ELG3311: Assignment #4

Problem 9-13:

A 7.5-hp, 120-V series dc motor has an armature resistance of 0.2 Ω and a series field resistance of 0.16 Ω. At full load, the current input is 58 A, and the rated speed is 1050 r/min. Its magnetization curve is shown in Figure P9-5. The core losses are 200 W, and the mechanical losses are 240 W at full load. Assume that the mechanical losses vary as the cube of the speed of the motor and that the core losses are constant.

(a) What is the efficiency of the motor at full load?

(b) What are the speed and efficiency of the motor if it is operating at an armature current of 35 A?

(c) Plot the torque-speed characteristic for this motor.

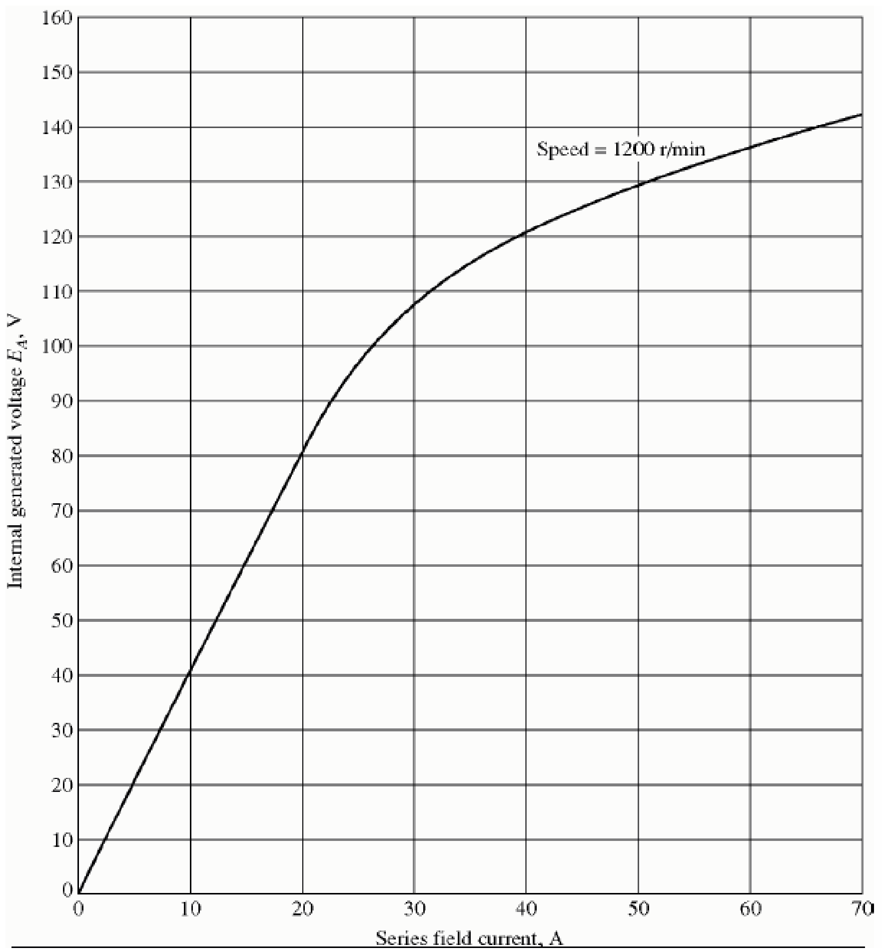


Figure P9-5

The magnetization curve for the series motor in Problem 9-13. This curve was taken at a constant speed of 1200 r/min.

Solution:

(a) The output power of this motor at full load is

$$P_{out} = (7.5hp)*(746W/hp) = 5595W$$

The input power is

$$P_{in} = V_T I_L = (120)(58) = 6960W$$

Therefore the efficiency is

$$\eta = \frac{P_{out}}{P_{in}} \times 100\% = \frac{5595}{6960} \times 100\% = 80.4\%$$

(b) If the armature current is 35 A, then the input power to the motor will be

$$P_{in} = V_T I_{L2} = (120)(35) = 4200W$$

The internal generated voltage at this condition is

$$E_{A2} = V_T - I_{A2}(R_A + R_S) = 120 - (35)(0.20 + 0.16) = 107.4V$$

And the internal generated voltage at rated conditions is

$$E_{A1} = V_T - I_{A1}(R_A + R_S) = 120 - (58)(0.20 + 0.16) = 99.1V$$

From Figure P9-5, the internal generated voltage $E_{Ao,2}$ for a current of 35A and a speed of n_o = 1200 r/min is $E_{Ao,2}$ = 115 V, and the internal generated voltage $E_{Ao,1}$ for a current of 58A and a speed of n_o = 1200 r/min is $E_{Ao,1}$ = 134V. So, the final speed is

$$n_2 = \frac{E_{A2}}{E_{A1}} \frac{E_{Ao,1}}{E_{Ao,2}} n_1 = \frac{107.4}{99.1} \frac{134}{115} (1050) = 1326 r/\min$$

The power converted from electrical to mechanical form is

$$P_{conv} = E_{A2} I_{A2} = (107.4)(35) = 3759W$$

The core losses in the motor are 200W, and the mechanical losses in the motor are 240W at a speed of 1050 r/min. The mechanical losses in the motor scale proportionally to the cube of the rotational speed. So the mechanical losses at 1326 r/min are

$$P_{mech2} = \left(\frac{n_2}{n_1}\right)^3 P_{mech1} = \left(\frac{1326}{1050}\right)^3 (240) = 483W$$

Therefore, the output power is

$$P_{out} = P_{conv} - P_{mech} - P_{core} = 3759 - 483 - 200 = 3076W$$

And the efficiency is

$$\eta = \frac{P_{out}}{P_{in}} \times 100\% = \frac{3076}{4200} \times 100\% = 73.2\%$$

