NAME:

TEST (5 points)

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20

Correct answer +1 point, incorrect answer -0.33 points

1. For a given existing wind farm, which of the following quantities does not depend on the wind resource
   a) AEP
   b) LCOE
   c) Wind turbine CAPEX
   d) All depend on the wind resource

2. About the generator of type 1 wind turbines, we can say that
   a) the slip is always negative
   b) the frequency depends on wind conditions
   c) shunt inductances are needed to compensate reactive power
   d) require maintenance for the slip rings

3. About type 2 wind turbines, we can say that
   a) they provide fault ride-through capability
   b) they are specially used offshore
   c) they are based on synchronous generators
   d) the possible operating turbine speed range is wider than type 1 WTs

4. In a DFIG wind turbine
   a) The machine can operate as a generator with negative, positive and zero slip
   b) The machine cannot operate as a motor
   c) The generator nominal power is smaller than the power converter nominal power
   d) the speed can be controlled in a very narrow range around synchronous speed (2-3 %)

For a PMSG type 4 wind turbine, calculate number of pole pairs needed for WT nominal speed of 10 min^{-1} with nominal electrical frequency of 20 Hz for the following cases:

5. Direct drive WT
   a) 120 pole pairs
   b) 40 pole pairs
   c) 3 pole pairs
   d) None of the above

6. Double stage gearbox WT, G = 40 (gearbox ratio)
   a) 120 pole pairs
   b) 40 pole pairs
   c) 3 pole pairs
   d) None of the above

7. For the previous wind turbine, how can the wind turbine rotate at 5 min^{-1}
   a) Applying an electrical frequency of 10 Hz

b) Applying an electrical frequency of 40 Hz
c) Changing the pole pairs
d) Changing the gear to the right setting

8. Type 4 wind turbines
a) Include current controllers both in the grid and machine side converters
b) Use doubly fed synchronous generators to generate power
c) Cannot be used for offshore wind due to the weight
d) Were the most common turbines installed during the 80s

9. Pitch control system
a) Can increase the nominal power of the wind turbine
b) Is able to limit the power generated by the wind turbine
c) Is used to orientate the wind turbine towards the wind direction
d) Is used to regulate the torque controlling the generator current

10. Type 4 direct-driven wind turbines
a) need a gearbox to adapt the speed between the high and low speed shafts
b) include a multi-polar generator to adapt the high and low speed shafts
c) can be connected directly to the network without power electronics
d) typically include doubly fed induction generators

11. The back-to-back converter in Type-3 wind turbines
a) is rated at the nominal power of the turbine
b) is rated at an approximately 10% of the nominal power of the machine
c) is rated at an approximately 30% of the nominal power of the machine
d) has a variable rating based on the current power produced

12. Increasing the wind from 4 to 8 m/s in a variable speed WT
a) Will increase the power by a factor of 2
b) Will increase the power by a factor of 4
c) Will increase the power by a factor of 8
d) Will increase the power by a factor of 16

13. Type 1 wind turbines
a) Do not require reactive power compensation
b) Use power converters to provide grid support
c) Require reactive inductive power compensation
d) Require reactive capacitive power compensation

14. Voltage source converters (VSC) used in variable speed wind turbines
a) Only control active power
b) Directly control active power and reactive power depends on the harmonic distortion.
c) Can independently control active and reactive power
d) Are only used to exchange reactive power with the generator

15. Type 1 wind turbines
a) Typically include two sets of pole pairs for double speed operation
b) Can adapt the speed of the turbine using the yaw

c) Can overcome the Betz limit during limited time
d) Can provide voltage support using pitch

16. Medium speed PMSG are currently being manufactured by some companies
    a) Due to concerns on the variable price of the magnets
    b) As they can avoid installing the gearbox
    c) Was the most installed wind turbine in the 80s decade
    d) To be used in vertical axis offshore wind turbines

17. The optimal tip speed ratio λ
    a) Is typically found for large values of the pitch angle
    b) is the value that provides the maximum of the $C_p - \lambda$ curve
    c) is the value that provides the minimum of the $C_p - \lambda$ curve
    d) is a theoretical concept without engineering application

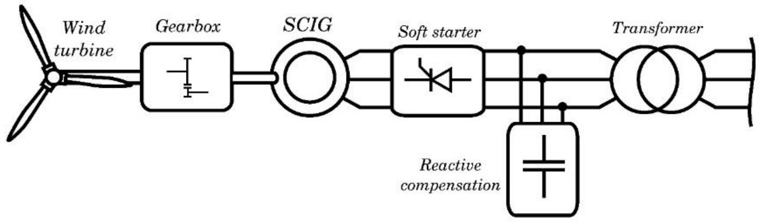
18. In Type 1 wind turbines
    a) The generator axis is rotating approximately 50 to 80 times slower than the blades
    b) The generator axis is rotating approximately 5 to 10 times faster than the blades
    c) The generator axis is rotating approximately 50 to 80 times faster than the blades
    d) The generator axis is rotating approximately 5 to 10 times slower than the blades

19. The power coefficient
    a) Is kept to a maximum in the partial load region in Type 1 wind turbines
    b) Is kept to a maximum in the partial load region in Type 4 wind turbines
    c) Is kept to a maximum when the turbine reaches nominal power in Type 4 wind turbines
    d) Is kept to a maximum when the turbine reaches nominal speed in Type 4 wind turbines

20. Weibull distribution is used to
    a) define wind data information in a location using two parameters
    b) define wind data, but the Raskolnikov approach is preferred because of its simplicity and accuracy
    c) define wind data information in a location using one parameter
    d) define wind data for all possible elevations, as it includes the information related to the wind shear and terrain roughness.

