EE362 HW#3

Table of Contents

NAME: *SOLUTION*

STUDENT NUMBER: 123456

Q.1)

a)

```
f = 50; % Hz
Nr_nl = 1480; % rpm
p = round(120*f/Nr_nl);
fprintf('Pole number of the machine is %d.\n',p);
```

```
Pole number of the machine is 4.
```

b)

```
Ns = 120*f/p; % rpm
fprintf('Synchronous speed of the machine is %d rpm.\n',Ns);
```

```
Synchronous speed of the machine is 1500 rpm.
```

c)

```
Nr = 0; % rpm
fr = p*(Ns-Nr)/120; % Hz
fprintf('Frequency of rotor induced currents is %d Hz.\n',fr);
```

```
Frequency of rotor induced currents is 50 Hz.
```

d)

```
s = 0.05;
Nr = (1-s)*Ns; % rpm
fprintf('Speed of the rotor is %d rpm.\n',Nr);
```

```
Speed of the rotor is 1425 rpm.
```

e)

```
fr = p*(Ns-Nr)/120; % Hz
fprintf('Frequency of rotor induced currents is %d Hz.\n',fr);
```

```
Frequency of rotor induced currents is 2.500000e+00 Hz.
```

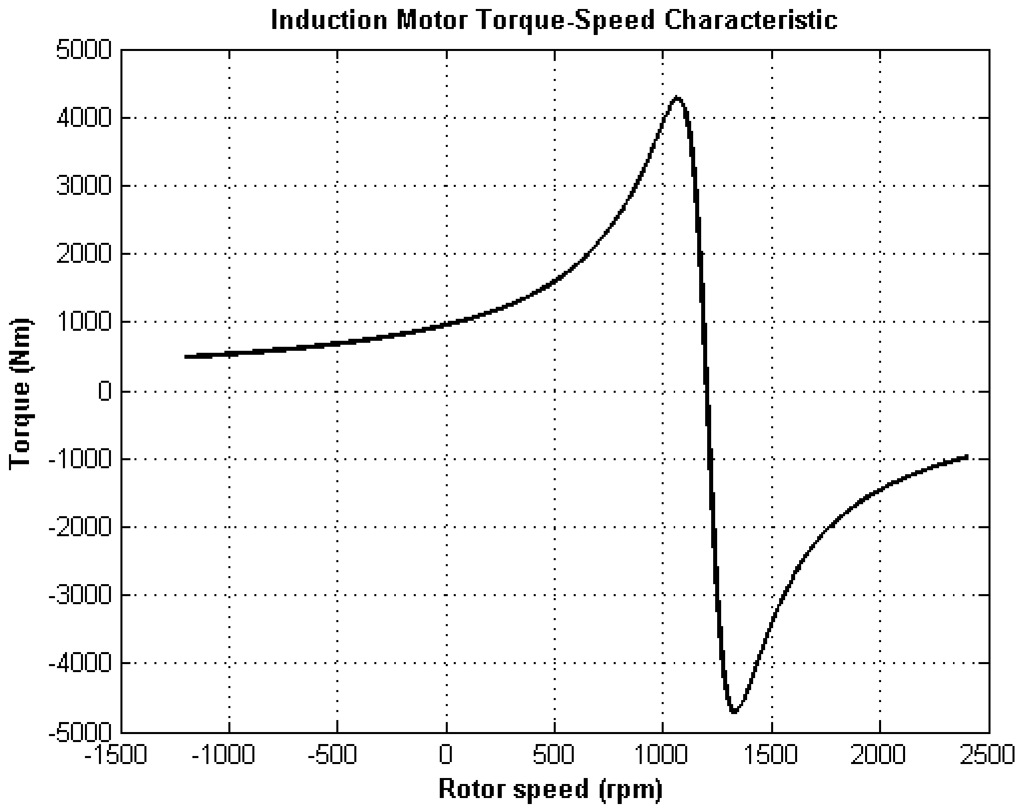
Q.2)