(c) A MATLAB program to plot the torque-speed characteristic of this motor is shown below:

```
% M-file: prob9_13.m
% M-file to create a plot of the torque-speed curve of the
% the series dc motor in Problem 9-13.

% Get the magnetization curve. Note that this curve is
% defined for a speed of 1200 r/min.
load p95_mag.dat
if_values = p95_mag(:,1);
ea_values = p95_mag(:,2);
n_0 = 1200;

% First, initialize the values needed in this program.
v_t = 120; % Terminal voltage (V)
r_a = 0.36; % Armature + field resistance (ohms)
i_a = 9:1:58; % Armature (line) currents (A)

% Calculate the internal generate voltage e_a.
e_a = v_t - i_a * r_a;

% Calculate the resulting internal generated voltage at
% 1200 r/min by interpolating the motor's magnetization
% curve. Note that the field current is the same as the
% armature current for this motor.
e_a0 = interp1(if_values,ea_values,i_a,'spline');

% Calculate the motor's speed, using the known fact that
% the motor runs at 1050 r/min at a current of 58 A. We
% know that
%
% Ea2 K' phi2 n2 Eao2 n2
% ----- = ----------- = ----------
% Ea1 K' phi1 n1 Eao1 n1
%
% Ea2 Eao1
% ==> n2 = ----- ------ n1
% Ea1 Eao2
%
% where Ea0 is the internal generated voltage at 1200 r/min
% for a given field current.
```

```
%
% Speed will be calculated by reference to full load speed
% and current.
n1 = 1050; % 1050 r/min at full load
Eao1 = interp1(if_values,ea_values,58,'spline');
Ea1 = v_t - 58 * r_a;

% Get speed
Eao2 = interp1(if_values,ea_values,i_a,'spline');
n = (e_a./Ea1) .* (Eao1 ./ Eao2) * n1;

% Calculate the induced torque corresponding to each
% speed from Equations (8-55) and (8-56).
t_ind = e_a .* i_a ./ (n * 2 * pi / 60);

% Plot the torque-speed curve
figure(1);
plot(t_ind,n,'b-','LineWidth',2.0);
hold on;
xlabel('\bf\tau_{ind} (N-m)');
ylabel('\bf\itn_{m} \rm\bf(r/min)');
title ('\bfSeries DC Motor Torque-Speed Characteristic');
grid on;
hold off;
```

Problem 9-15:

A 300-hp 440-V 560-A, 863 r/min shunt dc motor has been tested, and the following data were taken:

Blocked-rotor test:

$V_A = 16.3$ V exclusive of brushes $V_F = 440$ V

$I_A = 500$ A $I_F = 8.86$ A

No-load operation:

$V_A = 16.3$ V including brushes $V_F = 440$ V

$I_A = 23.1$ A n = 863 r/min

What is this motor's efficiency at the rated conditions? [Note: Assume that (1) the brush voltage drop is 2 V, (2) the core loss is to be determined at an armature voltage equal to the armature voltage under full load, and (3) stray load losses are 1 percent of full load.]

Solution:

The armature resistance of this motor is

$$R_A = \frac{V_{A,br}}{I_{A,br}} = \frac{16.3}{500} = 0.0326\Omega$$

Under no-load conditions, the core and mechanical losses taken together (that is, the rotational losses) of this motor are equal to the product of the internal generated voltage E_A and the armature current I_A, since this is no output power from the motor at no-load conditions. Therefore, the rotational losses at rated speed can be found as

$$E_A = V_A - V_{brush} - I_A R_A = 442 - 2 - (23.1)(0.0326) = 439.2V$$
$$P_{rot} = P_{conv} = E_A I_A = (439.2)(23.1) = 10.15kW$$

The input power to the motor at full load is

$$P_{in} = V_T I_L = (440)(560) = 246.4kW$$

The output power from the motor at full load is

$$P_{out} = P_{in} - P_{cu} - P_{rot} - P_{brush} - P_{stray}$$

The copper losses are

$$P_{cu} = I_A{}^2 R_A + V_F I_F = (560)^2(0.0326) + (440)(8.86) = 14.1kW$$

The brush losses are

$$P_{brush} = V_{brush} I_A = (2)(560) = 1120W$$

The stray load losses are

$$P_{stray} = 1\% P_{in} = (0.01)(246.4k) = 2.46kW$$

Therefore,

$$P_{out} = P_{in} - P_{cu} - P_{rot} - P_{brush} - P_{stray} = 246.4k - 14.1k - 10.15k - 1.12k - 2.46k = 218.6kW$$

The motor's efficiency at full load is

$$\eta = \frac{P_{out}}{P_{in}} \times 100\% = \frac{218.6k}{246.4k} \times 100\% = 88.7\%$$

Problem 9-22:

The magnetization curve for a separate excited dc generator is shown in Figure P9-7. The generator is rated at 6 kW, 120 V, 50 A, and 1800 r/min and is shown in Figure P9-8. Its field current is rated at 5 A. The following data are known about the machine:

$R_A = 0.18\Omega$

$R_{adj} = 0 to 30\Omega$

$N_F = 1000 turns/pole$

$V_F = 120V$

$R_F = 24\Omega$

Answer the following questions about this generator, assuming no armature reaction.

(a) If this generator is operating at no load, what is the range of voltage adjustments that can be achieved by changing R_{adj}?

(b) If the field rheostat is allowed to vary from 0 to 30 Ω and the generator's speed is allowed to vary from 1500 to 2000 r/min, what are the maximum and minimum no-load voltages in the generator?