1 Sketch the four types of wind turbines, indicating the main components which form each of them Comment on the main characteristics, advantages and drawbacks of each concept. (1 point)

Fixed speed wind turbine



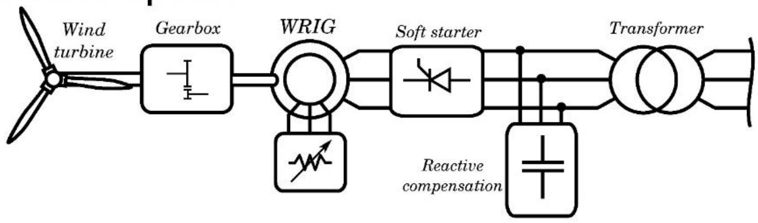
Concept

- Fixed speed wind turbine
- The 'Danish concept'
- Three-bladed rotor
- Multiple-stage gearbox
- Squirrel Cage Induction Generator (SCIG)
- Direct grid connection
- Most relevant turbine during the '80s and '90s

Advantages and Disadvantages

- Robustness
- Low production costs
- Straightforward control
- Constant speed operation
- High mechanical stress
- Reactive power compensation needed
- Soft-starter is required
- No ride-through capability/grid support

Limited variable speed



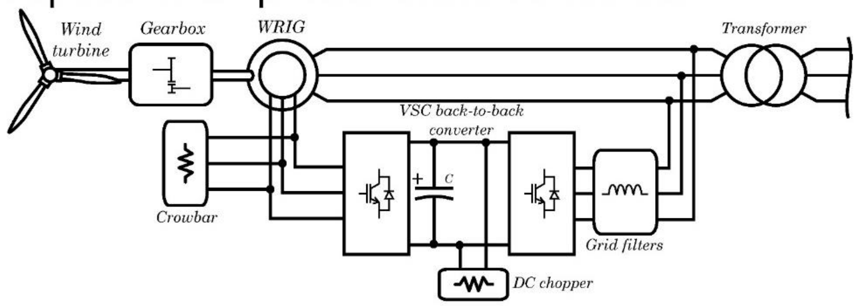
Concept

- Proposed during the '90s by Vestas®
- Wound Rotor Induction Generator (WRIG)
- Variable rotor resistance
- Direct connection to the grid
- Speed operation range (typically from 0 to 10%)

Advantages and Disadvantages

- Better wind power extraction than the fixed speed concept
- Reduced mechanical loading
- Relatively low production costs
- Power loss in the wound rotor resistances
- Possible slip rings
- Reactive power compensation needed
- No ride-through/grid support
- Soft-starter usually required

Variable speed with partial scale converter



Concept

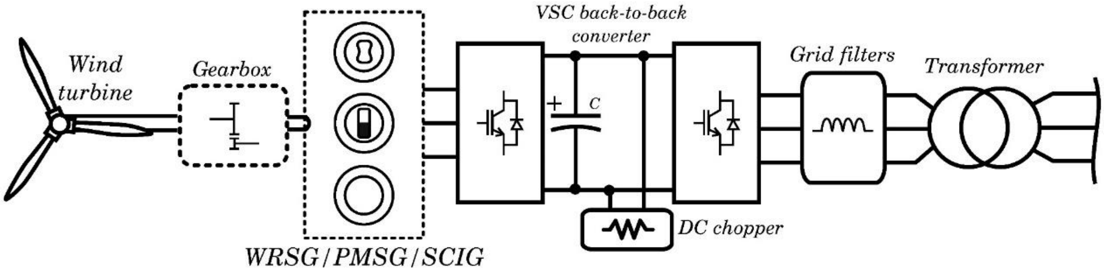
- Doubly Fed Induction Generation (DFIG)
- Wide speed range (typically from -40% to +30%)
- Active and reactive power control
- Most relevant during the first decade of the 2000's.

Advantages and Disadvantages

- Better power extraction from the wind.
- Reduced cost due to the partial-scale converter
- Active and reactive power controlled
- Ridethrough capability and grid support
- Slip rings are needed
- Stator connected to the grid
- Complex control during faults

CITCEA-UPC

Variable speed with full scale converter



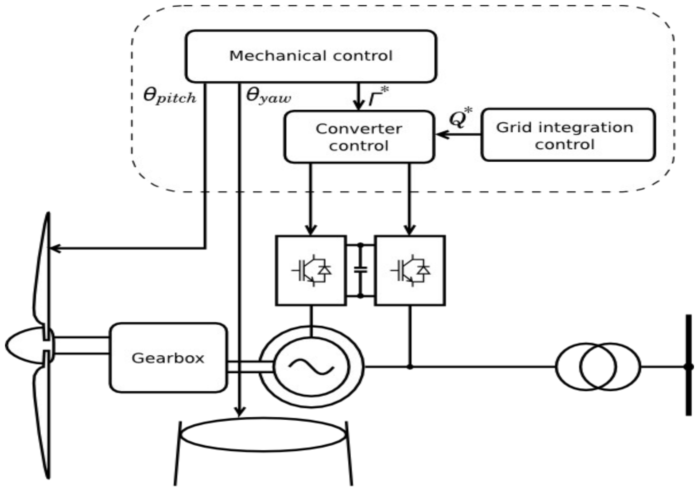
Concept

- Includes full power converter
- Speed is totally controllable
- Active and reactive power controlled
- Different feasible generators
- Optional gearbox

Features

- Maximum power extraction from the wind
- Full scale converter, generator isolated from the grid
- Active and reactive power controlled
- Ridethrough capability/grid support

2 How the controller a wind turbine (type 3 or 4) can track the maximum power from the wind? Explain it with the relevant drawings and equations. Include the key control diagrams. (1 pt)



Maximum Power Point Tracking

- Maximize the power output of the wind turbine
- Operate at maximum Cp (optimal λ)

- MPPT derivation

$$\frac{d}{d\lambda} C_P(\lambda)\Big|_{\lambda=\lambda^{opt}} = 0$$

$$\omega_t^{opt}(v_w) = \frac{\lambda^{opt}}{R} v_w$$

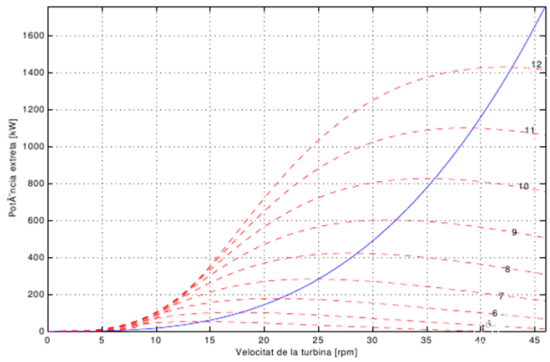
$$\Gamma_t(\omega_t^{opt}) = C_P(\lambda)\frac{1}{2}\rho A v_w^3 \frac{1}{\omega_t^{opt}}\Big|_{v_w=\frac{R\omega_t^{opt}}{\lambda^{opt}},\lambda=\lambda^{opt}}$$