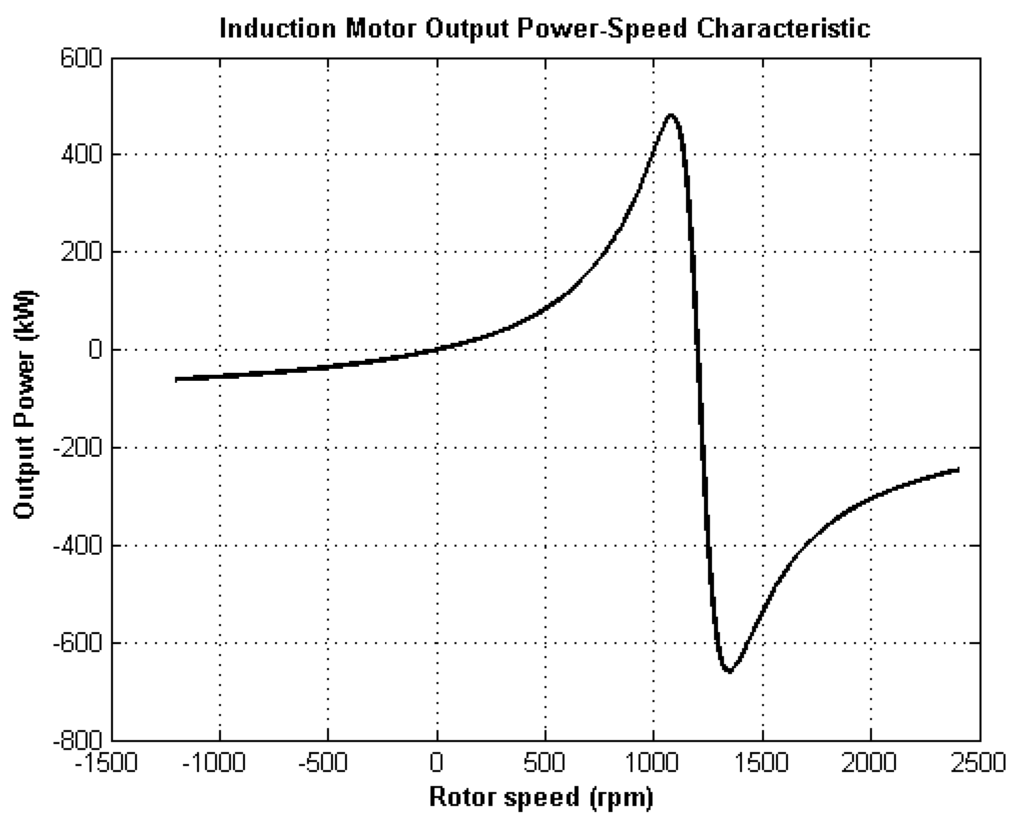
```
% Define given variables
R1 = 0.015; % ohms
R2p = 0.033; % ohms
L1 = 0.41e-3; % henry
L2p = 0.4e-3; % henry
Lm = 13.5e-3; % henry
Rc = 49.5; % ohms
Vline = 600; % volts
frequency = 60; % hz
Prated = 300e3; % watts
pole = 6;
```

