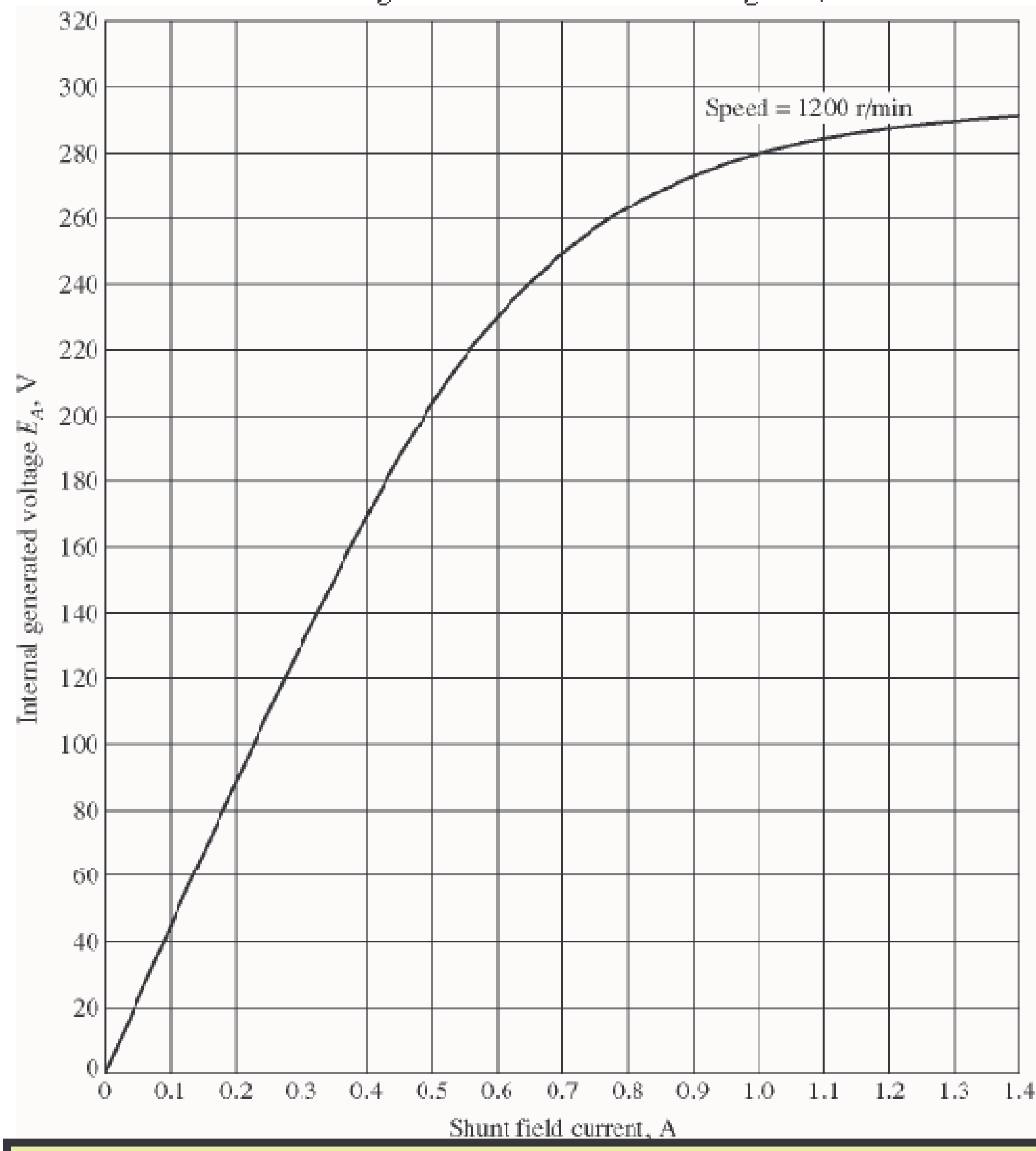
Problems 9-1 to 9-12 refer to the following dc motor:

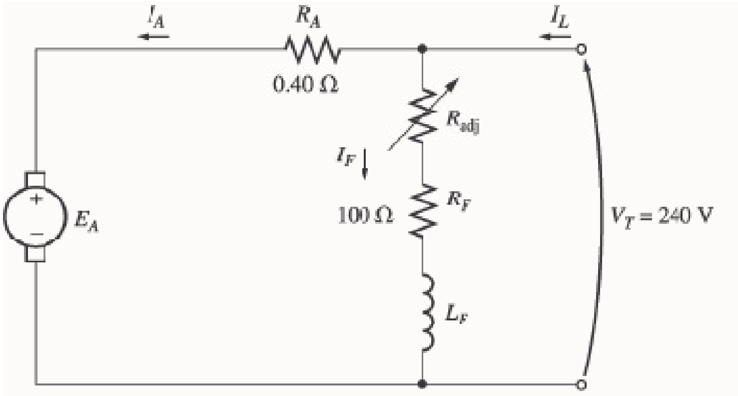
$P_{rated} = 15$ hp	$I_{L,rated} = 55$ A
$V_T = 240$ V	$N_F = 2700$ turns per pole
$n_{rated} = 1200$ r/min	$N_{SE} = 27$ turns per pole
$R_A = 0.40\ \Omega$	$R_F = 100\ \Omega$
$R_S = 0.04\ \Omega$	$R_{adj} = 100$ to $400\ \Omega$

Rotational losses = 1800 W at full load. Magnetization curve as shown in Figure P9-1.