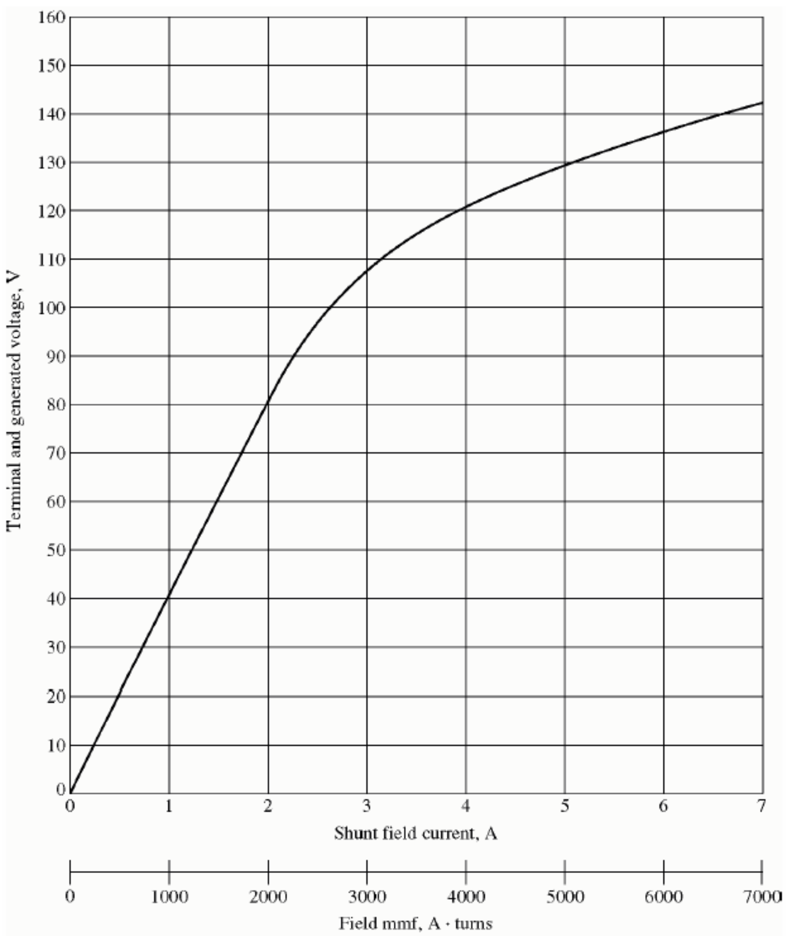


Figure P9-7

The magnetization curve for Problem 9-22. This curve was taken at a speed of 1800r/min.

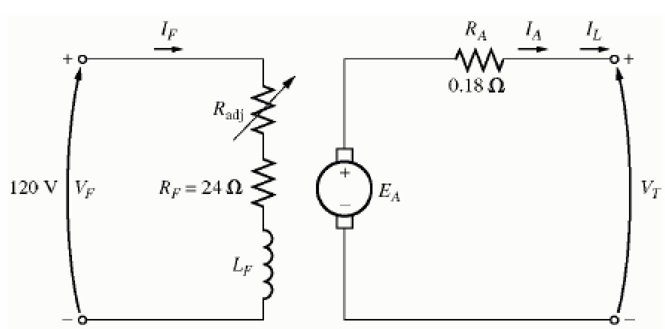


Figure P9-8

The separately excited dc generator in Problem 9-22.

Solution:

(a) If the generator is operating with no load at 1800 r/min, then the terminal voltage will equal the internal generated voltage E_A. The maximum possible field current occurs when R_{adj} = 0 Ω. The current is

$$I_{F,\max} = \frac{V_F}{R_F + R_{adj}} = \frac{120}{24+0} = 5A$$

From the magnetization curve, the voltage E_{Ao} at 1800 r/min is 129 V. Since the actual speed is 1800 r/min, the maximum no-load voltage is 129 V.

The minimum possible field current occurs when R_{adj} = 30 Ω. The current is

$$I_{F,\min} = \frac{V_F}{R_F + R_{adj}} = \frac{120}{24+30} = 2.22A$$

From the magnetization curve, the voltage E_{Ao} at 1800 r/min is 87.4 V. Since the actual speed is 1800 r/min, the minimum no-load voltage is 87 V.

(b) The maximum voltage will occur at the highest current and speed, and the minimum voltage will occur at the lowest current and speed. The maximum possible field current occurs when R_{adj} = 0 Ω. The current is

$$I_{F,\max} = \frac{V_F}{R_F + R_{adj}} = \frac{120}{24+0} = 5A$$

From the magnetization curve, the voltage E_{Ao} at 1800 r/min is 129 V. Since the actual speed is 2000 r/min, the maximum no-load voltage is

$$E_A = \frac{n}{n_o} E_{Ao} = \frac{2000}{1800}(129) = 143V$$

The minimum possible field current occurs when R_{adj} = 30 Ω. The current is

$$I_{F,\min} = \frac{V_F}{R_F + R_{adj}} = \frac{120}{24+30} = 2.22A$$

From the magnetization curve, the voltage E_{Ao} at 1800 r/min is 87.4 V. Since the actual speed is 1500 r/min, the minimum no-load voltage is

$$E_A = \frac{n}{n_o} E_{Ao} = \frac{1500}{1800}(87.4) = 72.8V$$

Problem 9-25:

The machine in Problem 9-22 is reconnected as a shunt generator and is shown in Figure P9-9. The shunt field resistor R_{adj} is adjusted to 10 Ω, and the generator's speed is 1800 r/min.

(a) What is the no-load terminal voltage of the generator?

(b) Assuming no armature reaction, what is the terminal voltage of the generator with an armature current of 20 A? 40 A?

(c) Assuming an armature reaction equal to 200 A·turns at full load, what is the terminal voltage of the generator with an armature current of 20 A? 40 A?

(d) Calculate and plot the terminal characteristics of this generator with and without armature reaction.