Part a)

```
% Obtain the variables that will be used in the torque equation:
Vphase = Vline/sqrt(3); % volts
X1 = L1*2*pi*frequency; % ohms
X2p = L2p*2*pi*frequency; % ohms
Xm = Lm*2*pi*frequency; % ohms
Nsync = 120*frequency/pole; % rpm
```

```
wsync = Nsync*2*pi/60; % rad/sec

% Thevenin variables
Zm = (1j*Xm*Rc)/(1j*Xm+Rc); % ohms
Z1 = R1+1j*X1; % ohms
Vth = Vphase*Zm/(Z1+Zm); % volts
Zth = Z1*Zm/(Z1+Zm); % ohms
Rth = real(Zth); % ohms
Xth = imag(Zth); % ohms

% Slip (and rotor speed) array
s = -1:0.001:2;
s = fliplr(s);
Nr = Nsync*(1-s); % rpm
wr = Nr*2*pi/60; % rad/sec
num = numel(s);
Tm = zeros(1,num); % Nm

% Torque array using the calculated variables and slip variation
Tm = (3*abs(Vth)^2/wsync)*(1./ ( (Rth+R2p./s).^2 + (Xth+X2p)^2 ) )...
    .*(R2p./s); % Nm

% At synchronous speed, torque will be zero (avobe equation cannot calculate)
Tm((s==0)) = 0; % Nm

% Plot the torque-speed curve
figure;
plot(Nr,Tm,'k-','LineWidth',2.0);
xlabel('Rotor speed (rpm)','Fontweight','Bold');
ylabel('Torque (Nm)','Fontweight','Bold');
title ('Induction Motor Torque-Speed Characteristic','Fontweight','Bold');
grid on;

% Obtain the output power characteristics
Pm = Tm.*wr; % Watts

% Plot the output power-speed curve
fig = figure;
plot(Nr,Pm*1e-3,'k-','LineWidth',2.0);
xlabel('Rotor speed (rpm)','Fontweight','Bold');
ylabel('Output Power (kW)','Fontweight','Bold');
title ('Induction Motor Output Power-Speed Characteristic','Fontweight','Bold');
grid on;

% Store the torque characteristics for further usage
Toriginal = Tm; % Nm
```


Induction Motor Torque-Speed Characteristic
Torque (Nm)
5000
4000
3000
2000
1000
0
-1000
-2000
-3000
-4000
-5000
-1500
-1000
-500
0
500
1000
1500
2000
2500
Rotor speed (rpm)


Induction Motor Output Power-Speed Characteristic
Output Power (kW)
600
400
200
0
-200
-400
-600
-800
-1500
-1000
-500
0
500
1000
1500
2000
2500
Rotor speed (rpm)

Part b)

```
% Calculate the asked parameters using the torque characteristics

starting_torque = Tm((s==1)); % Nm
max_torque = max(Tm); % Nm
max_power = max(Pm); % Watts
slip_max_torque = s((Tm==max_torque));
slip_max_power = s((Pm==max_power));

fprintf('The starting torque is %d Nm.\n', starting_torque);
fprintf('The maximum torque is %d Nm.\n', max_torque);
fprintf('The maximum power is %d Watts.\n', max_power);
fprintf('The slip at maximum torque is %d.\n', slip_max_torque);
fprintf('The slip at maximum power is %d.\n', slip_max_power);
```

```
The starting torque is 9.598169e+02 Nm.
The maximum torque is 4.271233e+03 Nm.
The maximum power is 4.812695e+05 Watts.
The slip at maximum torque is 1.100000e-01.
The slip at maximum power is 9.800000e-02.
```

Maximum power does not occur at the slip where maximum torque occurs. In fact, slip of maximum power is smaller that the other. In other words, speed of maximum power is higher. The reason is that, since P = T*wr, as the speed increases further from the maximum torque point, the increase of speed overcomes the decrease of torque for a while. After a point (Pmax), torque decay is much rapid.

Part c)