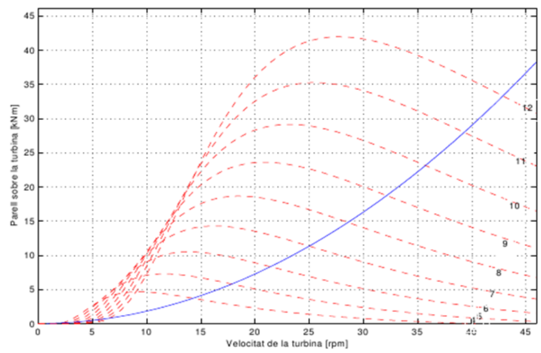
$$\Gamma_t(\omega_t^{opt}) = C_p^{opt}\frac{1}{2}\rho A \frac{R^3 {\omega_t^{opt}}^3}{\omega_t^{opt} {\lambda^{opt}}^3}$$

$$\Gamma_t(\omega_t^{opt}) = \boxed{C_p^{opt}\frac{\rho A R^3}{2{\lambda^{opt}}^3}} {\omega_t^{opt}}^2$$

$$\boxed{\Gamma_t(\omega_t^{opt}) = K_{C_P}\left(\omega_t^{opt}\right)^2}$$

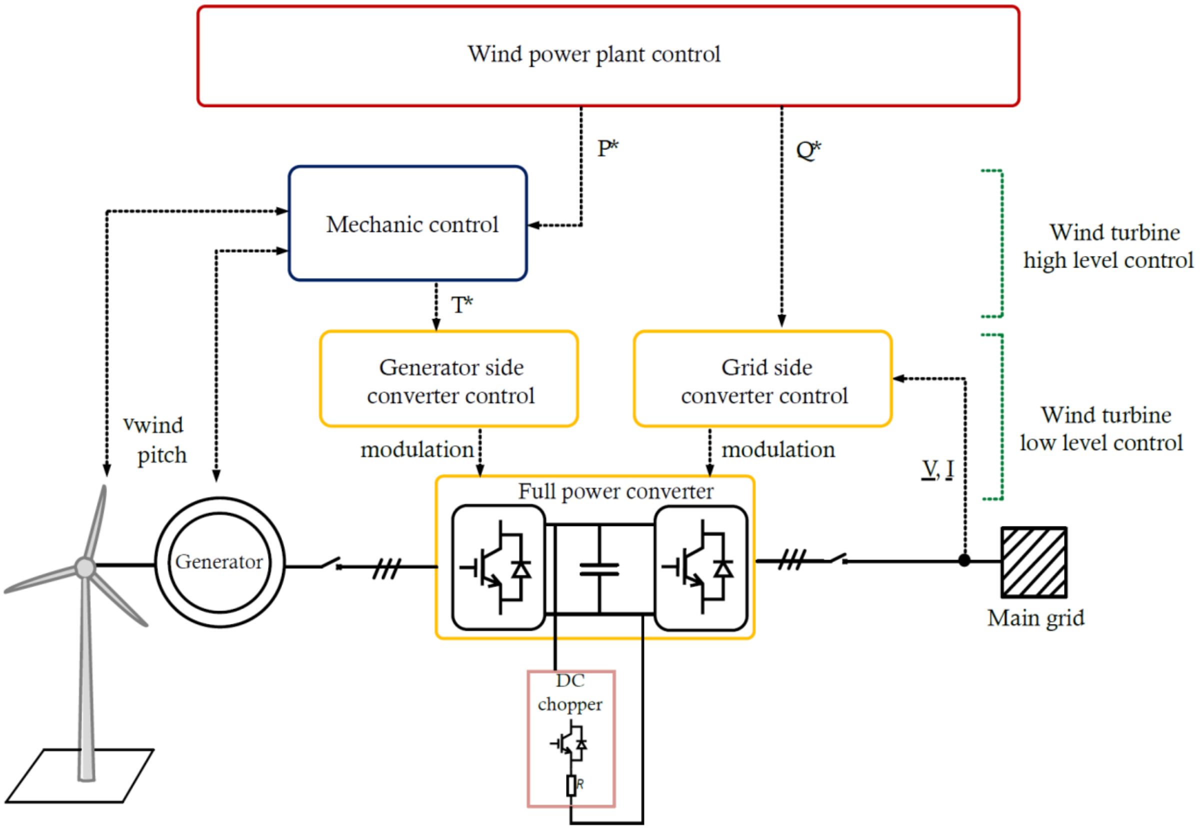
- Input → Rotational speed of the turbine ω_t
- Output → Torque reference Γ_t^*

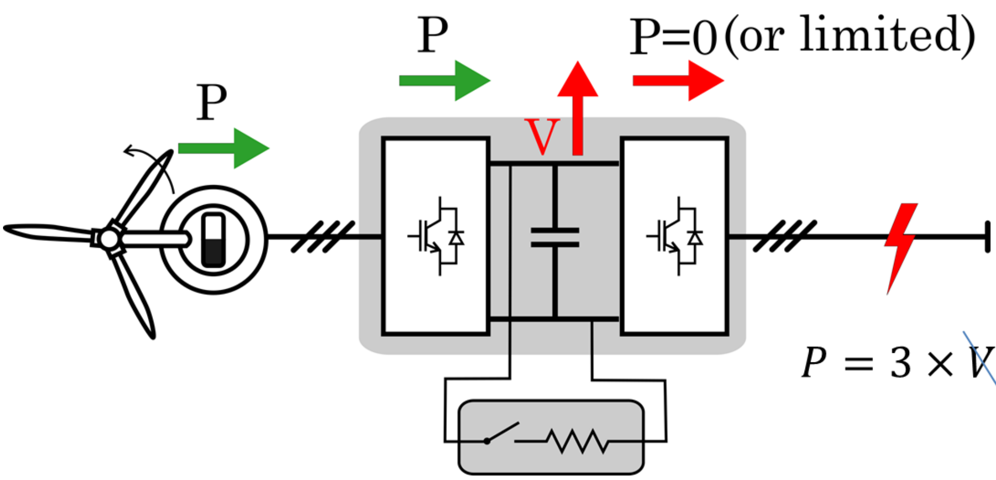




3 Draw a conceptual scheme of a type 4 wind turbine (select one of the different possibilities) and explain its main control parts (including high level control and the converter controllers).

Discuss how the wind turbine can deal with faults in the AC grid. Include relevant schematics and waveforms of key quantities. (2 pts)





$$P = 3 \times \cancel{V} \times I \approx 0$$

$$\approx 0$$

4 Assuming a defined wind and network conditions, explain step by step how you can calculate the active and reactive power exchanged by a type 1 wind turbine and the electrical network using steady state calculations (not simulations). (1 point)

See the exercises below.

PROBLEM 1. MECHANICAL POWER COMPUTATION FOR FIX SPEED WIND TURBINES.