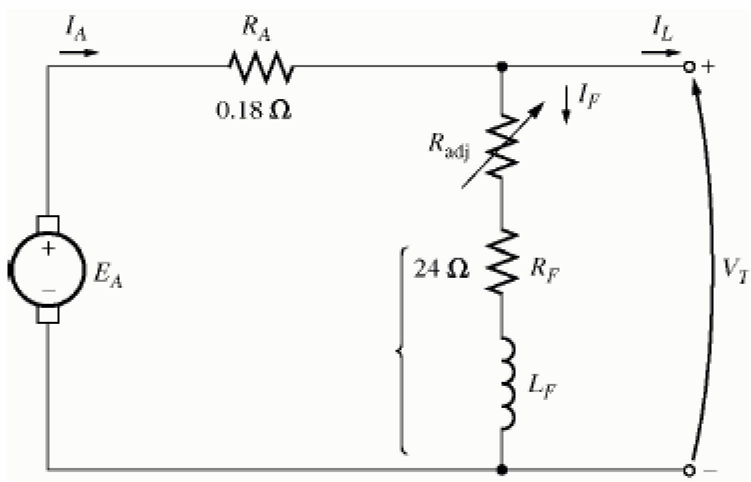
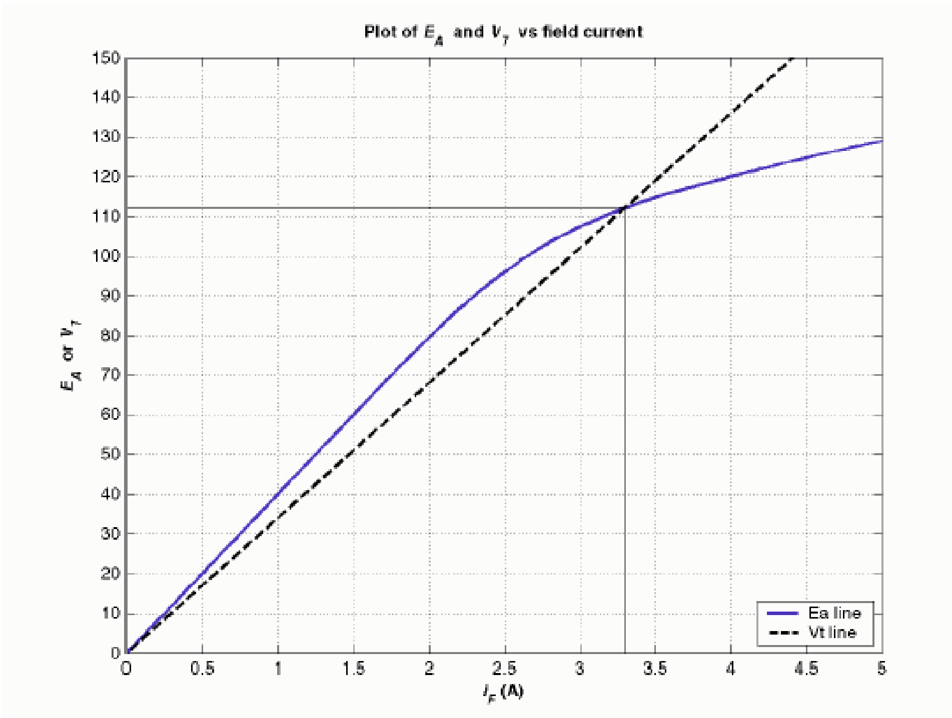


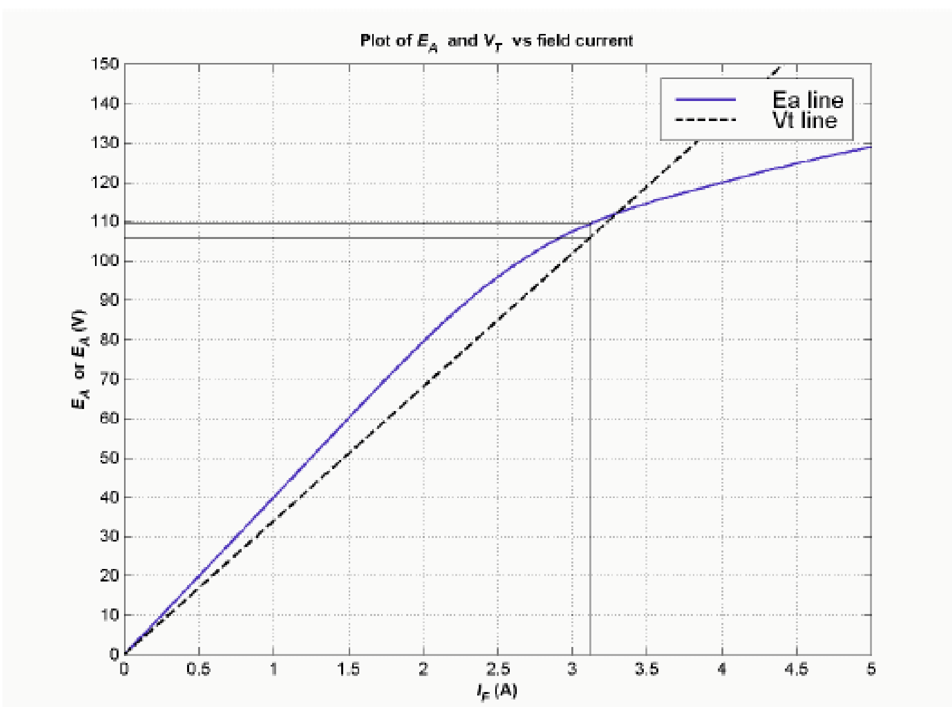
Figure P9-9
The shunt dc generator in Problem 9-25 and 9-26.

Solution:

(a) The total field resistance of this generator is 34 Ω, and the no-load terminal voltage can be found from the intersection of the resistance line with the magnetization curve for this generator. The magnetization curve and the field resistance line are plotted below. As you can see, they intersect at a terminal voltage of 112 V.



