Sustainable Electrical Systems

Imperial College London

Department of Electrical and Electronic engineering

Coursework 1

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Introduction

The aim of this coursework was to determine the power outputs and available energy for a wind turbine (WT) at a particular location with certain pre-defined parameters and compare the output for wind turbine generators (WTG) with maximum powers of 6MW and 12MW. This report details the findings for each WTG and compares and explains the outputs in each case.

Part 1

The calculations for this part are for a 90% efficient 6MW WTG.

Question 1

This part was calculated using equations 1 and 2:

$$P_a = 0.5 * \rho * A * v_w^3 \tag{1}$$

$$P_e = C_{p-opt} * \eta_{GB} \tag{2}$$

where A is the area, ρ is the air density, v_w is the wind speed, P_a is the power available, P_e is the power extracted, C_{p-opt} is the maximum power coefficient and η_{GB} is the efficiency.
Conditions were added to ensure the curve began at the cut-in speed, 4m/s and cut-out at 25m/s. Additional curves were plotted detailing the maximum available power for this specification and the Betz Limit available power using the efficiency and the maximum power coefficient. The plot

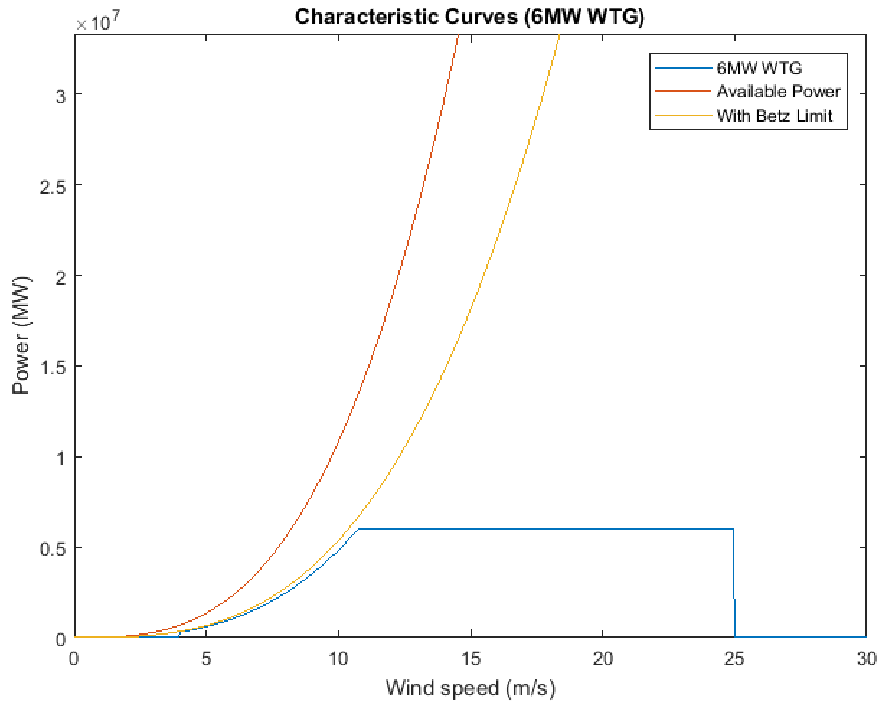

Figure 1: The Available Power, Power with the Betz Limit and Characteristic Curve for the 6MW WTG

in figure 1 shows after a certain speed, the rated speed, the characteristic curve levels out at the maximum output for the WTG. The rated speed was found to be 10.4m/s.

Question 2

8760 samples were obtained from the 'wblrnd' function using a scaling factor of A = 8.5 and k = 1.9. Once obtained these were saved into a variable 'vw' and into a file 'Harshil_Sumaria.mat', and the program modified to load these saved wind samples. This was then converted into a histogram with 23 bins as shown in figure 2 below. As can be seen, the modal bin was centred at 7.17m/s.

