ELEC 344 - 201: Applied Electronics and Electromechanics

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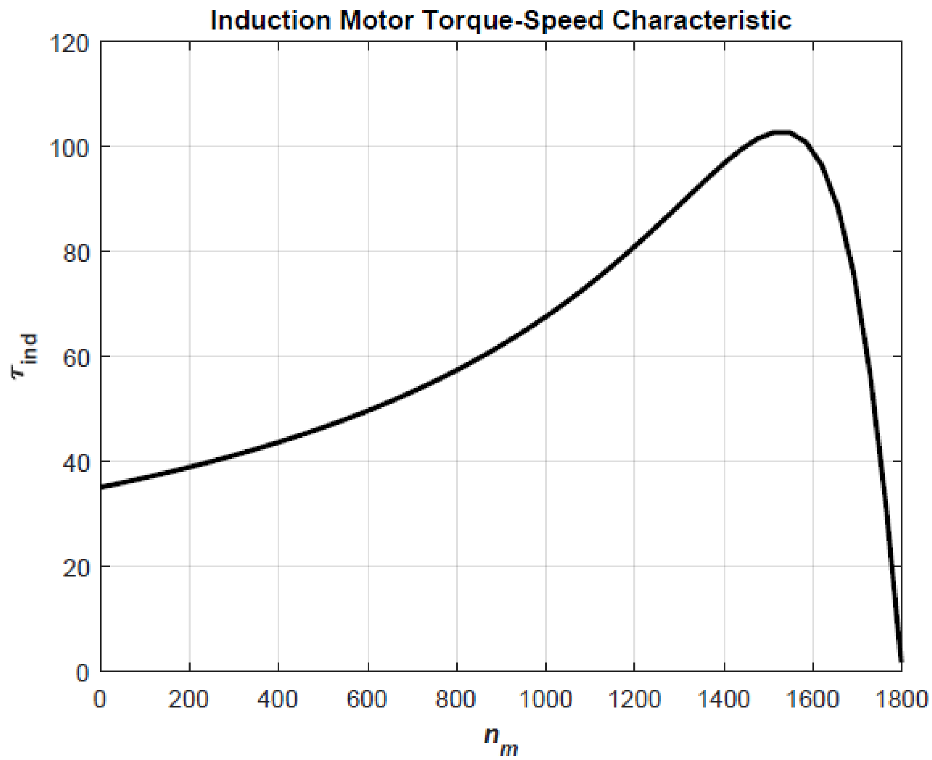
Tutorial 6

1) Mathematical demonstration of Rotating Magnetic Fields.

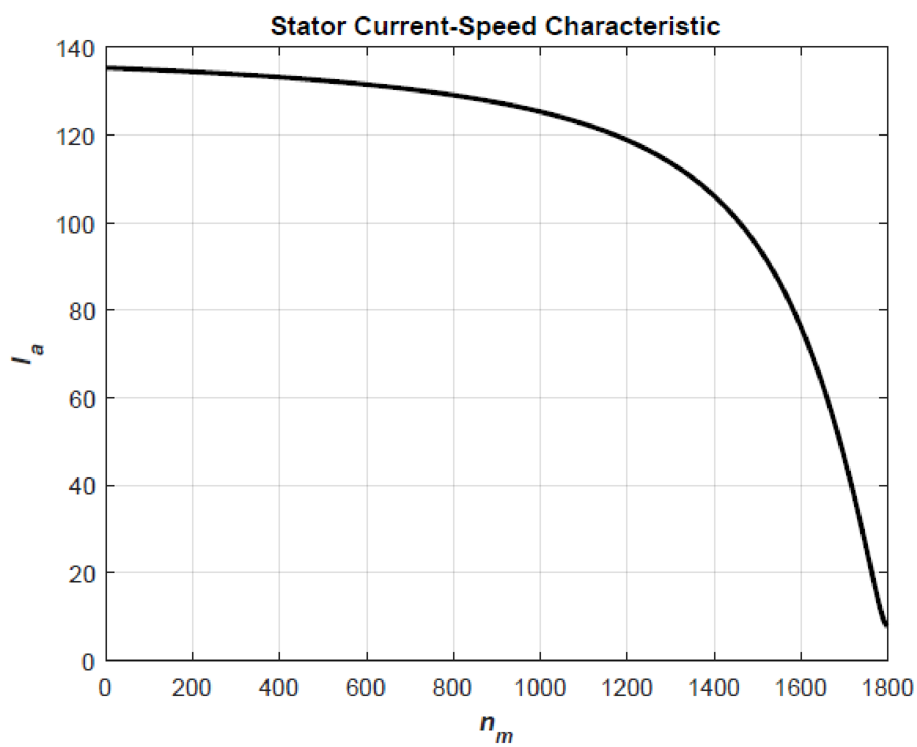
2) A three phase motor with the following parameters:
   - $\mathbf{R_1 = 220m\Omega}$,
   - $\mathbf{X_{l1} = 430m\Omega}$,
   - $\mathbf{R_2 = 127m\Omega}$,
   - $\mathbf{X_{l2} = 430m\Omega}$,
   - $\mathbf{X_m = 15\Omega}$,
   - $\mathbf{P_{mech} = 300W}$,
   - $\mathbf{P_{core} = 200W}$,
   - $\mathbf{P_{misc} = 0}$,
   - $\mathbf{\#Poles = 4}$,