(b) At an armature current of 20 A, the internal voltage drop in the armature resistance is (20A)(0.18Ω) = 3.6 V. As shown in the figure below, there is a difference of 3.6 V between E_A and V_T at a terminal voltage of about 106 V.

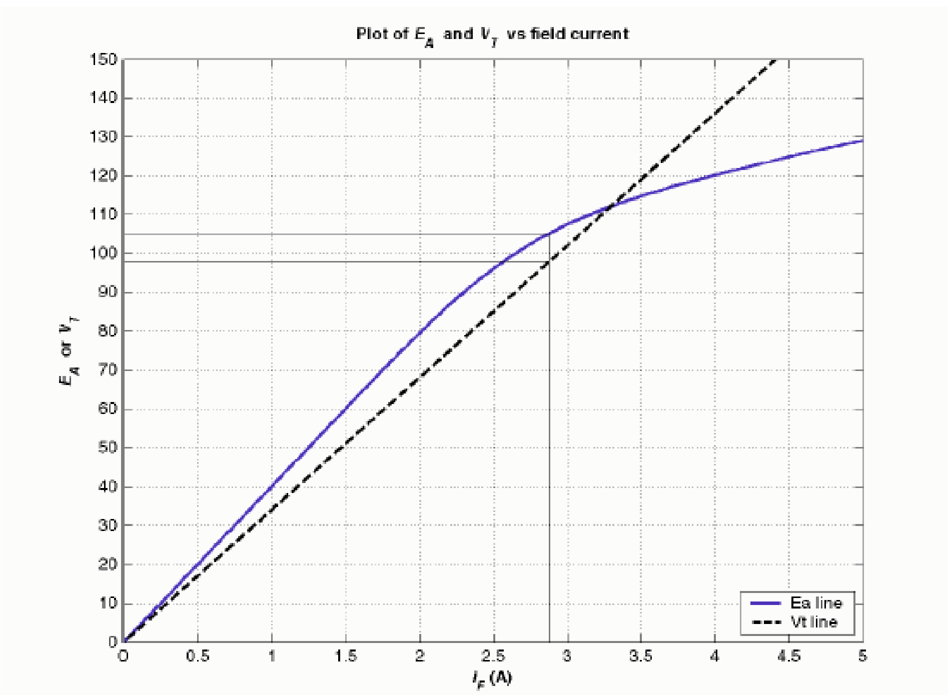


A MATLAB program to locate the position where the triangle exactly fits between the E_A and V_T lines is shown below. This program created the plot shown above. Note that there are actually two places where the difference between the E_A and V_T lines is 3.6 volts, but the low-voltage one of them is unstable. The code shown in bold face below prevents the program from reporting that first (unstable) point.

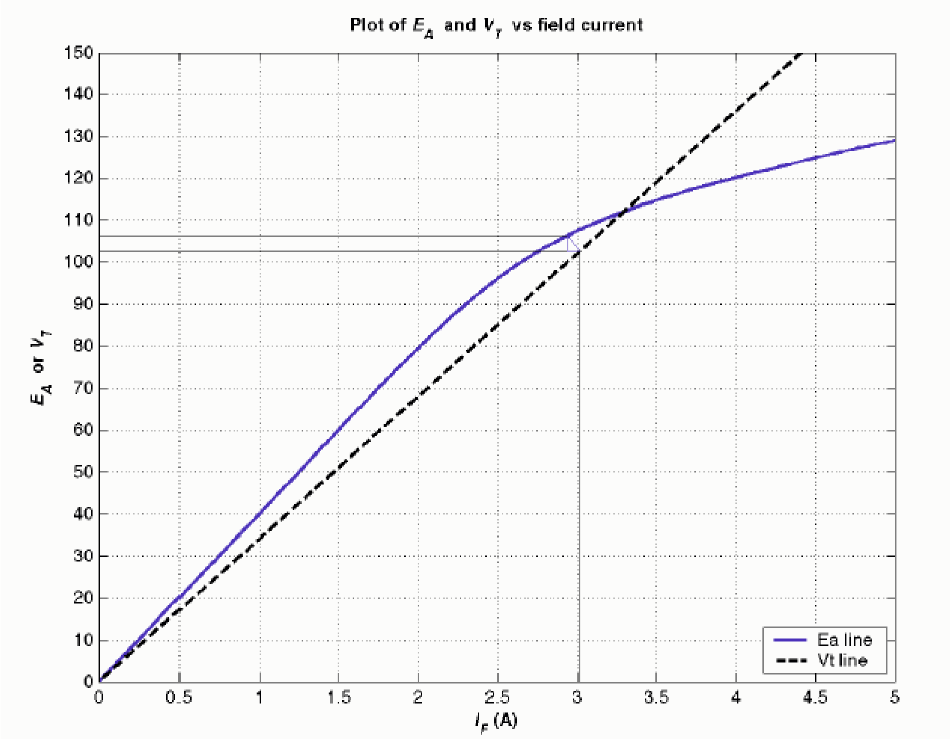
```
% M-file: prob9_25b.m
% M-file to create a plot of the magnetization curve and the
% field current curve of a shunt dc generator, determining
% the point where the difference between them is 3.6 V.

% Get the magnetization curve. This file contains the
% three variables if_values, ea_values, and n_0.
clear all
load p97_mag.dat;
if_values = p97_mag(:,1);
ea_values = p97_mag(:,2);
n_0 = 1800;

% First, initialize the values needed in this program.
r_f = 24; % Field resistance (ohms)
r_adj = 10; % Adjustable resistance (ohms)
r_a = 0.19; % Armature + series resistance (ohms)
i_f = 0:0.02:6; % Field current (A)
n = 1800; % Generator speed (r/min)

% Calculate Ea versus If
Ea = interp1(if_values,ea_values,i_f);

% Calculate Vt versus If
Vt = (r_f + r_adj) * i_f;

% Find the point where the difference between the two
% lines is 3.6 V. This will be the point where the line
% line "Ea - Vt - 3.6" goes negative. That will be a
% close enough estimate of Vt.
diff = Ea - Vt - 3.6;

% This code prevents us from reporting the first (unstable)
% location satisfying the criterion.
      was_pos = 0;
      for ii = 1:length(i_f);
      if diff(ii) > 0
            was_pos = 1;
      end
      if ( diff(ii) < 0 & was_pos == 1 )
            break;
      end;
end;

% We have the intersection. Tell user.
disp (['Ea = ' num2str(Ea(ii)) ' V']);
disp (['Vt = ' num2str(Vt(ii)) ' V']);
disp (['If = ' num2str(i_f(ii)) ' A']);

% Plot the curves
figure(1);
```

```
plot(i_f,Ea,'b-','LineWidth',2.0);
hold on;
plot(i_f,Vt,'k--','LineWidth',2.0);

% Plot intersections
plot([i_f(ii) i_f(ii)], [0 Ea(ii)], 'k-');
plot([0 i_f(ii)], [Vt(ii) Vt(ii)],'k-');
plot([0 i_f(ii)], [Ea(ii) Ea(ii)],'k-');
xlabel('\bf\itI_{F} \rm\bf(A)');
ylabel('\bf\itE_{A} \rm\bf or \itV_{T}');
title ('\bfPlot of \itE_{A} \rm\bf and \itV_{T} \rm\bf vs field
current');
axis ([0 5 0 150]);
set(gca,'YTick',[0 10 20 30 40 50 60 70 80 90 100 110 120 130 140
150]')
set(gca,'XTick',[0 0.5 1.0 1.5 2.0 2.5 3.0 3.5 4.0 4.5 5.0]')
legend ('Ea line','Vt line',4);
hold off;
grid on;
```

