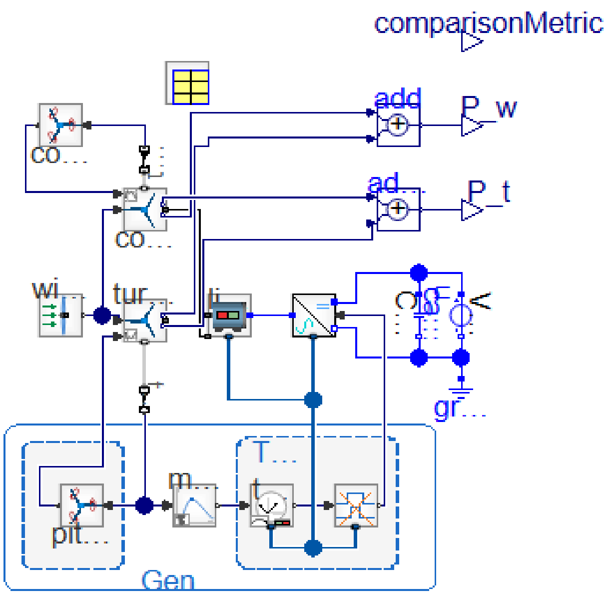


Fig. 5. Final version of the top layer of the CR-HAWT model.

IV. Sweep Functions

A single simulation of the CR-HAWT model analyzes the performance of the turbine with a fixed set of parameters. Utilizing sweep functions allows the rapid simulation of the same model under different parameters. The results can be plotted against each other to view the simulations that yield the most optimal results. Three sweep functions were created, each comparing a different variable: *comparisonMetric*, *contraTurbine.turbineBus.cp*, and *P_t*.

The objective of the project is to determine the optimal length of the rear rotor blades. All three sweep functions keep the front rotor blade length the default 40 meters. Each sweep function performs 20 iterations of the simulation; the rear rotor blade length increases linearly over the range of 22-60 meters. This change is accomplished by modifying two of the data parameters in the contraTurbine model: *contraTurbine.data.r_t* (blade length) and *contraTurbine.data.J_t* (blade inertia). Using the standard formula for inertia results in a cubic relationship between the change in blade inertia and the change in blade radius. This relationship assumes that an increase in blade mass is directly proportional to an increase in blade length:

$$J_0 = m_0 R_0^2$$
$$J = J_0 (R/R_0)^3$$

After modifying the sweep parameters as specified above, the model is translated and simulated over the specified amount of time, resulting in the following function:

```
function compMetricAnalysis
  input String pathToModel = "CRWT.ContraRotat
ing";
  input String[3] parametersToSweep = {"contra
Turbine.data.r_t","contraTurbine.data.J_t","co
mparisonMetric"};
  input Integer numSim = 20;
  input Real startVal = 22;
  input Real endVal = 60;
  input Real simTime = 500;
protected
  Real [:] lengthValues;
  Real [20] inertiaValues;
algorithm
  lengthValues := linspace(
    startVal,
    endVal,
    numSim);
  for i in 1:numSim loop
    inertiaValues[i] := 8.6e6*((20+2*i)/40)^3;
    translateModel(pathToModel);
    simulateExtendedModel(pathToModel, stopTim
e=simTime, method="dassl",
    resultFile="lengthSweep",
    initialNames={parametersToSweep[1],paramet
ersToSweep[2]},
    initialValues={lengthValues[i],inertiaValu
es[i]},
    finalNames={parametersToSweep[1],parameter
sToSweep[2],parametersToSweep[3]});
    plot({"comparisonMetric"},plotInAll=true);
  end for;
end compMetricAnalysis;
```

V. Methodology

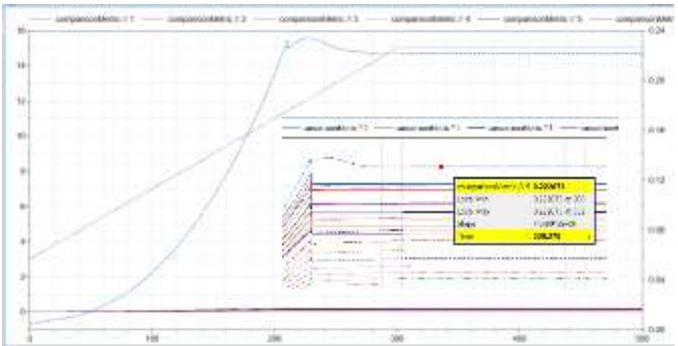
The CPU run times of function sweeps and the sum of individual function calls are very similar. The primary advantage of sweep functions is to save the user time by iteratively changing the desired parameters and plotting the results of specific variables. To keep the CPU runtimes reasonable, all sweeps conducted will run 20 simulations. Each simulation in the sweep will vary the *contraTurbine.data.r_t* and *contraTurbine.data.J_t* parameters in the same way. The only variable element in the sweep should be the simulation end time.