   is connected in Y configuration to a 60Hz source with 120V per phase.
   For a slip of 5%, determine:
   a) The phase current, and copper losses at the armature.
   b) The air-gap power, and the power converted to mechanical
   c) The induced and load torque
   d) The overall motor efficiency
   e) The motor speed in RPM and rad/sec

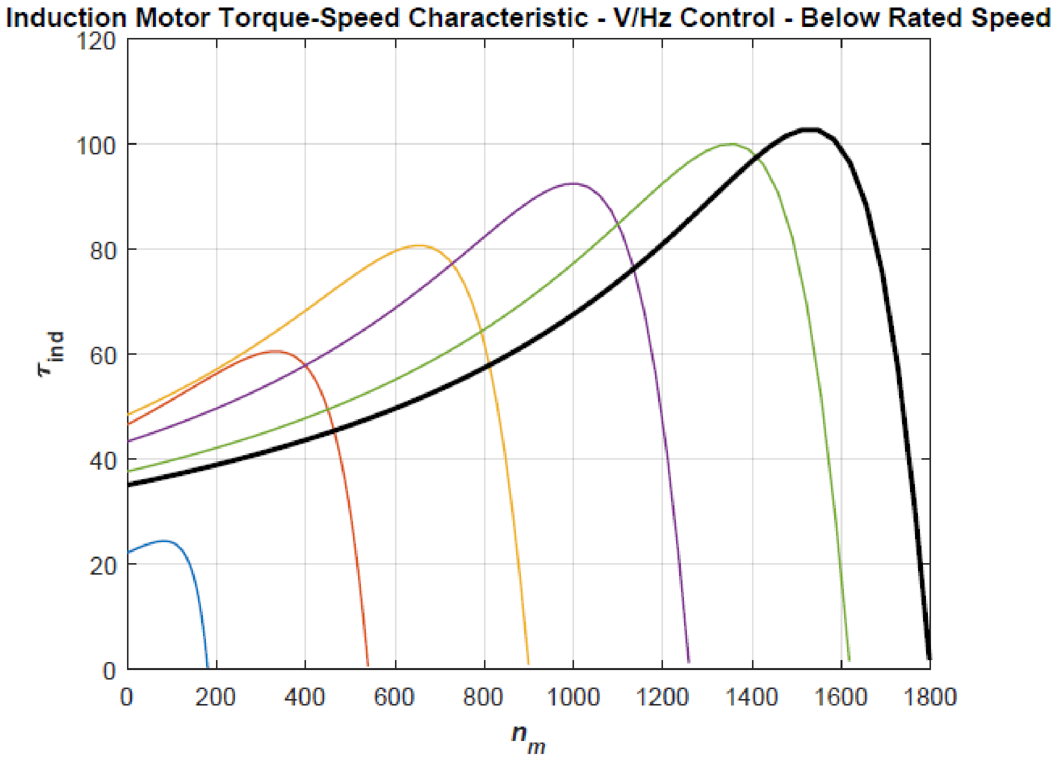
3) Speed-Control of Induction Motors. The torque speed characteristics for different control techniques will be analyzed. The MATLAB code and different plots are added here:

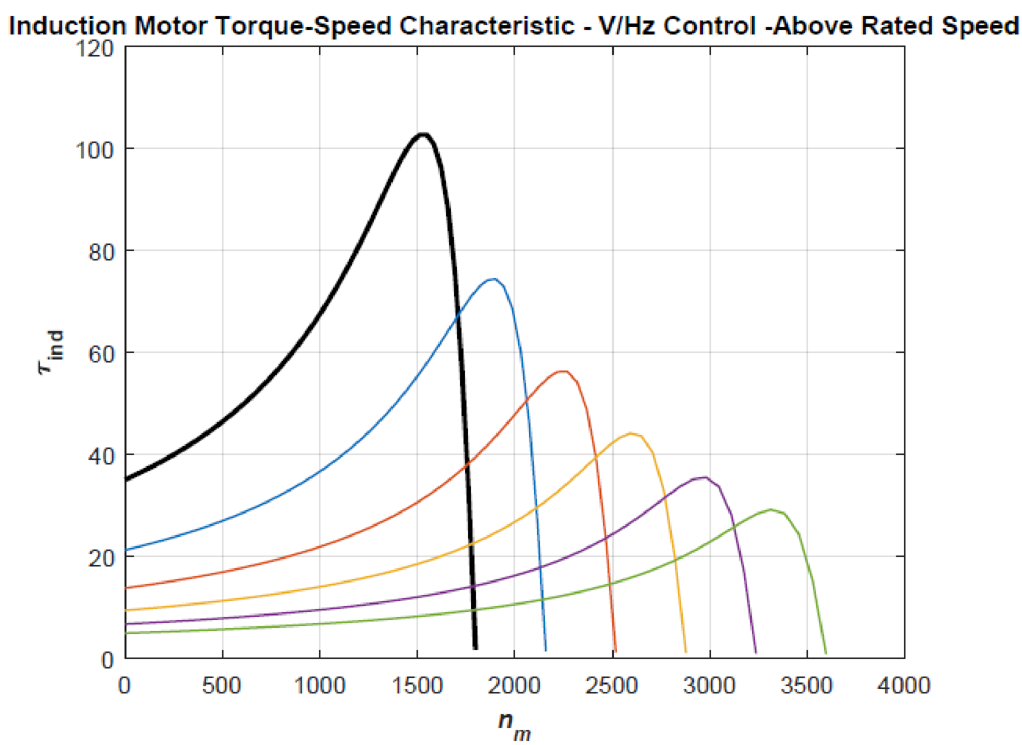


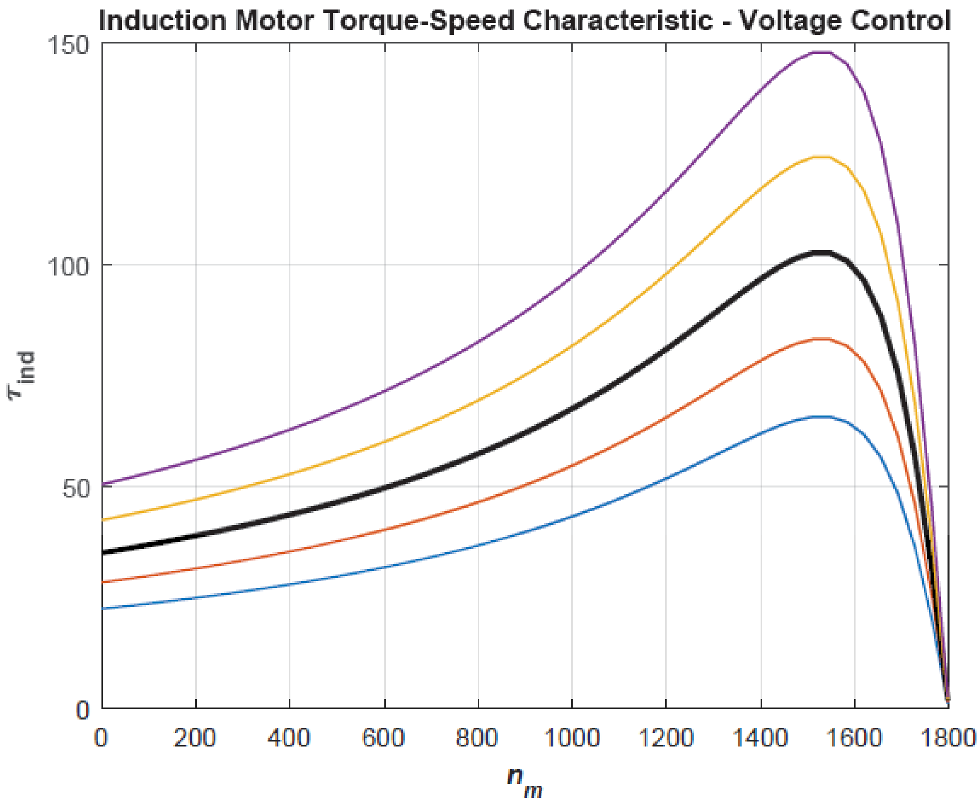
Induction Motor Torque-Speed Characteristic
τ_{ind}
n_m
0
20
40
60
80
100
120
200
400
600
800