No it is not. Because, Tload(wr=0) > Tstarting

Method : External rotor resistance

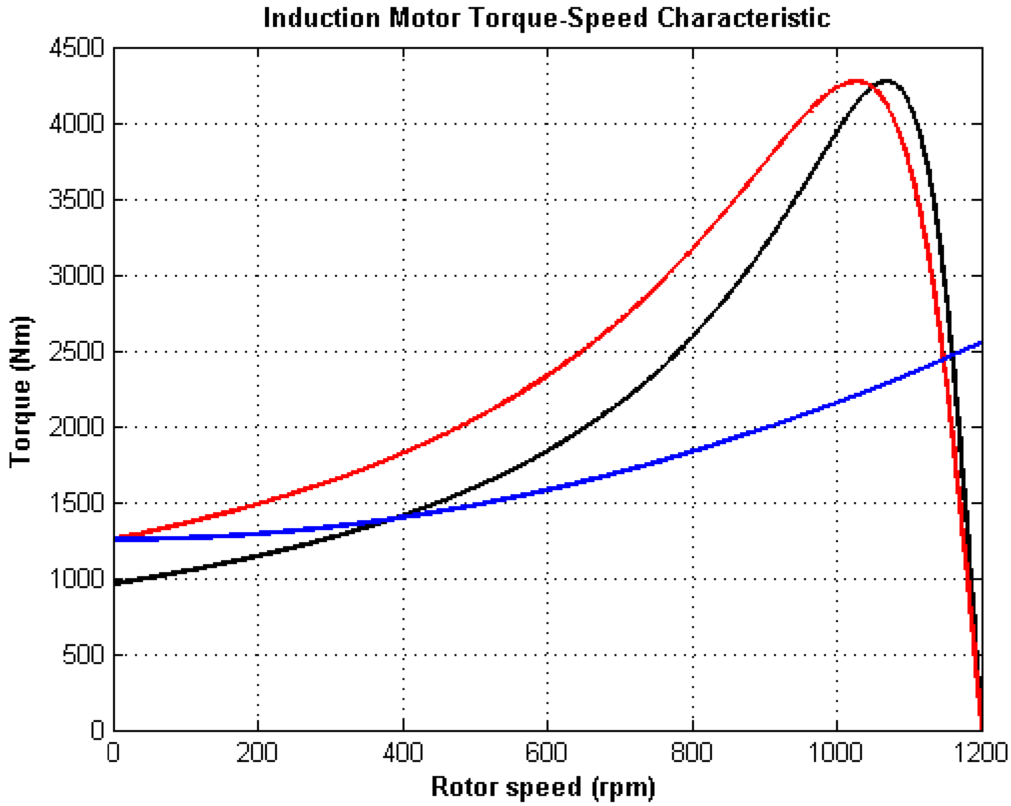
```
syms res
Tload_start = 1253; % Nm

add_resistance = double(solve((3*abs(Vth)^2/wsync)*((R2p+res)...
    /((Rth+R2p+res)^2+(Xth+X2p)^2))==Tload_start,...
    'IgnoreAnalyticConstraints',true));

fprintf('The possible external rotor resistance values are:\n');
fprintf('%d Ohms and\n',add_resistance(1));
fprintf('%d Ohms and\n',add_resistance(2));

add_res = add_resistance(2);
fprintf('Selected external rotor resistance is: %d Ohms\n',add_res);

% Calculate the new starting torque to check your solution
Tst_new = (3*abs(Vth)^2/wsync)*((R2p+add_res)/...
    ((Rth+R2p+add_res)^2+(Xth+X2p)^2));

fprintf('New starting torque is: %d Nm\n',Tst_new);
```

```
The possible external rotor resistance values are:
2.046524e+00 Ohms and
1.060100e-02 Ohms and
Selected external rotor resistance is: 1.060100e-02 Ohms
New starting torque is: 1.253000e+03 Nm
```

The equation provides two solutions: 2 Ohms and 10 mOhms. The 1st solution corresponds to a curve where maximum torque is in braking mode whereas the 2nd solution provides an increase on the starting torque by slightly shifting the curve to the left. Obviously, 1st solution is very inefficient and therefore the external resistance to be connected is chosen as 10 mOhms. After the startup, the external resistance should be removed (if possible) just after the original torque is higher than the load torque. After that point, the load torque should always be lower up to the steady state point. Otherwise, the motor may slow down and never reach the stable region of the torque-speed curve.

Part d)

```
% Torque with external resistance
Tm = (3*abs(Vth)^2/wsync)*(1./ ((Rth+(R2p+add_res)./s).^2+(Xth+X2p)^2))...
    .*((R2p+add_res)./s); % Nm
Tm((s==0)) = 0; % Nm

% Load torque
load_torque = 1253 + 0.0824*wr.^2; % Nm

% Plot the torque-speed curves
figure;
plot(Nr,Toriginal,'k-','LineWidth',2.0);
hold on;
plot(Nr,Tm,'r-','LineWidth',2.0);
hold on;
plot(Nr,load_torque,'b-','LineWidth',2.0);
hold off;
xlabel('Rotor speed (rpm)','Fontweight','Bold');
ylabel('Torque (Nm)','Fontweight','Bold');
title ('Induction Motor Torque-Speed Characteristic','Fontweight','Bold');
grid on;
xlim([0 1200]);
```



Part e)

Part e-1)

```
% Using the graph:
Nr_op = 1159; % rpm
fprintf('Rotor speed at this operating point is %d rpm.\n',Nr_op);
```

Rotor speed at this operating point is 1159 rpm.