It is important to include the option to change the length of the simulation as well as the end time so that analysis can be conducted on a smaller scale to determine the specifics behind why one rear rotor blade length is more efficient than another.

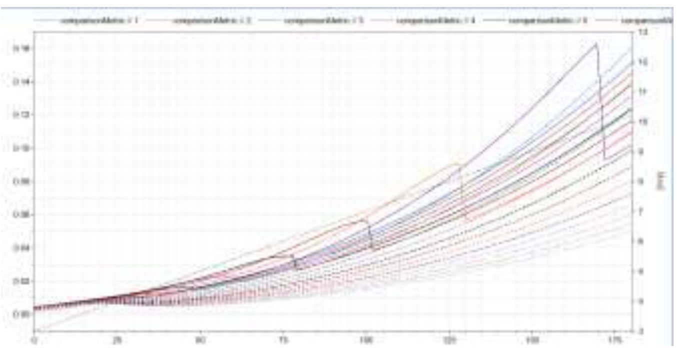
VI. Results and Discussion

A. *Comparison Metric Analysis*

The first variable compared using the sweep analysis was the comparison metric with the ninth iteration of the sweep performing with the highest efficiency after approximately 200 seconds into the simulation. After 200 seconds in the simulation, the wind speed is within the range of 11-15 meters per second with 15 m/s as the steady state wind speed value.

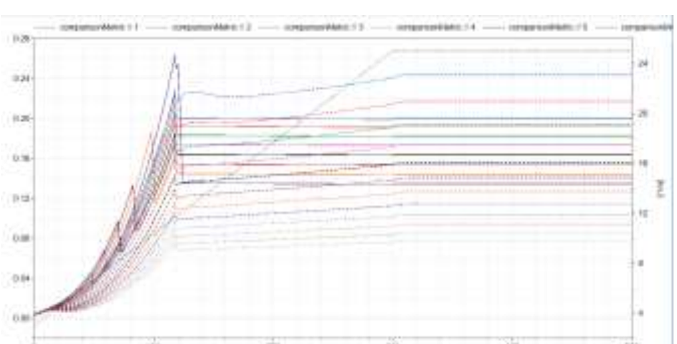


The above plot shows the isolated sweep result of the ninth iteration (blue) with the simulated wind speed (black). Results of the comparison metric sweep suggest that for wind speeds between 11-15 m/s, the optimal rear rotor length of the wind turbine rated for 2 MWH is 38 meters, 2 meters less than the front rotor length.

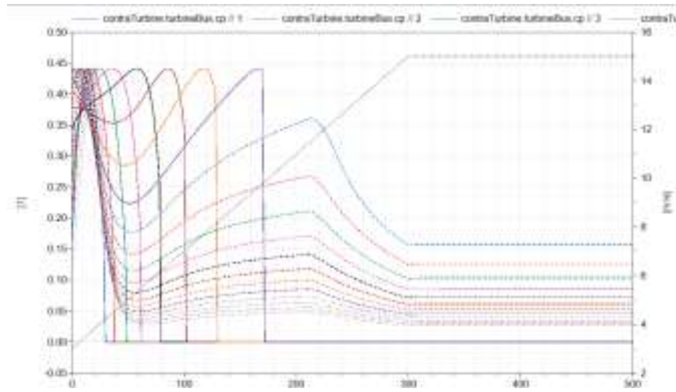


When the wind speed was below 11 m/s, the iterations that performed with the greatest efficiency changed as the wind speed increased. For example, a rear rotor length of 36 meters performed most efficiently between 130 and 170 seconds into the simulation, during which the wind speed ranged from around 8-10 m/s. In the graph elements above, the breakdown of performance relative to different windspeeds show a trend of a smaller rear rotor length (solid lines) performing better than lengths larger than the front rotor.

Extending the simulation to increase the range of wind speeds to 25 m/s, the maximum speed most turbines of this model can operate at before facing damages, produced the same overall trend of a smaller rear rotor length performing with a greater efficiency.