At an armature current of 40 A, the internal voltage drop in the armature resistance is (40A)(0.18Ω) = 7.2 V. As shown in the figure below, there is a difference of 7.2 V between E_A and V_T at a terminal voltage of about 98 V.



(c) The rated current of this generated is 50 A, so 20 A is 40% of full load. If the full load armature reaction is 200 A·turns, and if the armature reaction is assumed to change linearly with armature current, then the armature reaction will be 80 A·turns. The figure below shows that a triangle consisting of 3.6 V and (80 A·turns)/(1000 turns) = 0.08 A fits exactly between the E_A and V_T lines at a terminal voltage of 103 V.



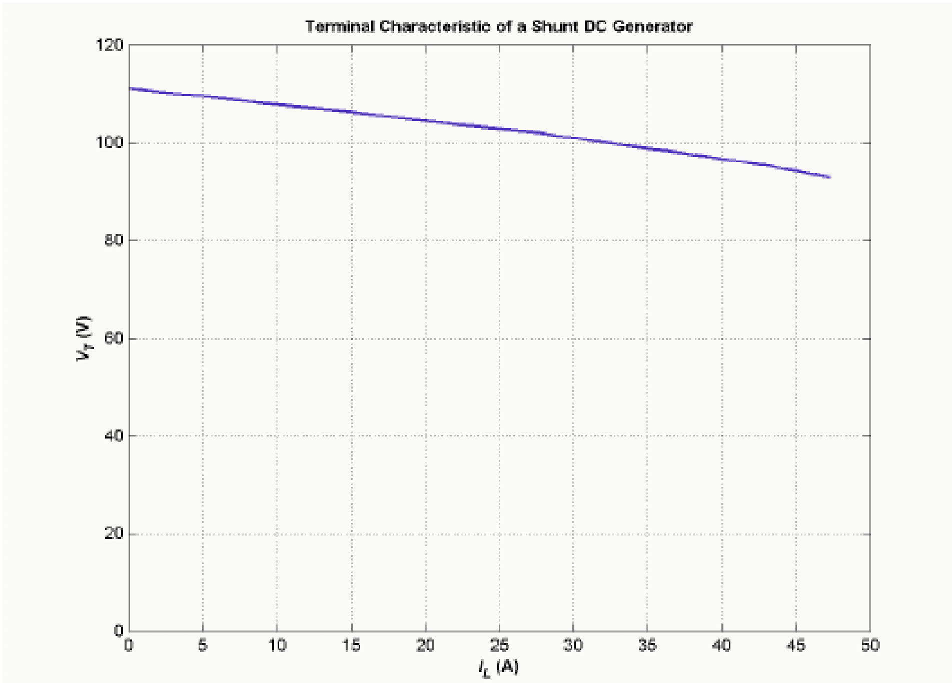
The rated current of this generated is 50 A, so 40 A is 80% of full load. If the full load armature reaction is 200 A·turns, and if the armature reaction is assumed to change linearly with armature current, then the armature reaction will be 160 A·turns. *There is no point* where a triangle consisting of 3.6 V and (80 A·turns)/(1000 turns) = 0.16 A fits exactly between the E_A and V_T lines, so this is not a stable operating condition.