1000
1200
1400
1600
1800



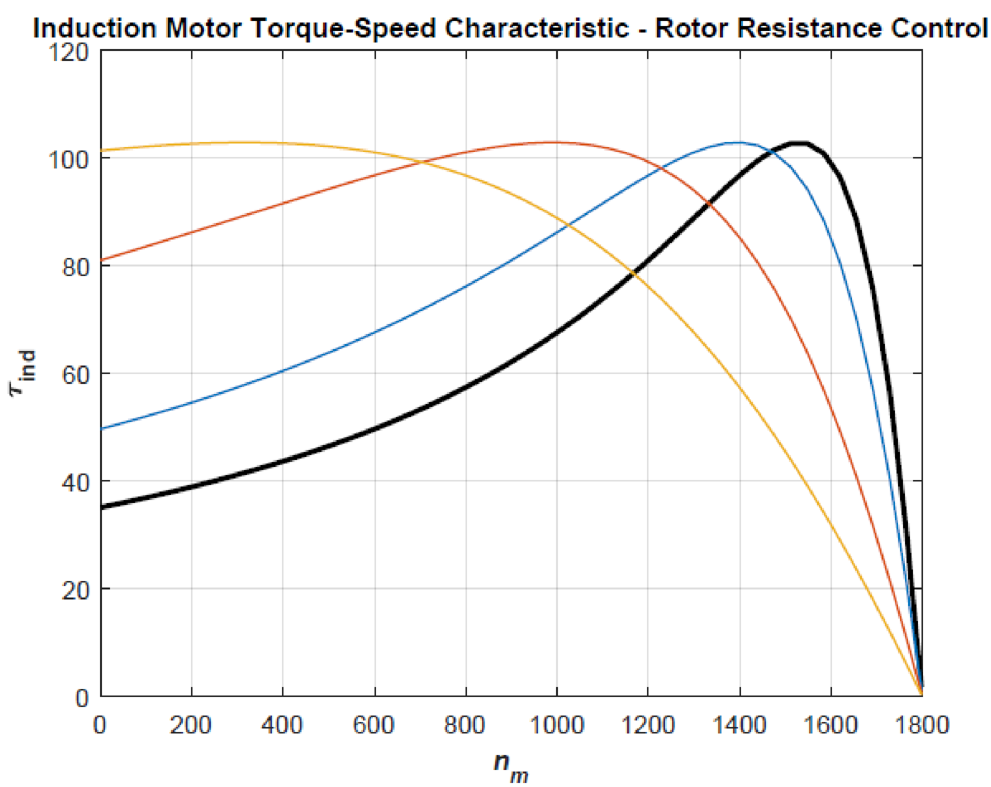
Stator Current-Speed Characteristic
I_a
n_m
0
20
40
60
80
100
120
140
200
400
600
800
1000
1200
1400
1600
1800