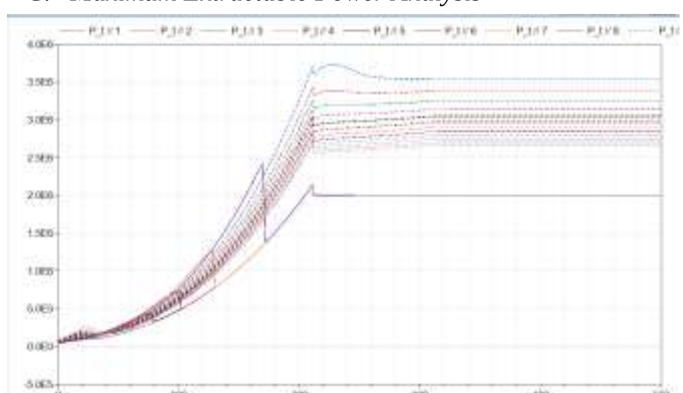


B. *Rear Rotor Power Coefficient Analysis*



Sweeping under the same conditions and plotting the power coefficient of the rear rotor also determined that a rear rotor length of 38 meters performs best when the wind speed is steady. These results suggest that the turbine with a 38-meter rear rotor length operates most efficiently between 10-15 meters per second, which is slightly different than the range determined by the comparison metric analysis. However, the power coefficient analysis test only considers the performance of the rear rotor and does not take into account the power output and inertia of the front rotor. This means that the wind speed suggestion based on the power coefficient analysis is less accurate than the comparison metric sweep analysis.

C. *Maximum Extractable Power Analysis*



Plotting the combined maximum extractable power from both turbines during the sweep provided yet another confirmation that the rear rotor with a length of 38 meters has the best overall performance. An interesting note about the maximum extractable power is that when the rear rotor length is less than 38 meters, the steady state maximum extractable output is 2 megawatts, whereas simulations with rear rotor lengths of 38 meters and greater produced steady state power outputs ranging from 2.7 to 3.5 megawatts.

Unlike the previous sweeps, the results suggest that better performance results from a rear rotor length that is larger than the front rotor length. Essentially, the larger rear rotor lengths increased the rating of the turbine to the steady state value. These results also suggest that at wind speeds above 11 m/s, the wind speed where the 38-meter rear rotor length overtakes the 36-meter rear rotor length as the most efficient performer, smaller rear rotor lengths are largely ineffective at power generation. If the SR-CRWT can produce 2 megawatts consistently, then there is not a need to add another rotor. These findings may be attributed to one of the limitations of the model, as the wake of the front rotor is not considered in the simulation.

VII. Conclusion

In this paper, a model for a CR-HAWT was developed using the Dassault Systèmes Wind Power library. The model's PMSM was modified to free the stator, allowing for a second turbine to be connected to the motor. After both turbines were attached to the motor and the wind source was applied, a sweep analysis was conducted to vary the rear rotor blade length and inertia. The sweep ran for twenty iterations of the simulation, and the results were analyzed using comparison metrics, rear rotor power coefficient, and maximum extractable power.

The results from the sweeps clearly indicate that a wind turbine rated for 2 MWH with a front rotor length of 40 meters would perform best with a rear rotor length of 38 meters. Wind speeds between 11-15 m/s were found to work best for this blade length. While lower blade lengths had a higher comparison metric at wind speeds below 10 m/s, the additional power produced was minimal compared to the maximum extractable power of a SR-HAWT. The final power output values for simulations with wind blades was 2 megawatts, the same final power output value as a SR-HAWT. If the SR-CRWT can consistently generate 2 megawatts, there is no requirement to include an additional rotor. It is possible that this outcome is due to a constraint of the model, as the simulation does not account for the front rotor's wake.

Future iterations of the model could improve the current model by accounting for the wake of the front rotor and adjusting the maximum angular velocity of the rear rotor as the sweep adjusts the rear rotor length and inertia. Smaller blade lengths have the advantage of being able to rotate at a higher angular velocity compared to longer counterparts.

References

[1] "Electricity generation from wind," U.S. Energy Information Administration, 2021. [Online]. Available: https://www.eia.gov/energyexplained/wind/electricity-generation-from-wind.php#:~:text=Wind%20electricity%20generation%20has%20increased%20significantly&text=Total%20annual%20U.S.%20electricity%20generation,U.S.%20utility%2Dscale%20electricity%20generation. [Accessed: May 11, 2023].

[2] "6 Advances in Wind Energy," ASME, [Online]. Available: https://www.asme.org/topics-resources/content/6-advances-in-wind-energy. [Accessed: May 11, 2023].

[3] C. Hetyei, F. Szlivka, S. Mantilla, J. Garcia, M. Reyes, and M. Gonzalez, "Counter-rotating dual rotor wind turbine layout optimisation," Acta Polytechnica, vol. 60, no. 6, pp. 674-682, 2020, doi: 10.14311/AP.2020.60.0674. Available: https://ojs.cvut.cz/ojs/index.php/ap/article/view/6721/5964 . [Accessed: May 11, 2023].

[4] Koehuan, Verdy & Kamal, Samsul & Sugiyono,. (2019). Numerical Analysis on Aerodynamic Performance of Counter-rotating Wind Turbine through Rear Rotor Configuration. Modern Applied Science. 13. 240. 10.5539/mas.v13n2p240. Available: https://www.researchgate.net/publication/330663009_Numerical_Analysis_on_Aerodynamic_Performance_of_Counter-rotating_Wind_Turbine_through_Rear_Rotor_Configuration. [Accessed: May 11, 2023].