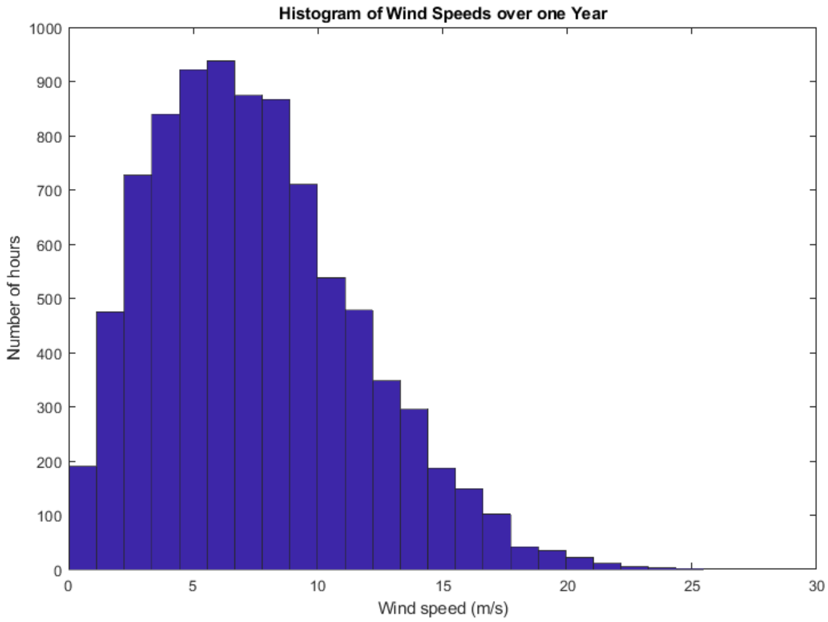

Figure 2: Histogram of the wind speed across the year

The average (mean) speed was calculated to be 7.51m/s and the median speed was 7.01m/s. This is to be expected due to the scaling factors used for the Weibull distribution.

Question 3

The amount of power available for each wind speed was multiplied by the number of hours at that wind speed to calculate the energy available and extracted at each wind speed. This can be seen in figure 3. The red bars are the total available energy, the green is taking account of the Betz Limit and the blue is taking into account the characteristics of the 6MW WTG such as cut-in speed, cut-out speed, efficiency and maximum power coefficient.
As expected the green bars follows a similar trend to the red bars as they are taking into account the Betz Limit. The blue bars follow a similar trend however they have a cut-in speed of 4m/s, a cut-out speed of 25m/s, and a maximum power output which is hit when the speed reaches the rated speed of 10.4m/s. Therefore despite the modal speed being the bin of 7.17m/s, the most energy extracted across the year was at the bin of 11.1m/s. It is clear that there is capacity for a larger WTG due to the large differences between the blue and green bar heights.

Question 4

A sum of the total energy available (red bars) and the total energy extracted (blue bars) was completed and used to calculate the percentage of available energy which was actually extracted. This value came to 20.6%. If the wind blew at the average speed all year, it was calculated this percentage would fall to 13.7%. This is due to the fact that as stated previously the wind speed at which the largest energy was extracted is larger than the average speed, and a considerable amount of energy is extracted at higher wind speeds.

Part 2

The calculations for this part are for a 90% efficient 12MW WTG with the same WT as before.

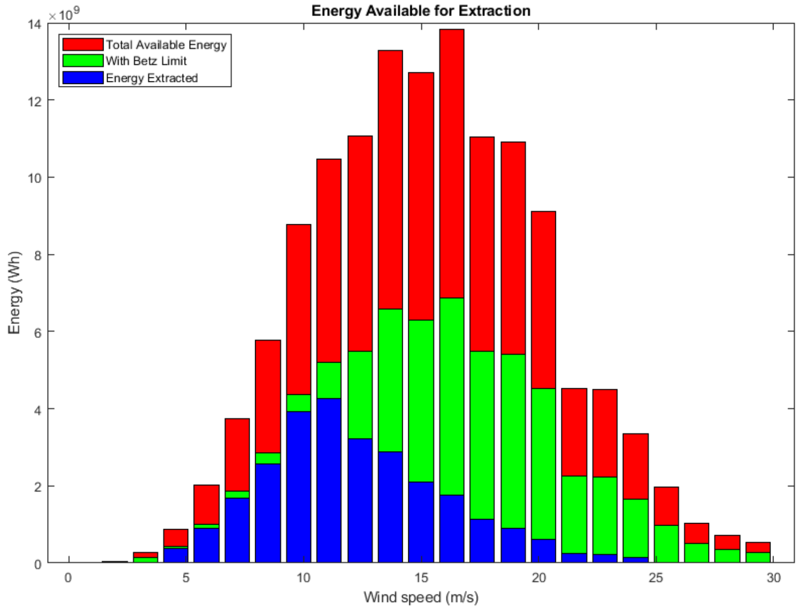

Figure 3: The energy available and extracted by the 6MW WTG across the year

Question 1

Using equations 1 and 2 as before the characteristic curve was plotted in figure 4. The characteristic curve for the 6MW WTG was included for reference, and it is clear the 12MW extracts more power and has a higher rated speed, as would be expected. The rated speed for the 12MW WTG is 13.1m/s, an increase from 10.4m/s.