A type 1 3.2 MW wind turbine with rotor diameter of D=100 m and gearbox ratio of N_{gb}=80 based on an induction generator (with 2 pole pairs) is connected to a 960 V 50 Hz grid . It can be assumed an air density of ρ=1.225 kg/m^3 and a power coefficient expression of

$$C_p = 0.0045\left(100 - (\lambda - 10)^2\right)$$

Neglecting slip (assuming s=0). Calculate the mechanical power generated for wind speeds of 5, 8, 11 and 14 m/s.

The mechanical power generated can be found using

$$P_{mech} = \frac{1}{2}\rho C_p A v_w^3$$

with air density ρ=1.225 kg/m^3, areas swept by the rotor $A = \pi D^2/4$ with diameter D=100 m and power coefficient $C_p = 0.0045\left(100 - (\lambda - 10)^2\right)$, where the tip speed ratio λ can be computed as

$$\lambda = \frac{\omega_t D}{2 v_w} = \frac{\omega_g D}{2 N_{gb} v_w}$$

Where ω_t is wind turbine speed (slow axis), ω_g is the generator speed (fast axis), and N_{gb} is the gearbox ratio.

The previous expressions can be combined as

$$P_{mech} = \frac{0.0045}{2}\rho\left(100-(\lambda-10)^2\right)Av_w^3$$

$$P_{mech} = \frac{0.0045}{2}\rho\left(100-\left(\frac{\omega_g D}{2N_{gb}v_w}-10\right)^2\right)v_w^3\pi D^2/4$$

where all the quantities are known except the generator speed ω_g.

The generator speed depends mainly on the slip s and the synchronous speed ω_s :

$$\omega_g = (1-s)\omega_s = (1-s)\frac{2\pi f}{p}$$

where p are pairs of poles. Assuming s=0, $\omega_g = \omega_s = 2\pi 50/p = \pi 50 \text{ rad/s}$

Therefore, the mechanical power can be computed as

$$P_{mech} = \frac{0.0045}{2}\rho\left(100-\left(\frac{\omega_s D}{2N_{gb}v_w}-10\right)^2\right)v_w^3\pi D^2/4$$

$$P_{mech} = \frac{0.0045}{2}1.225\left(100-\left(\frac{\pi 50\times 100}{2\times 80\times v_w}-10\right)^2\right)v_w^3\pi 100^2/4$$

The following resultants are obtained:

ω_e = 3.141592653589793e+002 rad/s
ω_s = 1.570796326794897e+002 rad/s
ω_g = 1.570796326794897e+002 rad/s
ω_t = 1.963495408493621 rad/s
λ = 19.634954084936204
C_p = 0.032254469015270
P = 1.939527243080785e+004 W

The calculations can be extended to the other wind speeds, obtaining:

v_w=5	8	11	14	m/s
ω_s = 157.0796	157.0796	157.0796	157.0796	rad/s
ω_g = 157.0796	157.0796	157.0796	157.0796	rad/s
ω_t = 1.9635	1.9635	1.9635	1.9635	rad/s
λ = 19.6350	12.2718	8.9250	7.0125	
C_p = 0.0323	0.4268	0.4448	0.4098	
P = 1.9395e+004	1.0511e+006	2.8480e+006	5.4099e+006	W
			P=3.2 MW Pitch!!	

where it can be noted that when the mechanical power exceeds the nominal power (3.2 MW), the pitch system must reduce the mechanical power to its nominal value.

Develop a Matlab program to solve the previous exercise.

Code:

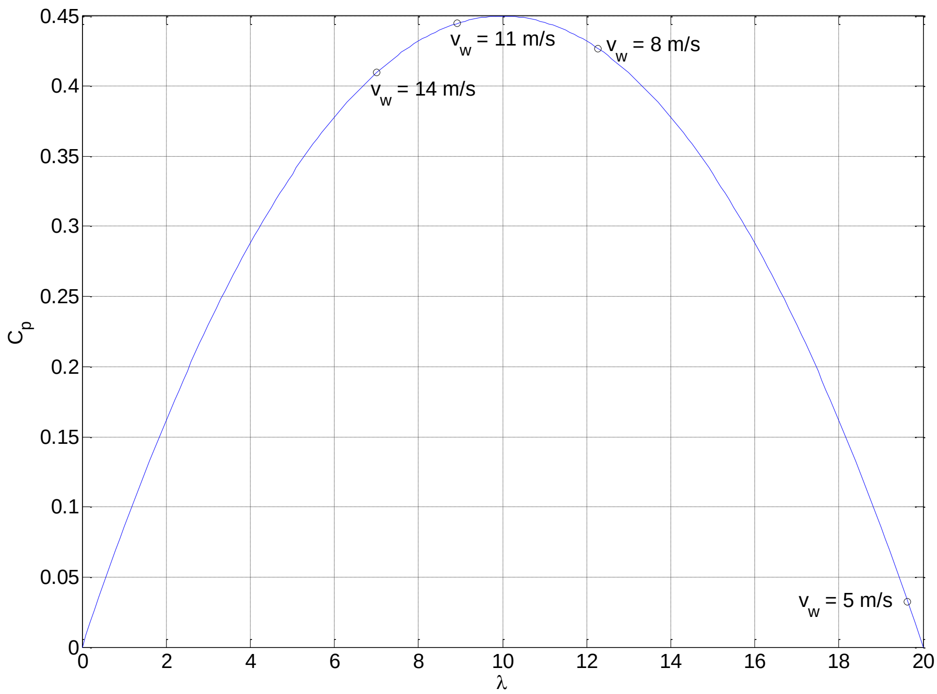
```
clear;clc;
vw=[5 8 11 14]
ss=0;rho=1.225;N=80;D=100;poles=2;Ugrid=960;f=50;

we=2*pi*f;
ws=we/poles;
wg=ws*(1-ss);
wt=wg/N;

lam= wt*(D/2) ./ vw
Cpp= 0.0045 * (100 - (lam-10).^2)
P1=0.5*rho*Cpp*(pi*(D^2)/4).*vw.^3
```

Develop a Matlab program to locate the operating points in the Cp- λ curve.