(d) A MATLAB program to calculate the terminal characteristic of this generator without armature reaction is shown below:

```
% M-file: prob9_25d.m
% M-file to calculate the terminal characteristic of a shunt
% dc generator without armature reaction.

% Get the magnetization curve. This file contains the
% three variables if_values, ea_values, and n_0.
load p97_mag.dat;
if_values = p97_mag(:,1);
ea_values = p97_mag(:,2);
n_0 = 1800;

% First, initialize the values needed in this program.
r_f = 24; % Field resistance (ohms)
r_adj = 10; % Adjustable resistance (ohms)
r_a = 0.18; % Armature + series resistance (ohms)
i_f = 0:0.005:6; % Field current (A)
n = 1800; % Generator speed (r/min)

% Calculate Ea versus If
Ea = interp1(if_values,ea_values,i_f);

% Calculate Vt versus If
```

```
Vt = (r_f + r_adj) * i_f;

% Find the point where the difference between the two
% lines is exactly equal to i_a*r_a. This will be the
% point where the line line "Ea - Vt - i_a*r_a" goes
% negative.
i_a = 0:1:50;
for jj = 1:length(i_a)

      % Get the voltage difference
      diff = Ea - Vt - i_a(jj)*r_a;

      % This code prevents us from reporting the first (unstable)
      % location satisfying the criterion.
      was_pos = 0;
      for ii = 1:length(i_f);
            if diff(ii) > 0
                  was_pos = 1;
            end
            if ( diff(ii) < 0 & was_pos == 1 )
                  break;
            end;
      end;

      % Save terminal voltage at this point
      v_t(jj) = Vt(ii);
      i_l(jj) = i_a(jj) - v_t(jj) / ( r_f + r_adj);

end;

% Plot the terminal characteristic
figure(1);
plot(i_l,v_t,'b-','LineWidth',2.0);
xlabel('\bf\itI_{L} \rm\bf(A)');
ylabel('\bf\itV_{T} \rm\bf(V)');
title ('\bfTerminal Characteristic of a Shunt DC Generator');
hold off;
axis( [ 0 50 0 120]);
grid on;
```

The resulting terminal characteristic is shown below:

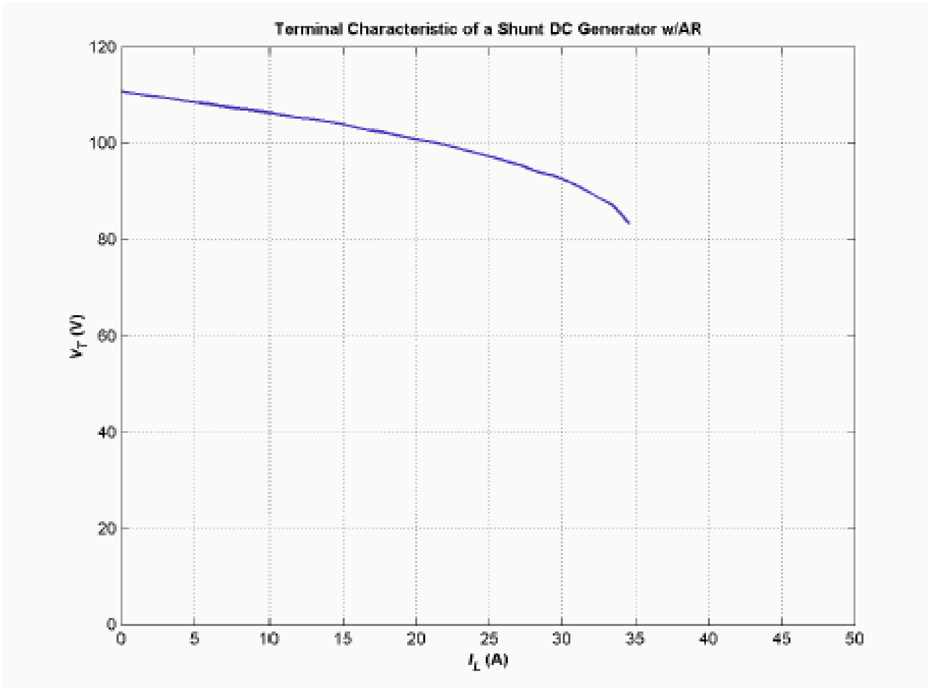


A MATLAB program to calculate the terminal characteristic of this generator with armature reaction is shown below:

```
% M-file: prob9_25d2.m
% M-file to calculate the terminal characteristic of a shunt
% dc generator with armature reaction.

% Get the magnetization curve. This file contains the
% three variables if_values, ea_values, and n_0.
clear all
load p97_mag.dat;
if_values = p97_mag(:,1);
ea_values = p97_mag(:,2);
n_0 = 1800;

% First, initialize the values needed in this program.
r_f = 24; % Field resistance (ohms)
r_adj = 10; % Adjustable resistance (ohms)
r_a = 0.18; % Armature + series resistance (ohms)
i_f = 0:0.005:6; % Field current (A)
n = 1800; % Generator speed (r/min)
n_f = 1000; % Number of field turns

% Calculate Ea versus If
Ea = interp1(if_values,ea_values,i_f);

% Calculate Vt versus If
Vt = (r_f + r_adj) * i_f;

% Find the point where the difference between the Ea
% armature reaction line and the Vt line is exactly
% equal to i_a*r_a. This will be the point where

% the line "Ea_ar - Vt - i_a*r_a" goes negative.
```

```
i_a = 0:1:37;
for jj = 1:length(i_a)

      % Calculate the equivalent field current due to armature
      % reaction.
      i_ar = (i_a(jj) / 50) * 200 / n_f;

      % Calculate the Ea values modified by armature reaction
      Ea_ar = interp1(if_values,ea_values,i_f - i_ar);

      % Get the voltage difference
      diff = Ea_ar - Vt - i_a(jj)*r_a;

      % This code prevents us from reporting the first (unstable)
      % location satisfying the criterion.
      was_pos = 0;
      for ii = 1:length(i_f);
            if diff(ii) > 0
                  was_pos = 1;
            end
            if ( diff(ii) < 0 & was_pos == 1 )
                  break;
            end;
      end;

      % Save terminal voltage at this point
      v_t(jj) = Vt(ii);
      i_l(jj) = i_a(jj) - v_t(jj) / ( r_f + r_adj);

end;

% Plot the terminal characteristic
figure(1);
plot(i_l,v_t,'b-','LineWidth',2.0);
xlabel('\bf\itI_{L} \rm\bf(A)');
ylabel('\bf\itV_{T} \rm\bf(V)');
title ('\bfTerminal Characteristic of a Shunt DC Generator w/AR');
hold off;
axis([ 0 50 0 120]);
grid on;
```