Question 2

Due to the higher maximum power output of the 12MW WTG, it will extract more energy. In the same way that figure 3 was created, the power available at each wind speed was read from the characteristic curve and multiplied by the hours of wind at that speed to calculate the energy extracted at each speed. The output is seen in figure 5. The trend is clear that due to the higher rated speed and higher power the 12MW WTG extracts more energy than the 6MW WTG. In this case, the maximum energy extracted by the 12MW WTG was at 13.7m/s, whereas it was 11.1m/s for the 6MW WTG.

Question 3

The percentage of energy extracted from the available energy was 29.8%. This is much higher than the 6MW WTG (20.6%) as expected as the 12MW is able to capture more of the available energy.

Question 4

The 6MW WTG was able to extract 20.6% of the available energy whereas the 12MW WTG was 29.8%. This is a change in yield of 9.24%.

Conclusion

As was expected, the 12MW WTG was able to extract more energy than the 6MW WTG due to its higher maximum output and rated speed. There is potential for a slightly larger WTG To be run instead to extract the maximum possible energy. This would be equivalent to the green plot in figure 3.

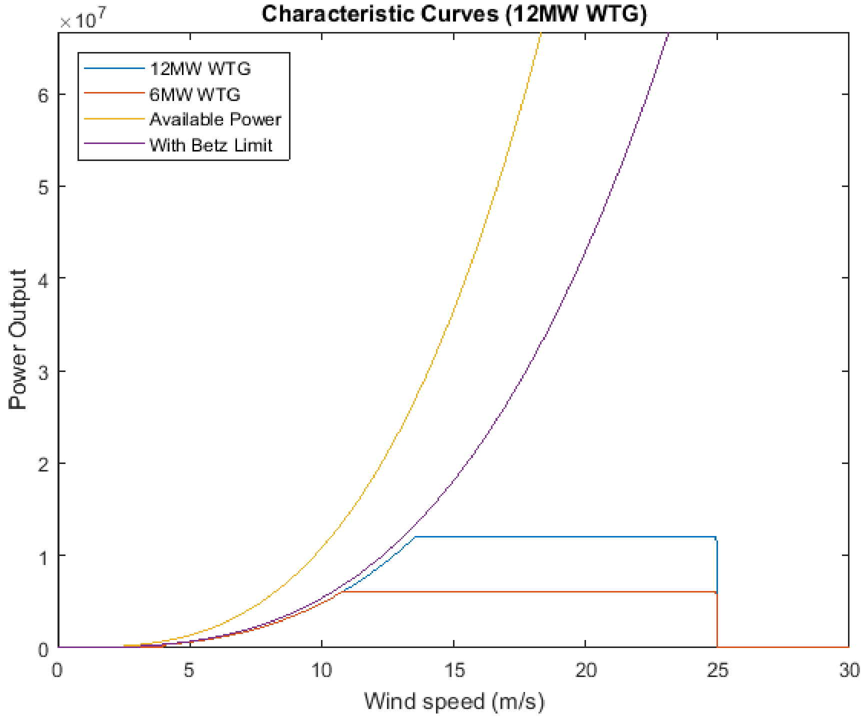

Figure 4: The Available Power, Power with the Betz Limit and Characteristic Curve for the 12MW WTG