Code:

```
%% Develop a Matlab program to locate the  operating points in the
Cp-lambda curve.

lam1=0:.1:20;
Cpp1= 0.0045 * (100 - (lam1-10).^2);
plot(lam1,Cpp1);hold on;grid on;
plot(lam,Cpp,'ko');
for ii=1:1:4
    txt{ii}=['v_w = ' num2str(vw(ii)) ' m/s'];
    text(lam(ii),Cpp(ii),txt{ii},'FontSize',18);
end;
xlabel('\lambda','FontSize',18);
ylabel('C_p','FontSize',18);
```

Results:

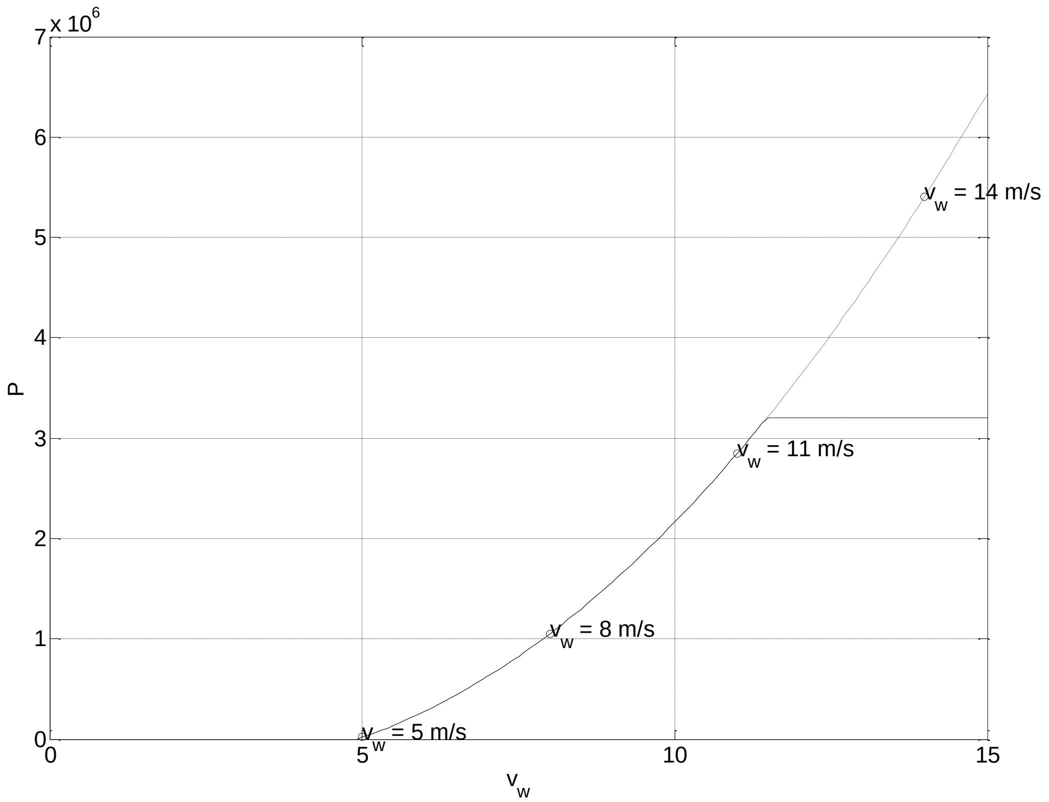


Develop a Matlab program to plot the power generated for different wind speeds.

Code:

```
%% Develop a Matlab program to plot the power generated for different
wind
%% speeds. Include a comparison between the obtained power and the
maximum available power.
figure(2);
vw2=0:.1:15
lam2= min(20,max(wt*(D/2) ./ vw2,0));
Cpp2= 0.0045 * (100 - (lam2-10).^2)
P2=0.5*rho*Cpp2*(pi*(D^2)/4).*vw2.^3;
P2a=min(0.5*rho*Cpp2*(pi*(D^2)/4).*vw2.^3,Pn);

h=subplot(1,1,1);
plot(vw2,P2,':k');hold on;grid on;
plot(vw2,P2a,'k');
plot(vw,P1,'ko');
for ii=1:1:4
    txt{ii}=['v_w = ' num2str(vw(ii)) ' m/s'];
    text(vw(ii),P1(ii),txt{ii},'FontSize',18);
end;
xlabel('v_w','FontSize',18);
ylabel('P','FontSize',18);
set(h,'FontSize',18);
```

Results:

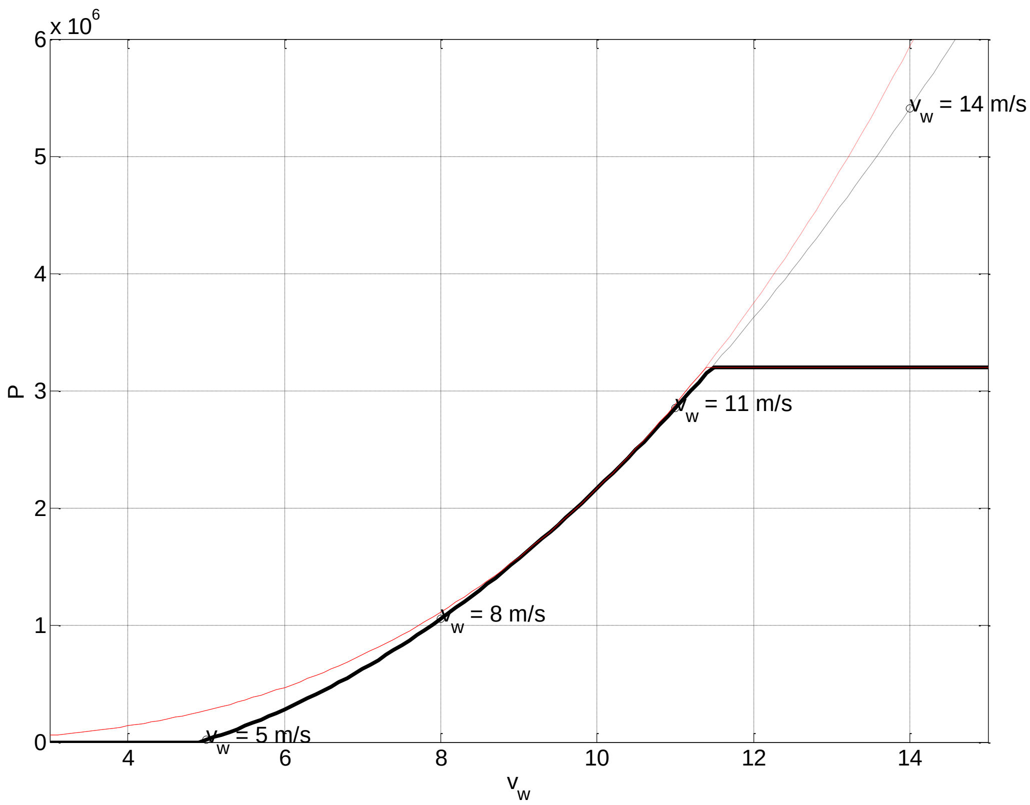


Include a comparison between the obtained power and the maximum available power.