Part e-2)

```
% This can both be calculated by using graph and using the load torque at
% the given speed:
Tm_op = 2467; % Nm
wr_op = Nr_op*2*pi/60; % rad/sec
Tm_op = 1253 + 0.0824*wr_op^2; % Nm
fprintf('Torque at this operating point is %d Nm.\n',Tm_op);
```

Torque at this operating point is 2.466812e+03 Nm.

Part e-3)

```
slip = (Nsync-Nr_op)/Nsync;
```

```
Pm_op = Tm_op*wr_op; % watts
Pout = Pm_op; % watts
I2p = sqrt((slip/(1-slip))*(Pm_op/(3*R2p))); % amps
Pcur = 3*I2p^2*R2p; % watts
Pag = Pcur + Pm_op; % watts
I1 = I2p; % amps
Pcus = 3*I1^2*R1; % watts
Pc = 3*Vphase^2/Rc; % watts
Pin = Pag + Pcus + Pc; % watts
efficiency = Pout/Pin*100; % percent

fprintf('Efficiency at this operating point is %d %%\n',efficiency);
```

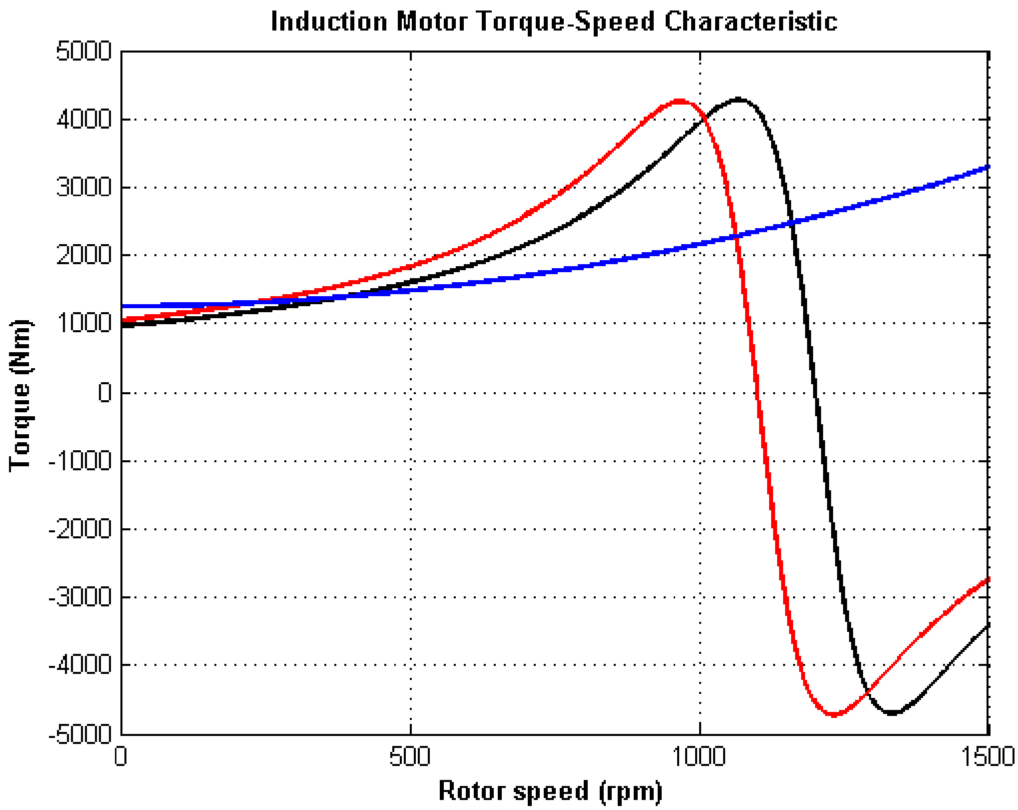
Efficiency at this operating point is 9.295873e+01 %