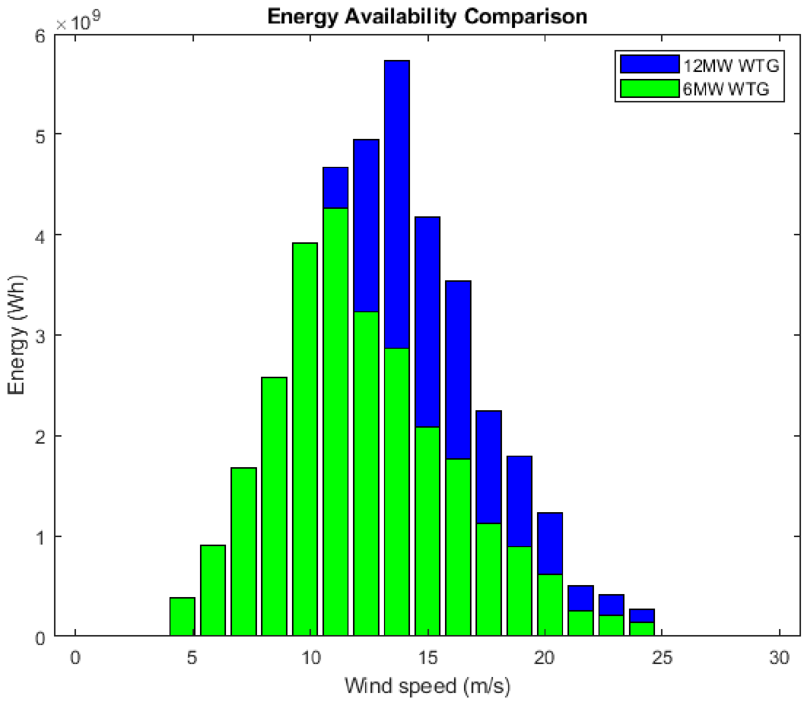

Figure 5: The energy extracted by the 6MW and 12MW WTGs across the year

Appendix A

MATLAB Code

```
%% Initial Set up of parameters

clear variables;
clc;

A = 8.5;
d = 150;
area = pi*((d/2)^2);
cp = 0.496;
efficiency = 0.9;
filename = 'Harshil_Sumaria.mat';
k = 1.9;
steps = [0:0.05:30]; %can change 0.1 to control the step size and smoothness of plots
n = length (steps);
no_bins = 23;
pout_6 = 6000000;
pmax_6 = pout_6/efficiency;
pout_12 = 12000000;
pmax_12 = pout_12 / efficiency;
rho = 1.225;


 %% PART 1 Question 1
figure
% do your job here
drawnow;
set(get(handle(gcf),'JavaFrame'),'Maximized',1);
subplot(2,3,1);
%Characteristic curve and rated speed for 6MW WTG
[power_6, ratedspeed_6] = characteristic_curve ( steps, rho, cp, pmax_6, efficiency, area);
ratedspeed_6
plot (steps, power_6);
axis([0 steps(n) 0 pmax_6*5]);
hold on;

%Total power available
[power_no_limit] = power_betz (steps, rho,1,area);

plot (steps, power_no_limit);

%Total power available with Betz Limit
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```
[power_betz_limit] = power_betz(steps, rho, cp, area);
plot (steps, power_betz_limit);
title('Characteristic Curves (6MW WTG)');
xlabel('Wind speed (m/s)');
ylabel('Power (MW)');
legend('6MW WTG','Available Power','With Betz Limit')
hold off;

%% Part 1 Question 2
sample_size = 365*24;          %Number of hours in a year

%vw = wblrnd(A, k, [sample_size, 1]);      %random weibull data for wind speeds
%save(filename,'vw')                                  %save windspeeds to file for repeatability
load(filename,'vw')                                %load windspeeds from file for repeatability

%figure
subplot(2,3,2);
hist(vw, no_bins);      %histogram of wind speeds
histval = hist(vw, no_bins);        %save quantity in each bin for later
title ('Histogram of Wind Speeds over One Year');
xlabel('Wind speed (m/s)');
ylabel('Number of hours');
avgwindspeed = mean(vw)
medwindspeed = median(vw)%save average speed


%% Part 1 Question 3

%get the middle of each histogram bin
mids = steps(n)/no_bins;
for p = 1:no_bins
    wind_speeds(p) = (mids*(p-1) + mids*(p))/2;
end

%Available energy for ideal, betz limit and real WTG
[sum_energy_ideal, energy_ideal] = e_for_extraction (rho, 1,  area, no_bins, histval, wind_speeds);
[~, energy_betz] = e_for_extraction (rho, cp,  area, no_bins, histval, wind_speeds);
[sum_energy_real, energy_real] = real_e_for_extraction (rho, cp, pmax_6, efficiency, area,no_bins,  histval, wind_speeds, ratedspeed_6);

%Plot available energy on same graph for three cases
subplot(2,3,3);
bar(wind_speeds, energy_ideal,'red');
%figure
hold on;
bar(wind_speeds, energy_betz,'green');
%figure
hold on;
bar(wind_speeds, energy_real,'blue');
title('Energy Available for Extraction (6MW WTG)');
xlabel('Wind speed (m/s)');
ylabel('Energy (Wh)');
legend('Total Available Energy','With Betz Limit','Energy Extracted')
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```
legend('Location','northwest')

%% Part 1 Question 4
%Percentage change between available energy and energy extracted by 6MW WTG
perc_energy_produced_actual = 100*(sum_energy_real/sum_energy_ideal)

%Energy produced if the WTG were to run at average speed all year