Code:

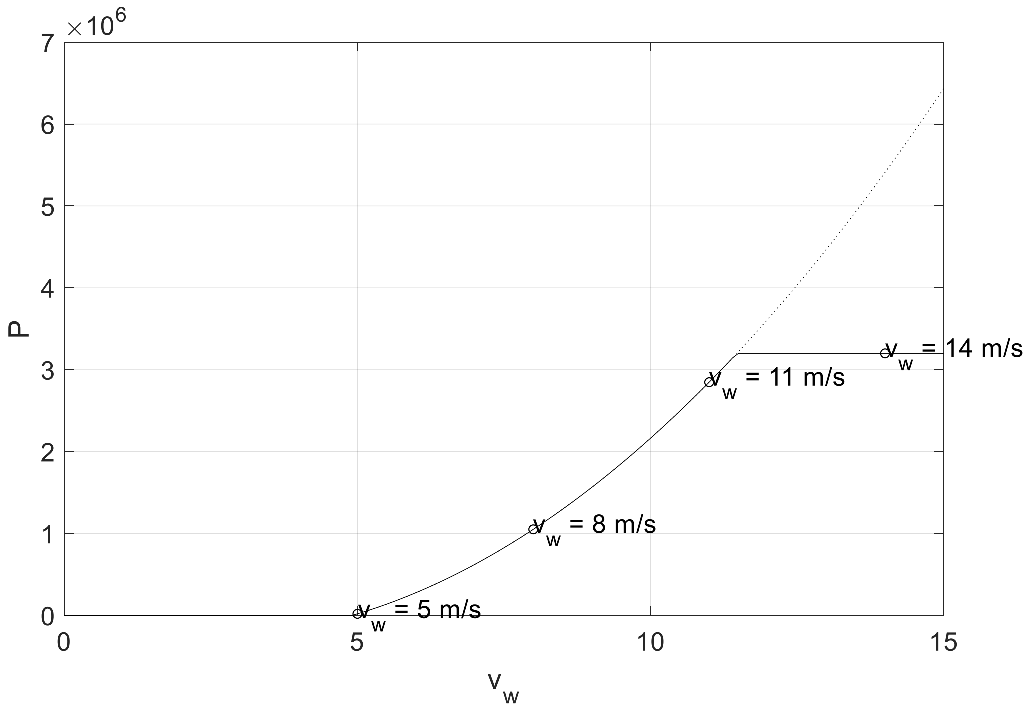
```
figure(3);
lam2b= 10;
Cpp2b= 0.45;
P3=0.5*rho*Cpp2b*(pi*(D^2)/4).*vw2.^3;
P3a=min(0.5*rho*Cpp2b*(pi*(D^2)/4).*vw2.^3,Pn);

h=subplot(1,1,1);
plot(vw2,P2,':k');hold on;grid on;
plot(vw2,P2a,'k','LineWidth',3);
plot(vw,P1,'ko');
plot(vw2,P3,':r');
plot(vw2,P3a,'r');

for ii=1:1:4
    txt{ii}=['v_w = ' num2str(vw(ii)) ' m/s'];
    text(vw(ii),P1(ii),txt{ii},'FontSize',18);
end;
xlabel('v_w','FontSize',18);
ylabel('P','FontSize',18);
set(h,'FontSize',18);
axis([3 15 0 6e6]);
```

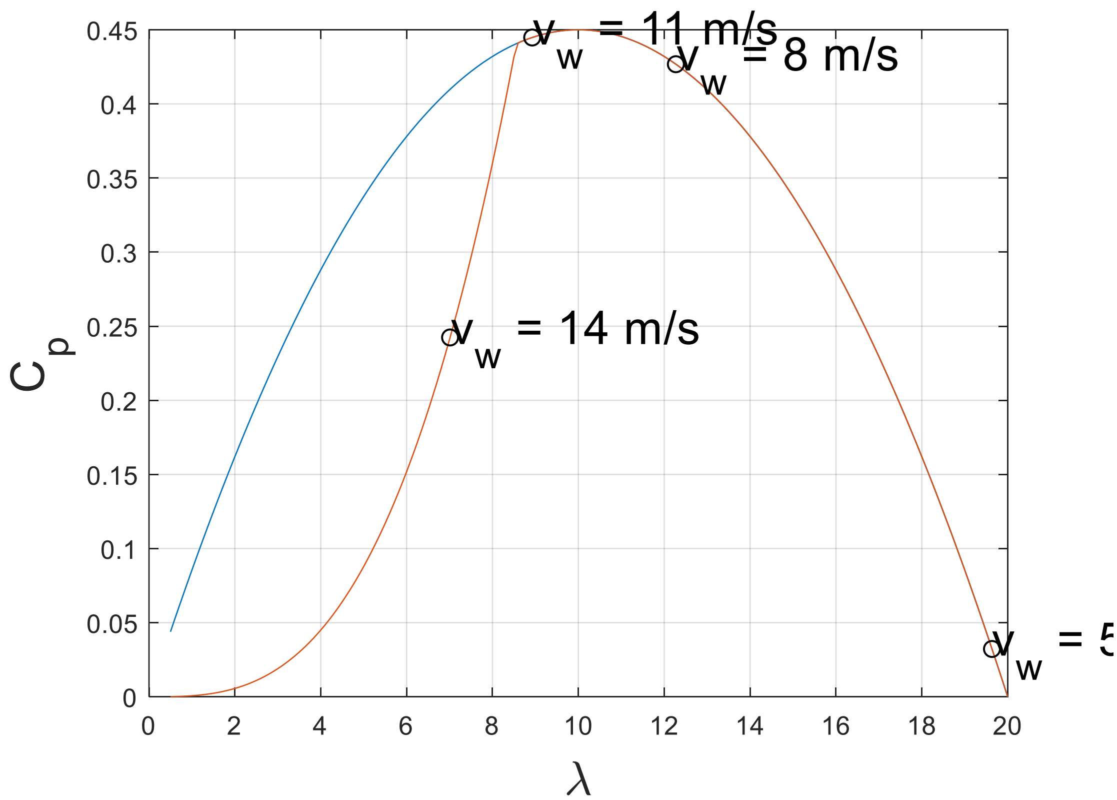
Results:



How should we modify the scripts in order to consider appropriately the maximum power limitation (with implied pitch control to limit the power)?