Part f)

Part f-1)

```
% Define new variables
frequency_new = 55; % hz
Vline_new = Vline*(frequency_new/frequency); % volts

% Calculate all the parameters to be used in the torque equation, with the
% new frequency and voltage:

Vphase = Vline_new/sqrt(3); % volts
X1 = L1*2*pi*frequency_new; % ohms
X2p = L2p*2*pi*frequency_new; % ohms
Xm = Lm*2*pi*frequency_new; % ohms
Nsync = 120*frequency_new/pole; % rpm
wsync = Nsync*2*pi/60; % rad/sec

Zm = (1j*Xm*Rc)/(1j*Xm+Rc); % ohms
Z1 = R1+1j*X1; % ohms
Vth = Vphase*Zm/(Z1+Zm); % volts
Zth = Z1*Zm/(Z1+Zm); % ohms
Rth = real(Zth); % ohms
Xth = imag(Zth); % ohms

% Define a new slip array and obtain a new speed array
% Note that the synchronous speed is now changed
s2 = -1:0.001:2;
s2 = fliplr(s2);
Nr2 = Nsync*(1-s2);
num = numel(s2);
Tm = zeros(1,num);

% Obtain the torque
Tm = (3*abs(Vth)^2/wsync)*(1./((Rth+R2p./s2).^2+(Xth+X2p)^2)).*(R2p./s2);
Tm((s2==0)) = 0;
```

```
% Plot the torque-speed curves
figure;
plot(Nr,Toriginal,'k-','LineWidth',2.0);
hold on;
plot(Nr2,Tm,'r-','LineWidth',2.0);
hold on;
plot(Nr,load_torque,'b-','LineWidth',2.0);
hold off;
xlabel('Rotor speed (rpm)','Fontweight','Bold');
ylabel('Torque (Nm)','Fontweight','Bold');
title ('Induction Motor Torque-Speed Characteristic','Fontweight','Bold');
grid on;
xlim([0 1500]);
```



Part f-2)

Just after the frequency (and voltage) reduction, the characteristics is shifted to the left as shown in Part 1. The electrical time constant is related to the inductances and resistances of the machine whereas the mechanical time constant is related to the inertia of the system. Also note that, change in the torque is directly related to change in the current and therefore the electrical time constant whereas change in the speed of a mechanical system is directly related to the mechanical time constant. Generally, mechanical time constants are much higher that electrical time constants such that electrical time constant can be neglected. All in all, torque of the machine can be altered suddenly.

In our case, as the characteristics is shifted, the operating point is moved down vertically to a new point which is in the generating region. This new point should be on the new machine torque curve. As time goes on, depending on the system inertia, the machine starts to slow down because, at the new point, net torque is negative. The operating point reaches the new synchronous speed (Tm = 0), but the machine continues to slow down since the net torque is still negative. The machine is now in the motoring region. Up to the point where Tnet = 0 which is denoted as point B, the machine speed decreases following the machine characteristics.

Part f-3)

```
% Let us call this point as C.
% Using the graph:
Nr_C = 1159; % rpm
Tm_C = -3497; % Nm

fprintf('Rotor apeed just after the frequency reduction is %d rpm\n',Nr_C);
fprintf('Torque just after the frequency reduction is %d Nm\n',Tm_C);
```

```
Rotor apeed just after the frequency reduction is 1159 rpm
Torque just after the frequency reduction is -3497 Nm
```

Part f-4)