The resulting terminal characteristic is shown below:

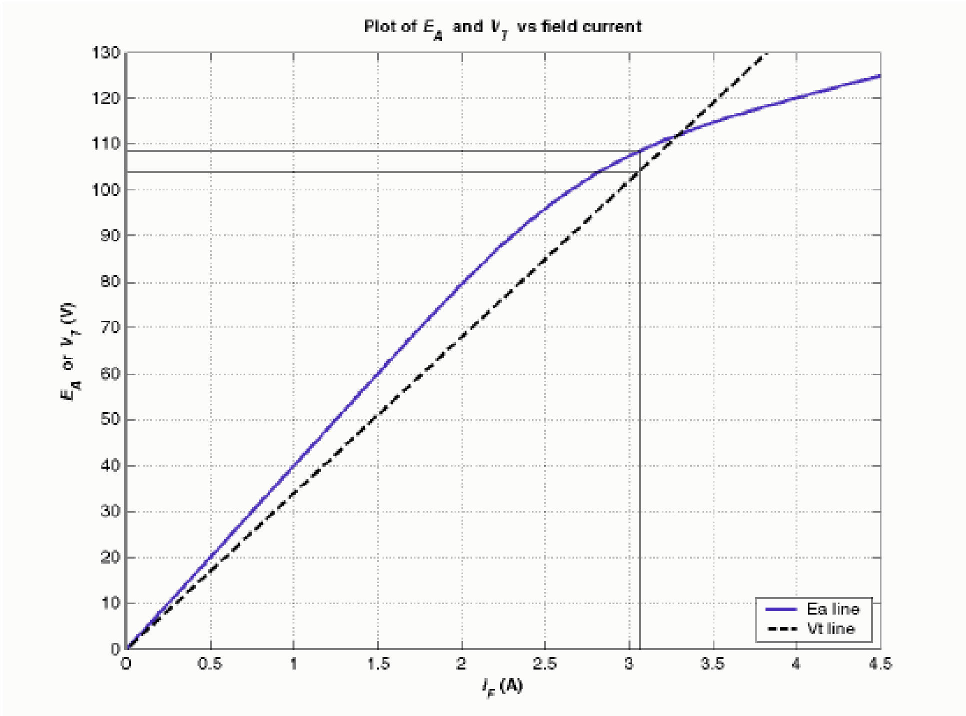


Problem 9-26:

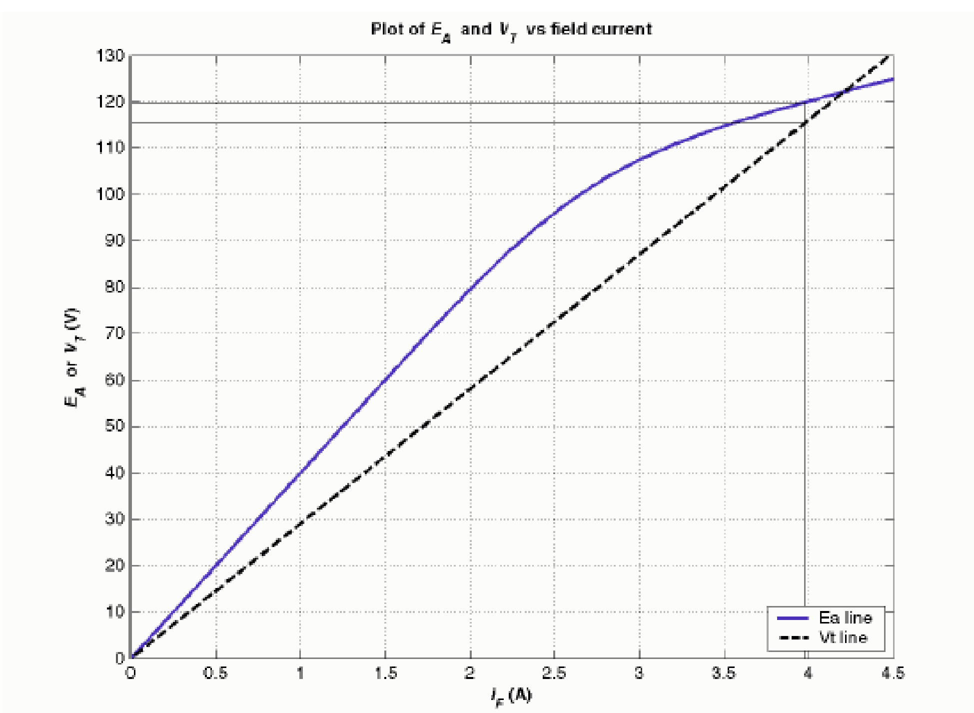
If the machine in Problem 9-25 is running at 1800 r/min with a field resistance $R_{adj} = 10\ \Omega$ and an armature current of 25 A, what will the resulting terminal voltage be? If the field resistor decreases to 5 Ω while the armature current remains 25 A, what will the new terminal voltage be? (Assume no armature reaction.)

Solution:

If $I_A = 25$ A, then $I_A R_A = (25\text{A})(0.18\Omega) = 4.5$ V. The point where the distance between the E_A and V_T curves is exactly 4.5 V corresponds to a terminal voltage of 104 V, as shown below.



If R_{adj} decreases to 5 Ω, the total field resistance becomes 29 Ω, and the terminal voltage line gets shallower. The new point where the distance between the E_A and V_T curves is exactly 4.5 V corresponds to a terminal voltage of 115 V, as shown below.



Note that decreasing the field resistance of the shunt generator increases the terminal voltage.