energy_prod_avg = 0.5*rho*area*(avgwindspeed^3)*365*24*cp*efficiency;

%Percentage change between available energy and energy extracted by 6MW WTG running at average speed all year
perc_energy_produced_average = 100*(energy_prod_avg/sum_energy_ideal)

%% Part 2 Question 1

subplot(2,3,4);
[power_12, ratedspeed_12] = characteristic_curve (steps, rho, cp, pmax_12, efficiency, area); %Generating Characteristic Curve with rated speed and power being returned
ratedspeed_12
plot (steps, power_12);
axis([0 steps(n) 0 (pmax_12)*5]);

hold on;
plot (steps, power_6); %plot the s6MW characteristic curve for reference
plot (steps, power_no_limit); %plot the no limit curve
plot (steps, power_betz_limit);%plot the betz limit curve
title('Characteristic Curves (12MW WTG)');
xlabel('Wind speed (m/s)');
ylabel('Power Output');
legend('12MW WTG', '6MW WTG','Available Power','With Betz Limit')
legend('Location','northwest')
hold off;

%% Part 2 Question 2

%bar graph as in part 1 question 3
[sum_energy_real_12, energy_real_12] = real_e_for_extraction ( rho, cp, pmax_12, efficiency, area, no_bins, histval, wind_speeds, ratedspeed_12);
subplot(2,3,5);
bar(wind_speeds, energy_real_12,'blue');
hold on;
bar(wind_speeds, energy_real,'green');
title('Energy Availability Comparison');
ylabel('Energy (Wh)');
xlabel('Wind speed (m/s)');
legend('12MW WTG', '6MW WTG')
hold off;

%% Part 2 Question 3
%Percentage change between available energy and energy extracted by 12 MW WTG
perc_energy_produced_actual_12 = 100*(sum_energy_real_12/sum_energy_ideal)

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```matlab

%% Part 2 Question 4

%percentage difference between yield of 6MW and 12MW WTG
yield_change = 100*(sum_energy_real_12 - sum_energy_real)/sum_energy_real

%% FUNCTION DEFINITIONS

%generate the characteristic curve
function [power, rated_speed] = characteristic_curve (steps, rho, Cp, power_max, efficiency, a)
n = length (steps);
rated_speed = 0;
flag = 0;
for ii = 1:n
    power(ii) = 0.5*rho*a*(steps(ii)^3)*Cp*efficiency;

    if steps(ii)>= 25 || steps(ii) < 4
        power(ii)=0;

    elseif power(ii) > efficiency*power_max
        if flag == 0
            rated_speed = steps(ii);
        end
        power(ii) = power_max*efficiency;
        flag = 1;
    end

end
end


%generate the bar charts of available energy
function [sum_energy, energy] = e_for_extraction ( rho, cp,  a, no_bins, no_hours, wind_speeds)

for ii = 1:no_bins
    energy(ii) = 0.5*rho*a*(wind_speeds(ii)^3)*no_hours(ii)*cp;
end
sum_energy = sum(energy);

end


%generate the bar charts of available energy for the WTG
function [sum_energy, energy] = real_e_for_extraction ( rho, cp, power_max, efficiency, a, no_bins, no_hours, wind_speeds, rated_speed)

for ii = 1:no_bins
    energy(ii) = 0.5*rho*a*(wind_speeds(ii)^3)*no_hours(ii)*cp*efficiency;
    if wind_speeds(ii)>=25 || wind_speeds(ii) < 4        %cut-out and cut in condition
         energy(ii)=0;
    elseif wind_speeds(ii)>=rated_speed  %rated maximum speed
        energy(ii) = power_max*efficiency*no_hours(ii);
```

```
        end
end
sum_energy = sum(energy);

end


%plot ideal and betz limit curves
function [Pwbetz] = power_betz( steps, rho, cp,  a)

n = length (steps);
for ii = 1:n
        Pwbetz(ii) = 0.5*rho*a*(steps(ii)^3)*cp;

end
end
```