Induction Motor Torque-Speed Characteristic - V/Hz Control - Below Rated Speed
τ_{ind}
n_m
0
20
40
60
80
100
120
0
200
400
600
800
1000
1200
1400
1600
1800


Induction Motor Torque-Speed Characteristic - V/Hz Control -Above Rated Speed
τ_{ind}
n_m
0
20
40
60
80
100
120
0
500
1000
1500
2000
2500
3000
3500
4000



Induction Motor Torque-Speed Characteristic - Voltage Control
150
100
50
0
0
200
400
600
800
1000
1200
1400
1600
1800
τ_{ind}
n_m



Induction Motor Torque-Speed Characteristic - Rotor Resistance Control
120
100
80
60
40
20
0
0
200
400
600
800
1000
1200
1400
1600
1800
τ_{ind}
n_m

MATLAB Code

```
%% %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% Tutorial 6 - Induction Motors - Elec 344                   %
% Instructor: Mr. Ignacio Galiano                            %
% TAs:        Mr. Franco Degioanni                           %
%             Mr. Daniel Hsu                                 %
%             Mr. Tomas Syskakis                             %
%                                                            %
% This file creates different characteristics of induction   %
% machines. The torque vs speed charactersitics are analyzed. %
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

close all;
clc;
clear all;

%% Variable inicialization (Tutorial problem)

L1 = 0.0011; % Stator inductance [H]
L2 = 0.0011; % Rotor inductance [H]
Lm = 0.0398; % Magentizing inductance [H]
r1 = 0.220;  % Stator resistance [Ohm]
r2 = 0.127;  % Rotor resistance [Ohm]

poles = 4;   % Number of poles
fe = 60;     % Line frequency [Hz]

v_phase = 208 / sqrt(3); % Phase voltage [Vrms]
n_sync = 120*fe/4;  % Synchronous speed [rpm]
w_sync = n_sync*2*pi/60; % Synchronous speed [rad/s]


x1 = 2*pi*fe*L1; % Stator Reactance [Ohm]
x2 = 2*pi*fe*L2; % Rotor Reactance [Ohm]
xm = 2*pi*fe*Lm; % Magnetizing Reactance [Ohm]




%% Torque - Speed Characteristics [Nominal Values]

% 1 - Calculate the Thevenin voltage and impedance
v_th = v_phase * ( xm / sqrt(r1^2 + (x1 + xm)^2) );
z_th = ((j*xm) * (r1 + j*x1)) / (r1 + j*(x1 + xm));
r_th = real(z_th);
x_th = imag(z_th);

% Now calculate the torque-speed characteristic for many slips between 0
% and 1. Note that the first slip value is set to 0.001 instead of exactly
% 0 to avoid divide-% by-zero problems.
s = (0:1:50) / 50; % Slip
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s(1) = 0.001;
nm = (1 - s) * n_sync; % Mechanical speed

% Calculate torque versus speed
for ii = 1:size(s') % Torque vs Speed equation
t_ind(ii) = (3 * v_th^2 * r2 / s(ii)) / ...
(w_sync * ((r_th + r2/s(ii))^2 + (x_th + x2)^2) );
end
% Plot the torque-speed curve
figure(1);
plot(nm,t_ind,'k-','LineWidth',2.0);

xlabel('\bf\itn_{m}');
ylabel('\bf\tau_{ind}');
title ('\bfInduction Motor Torque-Speed Characteristic');
grid on;
hold on

% Stator Current

s = (0:1:500) / 500; % Slip
s(1) = 0.001;
nm = (1 - s) * n_sync; % Mechanical speed

for ii = 1:size(s') % Stator Current vs Speed
r2p = r2 + r2*((1-s(ii))/s(ii));
Z2 = r2p + j*x2;
Zeq = 1/((1/(j*xm))+(1/(Z2)));
req = real(Zeq);
xeq = imag(Zeq);
iL = v_phase/(r1+req+j*(x1+xeq));
ia(ii) = abs(iL);
end
% Plot the torque-speed curve
figure(7);
plot(nm,ia,'k-','LineWidth',2.0);