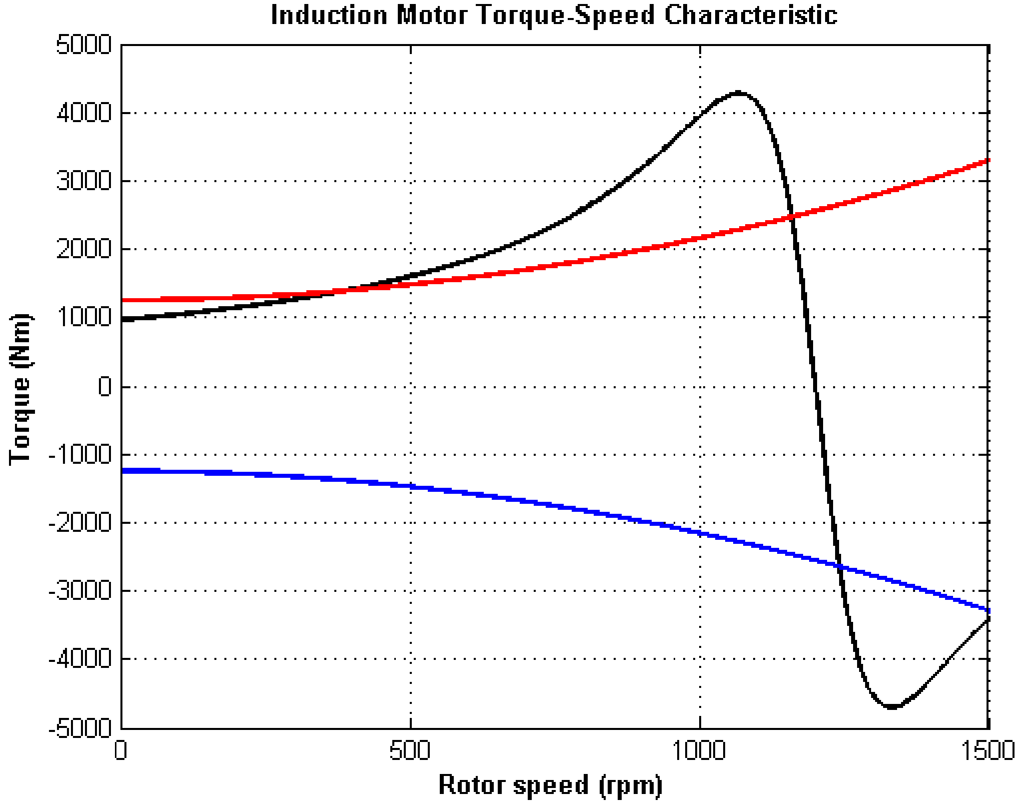
```
% Using the graph:
Nr_B = 1063; % rpm
Tm_B = -2274; % Nm

fprintf('Rotor apeed at final operating point is %d rpm\n',Nr_B);
fprintf('Torque  at final operating point is %d Nm\n',Tm_B);
```

```
Rotor apeed at final operating point is 1063 rpm
Torque  at final operating point is -2274 Nm
```

Part g)

Part g-1)

```
new_load_torque = -load_torque;

% Plot the torque-speed curves
figure;
plot(Nr,Toriginal,'k-','LineWidth',2.0);
hold on;
plot(Nr,load_torque,'r-','LineWidth',2.0);
hold on;
plot(Nr,new_load_torque,'b-','LineWidth',2.0);
hold off;
xlabel('Rotor speed (rpm)','Fontweight','Bold');
ylabel('Torque (Nm)','Fontweight','Bold');
title ('Induction Motor Torque-Speed Characteristic','Fontweight','Bold');
grid on;
xlim([0 1500]);
```



Part g-2)

The load characteristics is changed this time. Just after this, the net torque will be positive (Tm-TL > 0) so that the machine starts to accelerate. This acceleration will occur following the machine torque characteristics. It will reach the synchronous speed (Tm=0), but the acceleration will continue since the net torque is still positive. After that, the machine will operate in the generating region until it reaches the final operating point (pt B) where Tnet=0. the machine will remain at that point and generate power if no other change is applied to the system.

Part g-3)

```
% Using the graph:
Nr_B = 1242; % rpm
Tm_B = -2647; % Nm

fprintf('Rotor apeed at final operating point is %d rpm\n',Nr_B);
fprintf('Torque  at final operating point is %d Nm\n',Tm_B);
```

```
Rotor apeed at final operating point is 1242 rpm
Torque  at final operating point is -2647 Nm
```

Published with MATLAB® R2013a