Results





PROBLEM 2. MECHANICAL AND ELECTRICAL ANALYSIS OF FIX SPEED WIND TURBINES.

A 3.2 MW wind turbine with rotor diameter of *D*=100 m and gearbox ratio of N_{gb}=80 based on an induction generator (with the parameters of the table and 2 pairs of poles) is connected to a 960 V 50 Hz grid .

R_s=0.015 Ω	X_s=0.1 Ω	R_m=50 Ω	X_m=8 Ω	R_r=0.01 Ω	X_r=0.1 Ω

It can be assumed an air density of *ρ*=1.225 kg/m³ and a power coefficient expression of

$$C_p = 0.0045\left(100 - (\lambda - 10)^2\right)$$

Calculate the mechanical power generated for wind speed 8 m/s and the corresponding electrical active and reactive power exchanged with the grid.

Mechanical power calculation

The rationale of Problem 1 can be followed with the only difference of not assuming s=0. The mechanical power can be expressed as

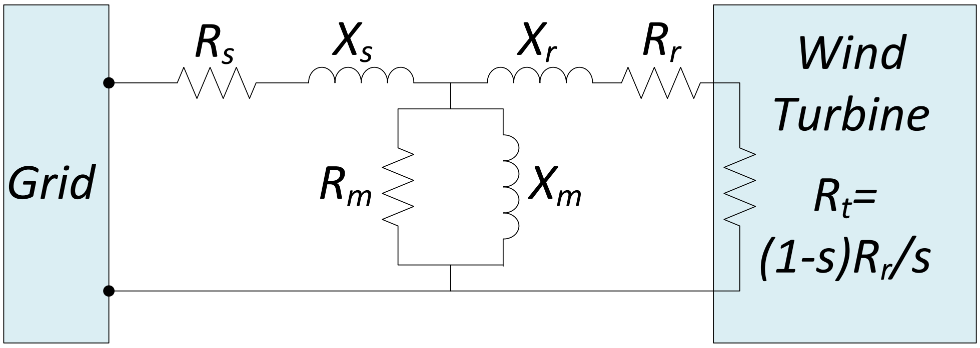
$$P_{mech} = \frac{0.0045}{2}\rho\left(100 - \left(\frac{\omega_g D}{2N_{gb}v_w} - 10\right)^2\right)v_w^3\pi D^2/4$$

$$P_{mech} = \frac{0.0045}{2}\rho\left(100 - \left(\frac{(1-s)\frac{2\pi f}{p}D}{2N_{gb}v_w} - 10\right)^2\right)v_w^3\pi D^2/4$$

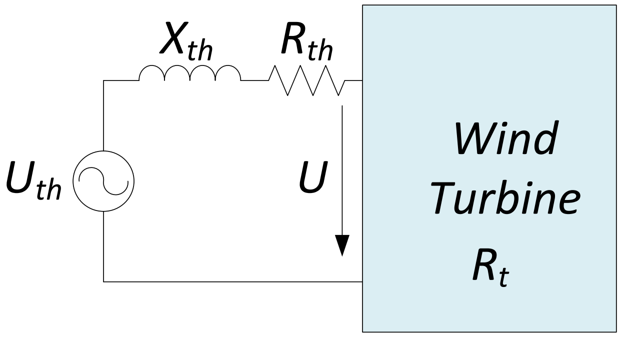
where it is clearly shown that for each wind speed a different generated power will be obtained depending on the slip *s*.

Electrical analysis

The equivalent one-phase model of an induction generator shown in the Figure can be used for the electrical analysis.



Neglecting mechanical losses, the power generated in the wind turbine is known from the previous analysis and corresponds to the power "generated" by the equivalent resistance R_t. The grid voltage is known, but the current must be calculated from the circuit analysis. This is a typical problem of two node power flow which can be solved using the Thevenin equivalent seen from the resistance R_t.



Using $\underline{Z}_{sm} = R_m // \mathrm{j} X_m = \dfrac{\mathrm{j} R_m X_m}{R_m + \mathrm{j} X_m}$, the Thevenin equivalent impedance can be found:

$$\underline{Z}_{th} = R_{th} + \mathrm{j} X_{th} = \left(R_s + \mathrm{j} X_s\right) // \underline{Z}_{sm} + \left(R_r + \mathrm{j} X_r\right)$$

The Thevenin equivalent voltage can be found:

$$\underline{U}_{th} = \frac{\underline{U}_{pn-grid}}{\left(R_s + \mathrm{j} X_s\right) + \underline{Z}_{sm}} \underline{Z}_{sm}$$

Where $\underline{U}_{pn-grid}$ is the phase to neutral voltage. Once the Thevenin equivalent is known, the voltage U can be found from

$$U^4 + U^2\left(2R_{th}P + 2X_{th}Q - U_{th}^2\right) + \left(R_{th}^2 + X_{th}^2\right)\left(P^2 + Q^2\right) = 0$$

Where the power P and Q are the **one-phase** active and reactive power exchanged between the resistance R_t and the equivalent circuit using the load convention (P>0 load, P<0 generation). It can be noted that P will be the mechanical power generated (negative, one phase) $P_{1phase} = -P_{mech}/3$ and Q will be 0 since the model is a pure resistance.

$$U^4 + U^2\left(2R_{th}P_{1phase} - U_{th}^2\right) + \left(R_{th}^2 + X_{th}^2\right)P_{1phase}^2 = 0$$

Once the voltage U is known, the resistance R_t will be found

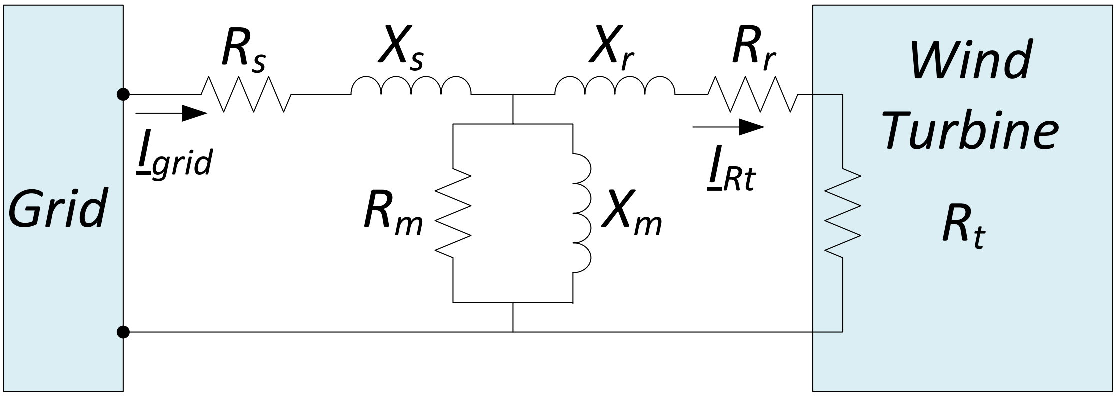
$$R_t = \frac{U^2}{P_{1phase}}$$

And the slip

$$s = \frac{R_r}{R_r + R_t}$$

The resistance R_t current can be calculated

$$\underline{I}_{Rt} = \frac{\underline{U}_{\mathrm{th}}}{\underline{Z}_{\mathrm{th}} + R_t}$$