xlabel('\bf\itn_{m}');
ylabel('\bf\I_{a}');
title ('\bfStator Current-Speed Characteristic');
grid on;
hold on

%% Speed Control: We are gonna see the different methods to control the speed

%% 1 - Frequency Control
% a) Below rated speed. The frequency of the stator is changed. At the same
% time the stator voltage must be reduced to avoid saturation of the
% magnetic core. It is call Volt/Hz control. Here, it is assumed that the
% voltage is decreased linearly with the frequency.


freq_variation = [0.1 : 0.2 : 1];     % Percentage of frequency variation
volt_variation = freq_variation;      % It is assumed the same (could be
different)
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```matlab
for(i=1 : 1 : size(freq_variation')) % for each new frequency, there is a new
characteristic

new_freq = fe * freq_variation(i);          % New electric frequency
new_voltage = v_phase * volt_variation(i);  % New phase voltage

n_sync = 120*new_freq/4;    % New synchronous speed [rpm]
w_sync = n_sync*2*pi/60;    % New synchronous speed [rad/s]

% If frequency changes, also the reactances
x1 = 2*pi*new_freq*L1;  % New stator reactance
x2 = 2*pi*new_freq*L2;  % New rotor reactance
xm = 2*pi*new_freq*Lm;

% The Thevenin equivalent is evaluated now
v_th = new_voltage * ( xm / sqrt(r1^2 + (x1 + xm)^2) );
z_th = ((j*xm) * (r1 + j*x1)) / (r1 + j*(x1 + xm));
r_th = real(z_th);
x_th = imag(z_th);

% Different slip points
s = (0:1:50) / 50; % Slip
s(1) = 0.001;
nm = (1 - s) * n_sync; % Mechanical speed
% Calculate torque versus speed
for ii = 1:51
t_ind(ii) = (3 * v_th^2 * r2 / s(ii)) / ...
(w_sync * ((r_th + r2/s(ii))^2 + (x_th + x2)^2) );
end
% Plot the torque-speed curve
figure(2);
if(freq_variation(i) == 1)
plot(nm,t_ind,'k-','LineWidth',2.0); % Nominal Speed
else
plot(nm,t_ind,'LineWidth',1.0);
end

xlabel('\bf\itn_{m}');
ylabel('\bf\tau_{ind}');
title ('\bfInduction Motor Torque-Speed Characteristic - V/Hz Control - Below
Rated Speed');
grid on;
hold on
end

% b) Above rated speed. The frequency of the stator is increased. In this
% case, the voltage is kept constant. The saturation of the core is not a
% problem. The voltage cannot be increased higher than the rated value.


freq_variation = [1 : 0.2 : 2];     % Percentage of frequency variation


for(i=1 : 1 : size(freq_variation')) % for each new frequency, there is a new
characteristic
```

```
new_freq = fe * freq_variation(i);          % New electric frequency

n_sync = 120*new_freq/4;   % New synchronous speed [rpm]
w_sync = n_sync*2*pi/60;   % New synchronous speed [rad/s]

% If frequency changes, also the reactances
x1 = 2*pi*new_freq*L1;  % New stator reactance
x2 = 2*pi*new_freq*L2;  % New rotor reactance
xm = 2*pi*new_freq*Lm;

% The Thevenin equivalent is evaluated now
v_th = v_phase * ( xm / sqrt(r1^2 + (x1 + xm)^2) );
z_th = ((j*xm) * (r1 + j*x1)) / (r1 + j*(x1 + xm));
r_th = real(z_th);
x_th = imag(z_th);

% Different slip points
s = (0:1:50) / 50; % Slip
s(1) = 0.001;
nm = (1 - s) * n_sync; % Mechanical speed
% Calculate torque versus speed
for ii = 1:51
t_ind(ii) = (3 * v_th^2 * r2 / s(ii)) / ...
(w_sync * ((r_th + r2/s(ii))^2 + (x_th + x2)^2) );
end
% Plot the torque-speed curve