The grid current can be calculated using different approaches. For example

$$\underline{I}_{grid} = \frac{\underline{U}_{pn-grid}}{\left(R_s + \mathrm{j}X_s\right) + \underline{Z}_{sm} // \left(R_t + R_r + \mathrm{j}X_r\right)}$$

The power exchanged with the grid yields:

$$\underline{S}_{grid} = 3\underline{U}_{pn-grid}\,\underline{I}^{*}_{grid}$$

<u>Iterative solution</u>

In the mechanical analysis it has been shown that for given wind conditions the mechanical power depends on the slip. In the electrical analysis it has been shown that for each generated power, the equivalent resistance and slip can be calculated.

An iterative solution procedure can be applied to the case of wind speed 8 m/s.

Implementation in Matlab for vw=8 m/s

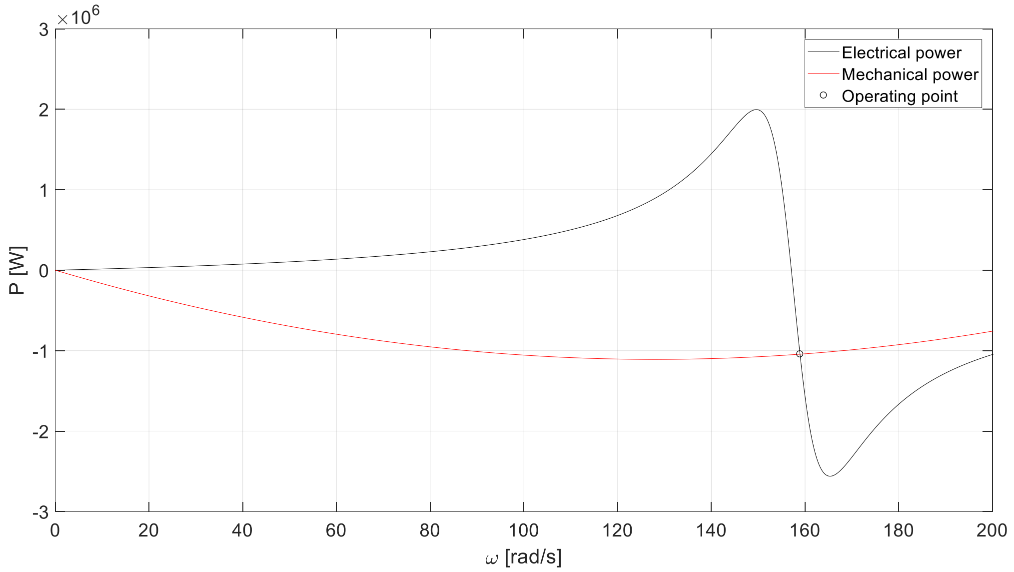
```
clc;clear;
% Parameters
rho=1.225;N=80;D=100;poles=2;Ugrid=960;f=50;
Rs=0.015;Xs=0.1;Rm=50;Xm=8;Rr=0.01;Xr=0.1;

% Equivalent model
Zs=Rs+j*Xs;Zm=Rm*(j*Xm)/(Rm+j*Xm);Zr=Rr+j*Xr;
Zsm=Zs*Zm/(Zs+Zm);
Zth=Zr+Zsm;
V=Ugrid/sqrt(3);
Uth= Zm*V/(Zm+Zs);
Uu=abs(Uth);

vw=8;

% Initialization
ss=0;kk=0;err=1;P1=0;

while ((kk<100)&&(err>1e-6))

    kk=kk+1;

    we=2*pi*f;ws=we/poles;wg=ws*(1-ss);wt=wg/N;
    lam= wt*(D/2) / vw;
```

```
    Cpp= 0.0045 * (100 - (lam-10)^2);
    P1a=0.5*rho*Cpp*(pi*(D^2)/4)*vw^3;
    err=abs(P1a-P1);
    P1=P1a;
    P1phase=-P1/3;
    a1=1;a2=2*real(Zth)*P1phase -Uu^2;a3=abs(Zth)^2*( P1phase ^2);
    sol=roots([a1 0 a2 0 a3]);
    Rt=sol.^2/ P1phase;
    s=Rr./(Rr+Rt);
    ss=s(2);
end;

P1
ss
Igrid = V/(Zs+Zm*(Zr+Rt(2))/(Zm+(Zr+Rt(2))))
Sgrid= 3*V*conj(Igrid)
losses=real(Sgrid)+P1
```

Results:

```
P1 =   1.0437e+06

ss =   -0.0117

Igrid =  -5.9875e+02 - 2.1262e+02i

Sgrid =   -9.9558e+05 + 3.5354e+05i

losses =   4.8108e+04
```

```
ssaux=-1:.00001:1;
Iaux=Uth./(Zth+Rr*(1-ssaux)./ssaux);
Paux=3*abs(Iaux).^2.*Rr.*(1-ssaux)./ssaux;
wgaux=ws*(1-ssaux);
wtaux=wgaux/N;
lamaux= wtaux*(D/2) / vw;
Cppaux= 0.0045 * (100 - (lamaux-10).^2);
Pauxmec=0.5*rho*Cppaux*(pi*(D^2)/4)*vw^3;

figure(1);
h=subplot(1,1,1);
plot(wgaux,Paux,'k');hold on;grid on;
plot(wgaux,-Pauxmec,'r');
plot(wg,-P1,'ok');
xlabel('\omega [rad/s]','FontSize',18);
ylabel('P [W]','FontSize',18);
legend('Electrical power','Mechanical power','Operating point');
set(h,'FontSize',18);
axis([0 200 -3e6 3e6]);
```


×10^6
3
2
1
0
-1
-2
-3
P [W]
0
20
40
60
80
100
120
140
160
180
200
ω [rad/s]
Electrical power
Mechanical power
Operating point