figure(3);
if(freq_variation(i) == 1)
plot(nm,t_ind,'k-','LineWidth',2.0); % Nominal Speed
else
plot(nm,t_ind,'LineWidth',1.0);
end

xlabel('\bf\itn_{m}');
ylabel('\bf\tau_{ind}');
title ('\bfInduction Motor Torque-Speed Characteristic - V/Hz Control -Above
Rated Speed');
grid on;
hold on
end



%% 2 - Voltage Control
% The voltage of the stator can be controlled to changed the torque-speed
% characteristics. The variations are usually small.

volt_variation = [0.8 : 0.1 : 1.2];     % Voltage variation

for(i=1 : 1 : size(volt_variation')) % for each new voltage, there is a new
characteristic


new_voltage = v_phase * volt_variation(i);  % New phase voltage
```

```
n_sync = 120*fe/4;    % New synchronous speed [rpm]
w_sync = n_sync*2*pi/60;    % New synchronous speed [rad/s]

% If frequency changes, also the reactances
x1 = 2*pi*fe*L1;  % New stator reactance
x2 = 2*pi*fe*L2;  % New rotor reactance
xm = 2*pi*fe*Lm;

% The Thevenin equivalent is evaluated now
v_th = new_voltage * ( xm / sqrt(r1^2 + (x1 + xm)^2) );
z_th = ((j*xm) * (r1 + j*x1)) / (r1 + j*(x1 + xm));
r_th = real(z_th);
x_th = imag(z_th);

% Different slip points
s = (0:1:50) / 50; % Slip
s(1) = 0.001;
nm = (1 - s) * n_sync; % Mechanical speed
% Calculate torque versus speed
for ii = 1:51
t_ind(ii) = (3 * v_th^2 * r2 / s(ii)) / ...
(w_sync * ((r_th + r2/s(ii))^2 + (x_th + x2)^2) );
end
% Plot the torque-speed curve
figure(4);
if(volt_variation(i) == 1)
plot(nm,t_ind,'k-','LineWidth',2.0); % Nominal Speed
else
plot(nm,t_ind,'LineWidth',1.0);
end

xlabel('\bf\itn_{m}');
ylabel('\bf\tau_{ind}');
title ('\bfInduction Motor Torque-Speed Characteristic - Voltage Control');
grid on;
hold on
end

%% 3 - Rotor Resistance Control
% The resistance of the rotor is changed. It is usually done during start-up
% for increase the initial torque of the machine. In steady state operation
% The resistance must be minimized to improve the efficiency

r2_variation = [1, 1.5, 3, 5.5];      % Voltage variation

for(i=1 : 1 : size(r2_variation')) % for each resistance, there is a new
characteristic


new_r2 = r2 * r2_variation(i);  % New rotor resistance

n_sync = 120*fe/4;    % New synchronous speed [rpm]
w_sync = n_sync*2*pi/60;    % New synchronous speed [rad/s]
```

```
% If frequency changes, also the reactances
x1 = 2*pi*fe*L1;  % New stator reactance
x2 = 2*pi*fe*L2;  % New rotor reactance
xm = 2*pi*fe*Lm;  % New magnetizing reactance

% The Thevenin equivalent is evaluated now
v_th = v_phase * ( xm / sqrt(r1^2 + (x1 + xm)^2) );
z_th = ((j*xm) * (r1 + j*x1)) / (r1 + j*(x1 + xm));
r_th = real(z_th);
x_th = imag(z_th);

% Different slip points
s = (0:1:50) / 50; % Slip
s(1) = 0.001;
nm = (1 - s) * n_sync; % Mechanical speed
% Calculate torque versus speed
for ii = 1:51
t_ind(ii) = (3 * v_th^2 * new_r2 / s(ii)) / ...
(w_sync * ((r_th + new_r2/s(ii))^2 + (x_th + x2)^2) );
end
% Plot the torque-speed curve
figure(5);
if(r2_variation(i) == 1)
plot(nm,t_ind,'k-','LineWidth',2.0); % Nominal Speed
else
plot(nm,t_ind,'LineWidth',1.0);
end

xlabel('\bf\itn_{m}');
ylabel('\bf\tau_{ind}');
title ('\bfInduction Motor Torque-Speed Characteristic - Rotor Resistance
Control');
grid on;
hold on
end
```