Note: An electronic version of this magnetization curve can be found in file p91_mag.dat, which can be used with MATLAB programs. Column 1 contains field current in amps, and column 2 contains the internal generated voltage E_A in volts.

In Problems 9-1 through 9-7, assume that the motor described above can be connected in shunt. The equivalent circuit of the shunt motor is shown in Figure P9-2.



Note: Figure P9-2 shows incorrect values for R_A and R_F in the first printing of this book. The correct values are given in the text, but shown incorrectly on the figure. This will be corrected at the second printing.

9-1. If the resistor R_{adj} is adjusted to 175 Ω what is the rotational speed of the motor at no-load conditions?

SOLUTION At no-load conditions, $E_A = V_T = 240$ V. The field current is given by

$$I_F = \frac{V_T}{R_{adj} + R_F} = \frac{240 \text{ V}}{175\ \Omega + 100\ \Omega} = \frac{240 \text{ V}}{250\ \Omega} = 0.873 \text{ A}$$

From Figure P9-1, this field current would produce an internal generated voltage E_{Ao} of 271 V at a speed n_o of 1200 r/min. Therefore, the speed n with a voltage E_A of 240 V would be

$$\frac{E_A}{E_{Ao}} = \frac{n}{n_o}$$

$$n = \frac{E_A}{E_{Ao}} n_o = \frac{240 \text{ V}}{271 \text{ V}} (1200 \text{ r/min}) = 1063 \text{ r/min}$$

9-3. If the motor is operating at full load and if its variable resistance R_{adj} is increased to 250 Ω, what is the new speed of the motor? Compare the full-load speed of the motor with R_{adj} = 175 Ω to the full-load speed with R_{adj} = 250 Ω. (Assume no armature reaction, as in the previous problem.)

SOLUTION If R_{adj} is set to 250 Ω, the field current is now

$$I_F = \frac{V_T}{R_{adj} + R_F} = \frac{240 \text{ V}}{250\ \Omega + 100\ \Omega} = \frac{240 \text{ V}}{325\ \Omega} = 0.686 \text{ A}$$

Since the motor is still at full load, E_A is still 218.3 V. From the magnetization curve (Figure P9-1), the new field current I_F would produce a voltage E_{Ao} of 247 V at a speed n_o of 1200 r/min. Therefore,

$$n = \frac{E_A}{E_{Ao}} n_o = \frac{218.3 \text{ V}}{247 \text{ V}} (1200 \text{ r/min}) = 1061 \text{ r/min}$$

Note that R_{adj} has increased, and as a result the speed of the motor n increased.

9-6. What is the starting current of this machine if it is started by connecting it directly to the power supply V_T? How does this starting current compare to the full-load current of the motor?

SOLUTION The starting current of this machine (ignoring the small field current) is

$$I_{L,start} = \frac{V_T}{R_A} = \frac{240 \text{ V}}{0.40 \ \Omega} = 600 \text{ A}$$

The rated current is 55 A, so the starting current is 10.9 times greater than the full-load current. This much current is extremely likely to damage the motor.

9-8. What is the no-load speed of this separately excited motor when $R_{adj} = 175\ \Omega$ and *(a)* $V_A = 120$ V, *(b)* $V_A = 180$ V, *(c)* $V_A = 240$ V?

SOLUTION At no-load conditions, $E_A = V_A$. The field current is given by

$$I_F = \frac{V_F}{R_{adj} + R_F} = \frac{240 \text{ V}}{175\ \Omega + 100\ \Omega} = \frac{240 \text{ V}}{275\ \Omega} = 0.873 \text{ A}$$

From Figure P9-1, this field current would produce an internal generated voltage E_{Ao} of 271 V at a speed n_o of 1200 r/min. Therefore, the speed n with a voltage of 240 V would be

$$\frac{E_A}{E_{Ao}} = \frac{n}{n_o}$$

$$n = \frac{E_A}{E_{Ao}} n_o$$

(a) If $V_A = 120$ V, then $E_A = 120$ V, and

$$n = \frac{120 \text{ V}}{271 \text{ V}} \left(1200 \text{ r/min}\right) = 531 \text{ r/min}$$

(a) If $V_A = 180$ V, then $E_A = 180$ V, and

$$n = \frac{180 \text{ V}}{271 \text{ V}} \left(1200 \text{ r/min}\right) = 797 \text{ r/min}$$

(a) If $V_A = 240$ V, then $E_A = 240$ V, and

$$n = \frac{240 \text{ V}}{271 \text{ V}} \left(1200 \text{ r/min}\right) = 1063 \text{ r/min}$$

9-9. For the separately excited motor of Problem 9-8:

(a) What is the maximum no-load speed attainable by varying both V_A and R_{adj}?

(b) What is the minimum no-load speed attainable by varying both V_A and R_{adj}?

SOLUTION

(a) The maximum speed will occur with the maximum V_A and the maximum R_{adj}. The field current when R_{adj} = 400 Ω is:

$$I_F = \frac{V_T}{R_{adj} + R_F} = \frac{240\text{ V}}{400\ \Omega + 100\ \Omega} = \frac{240\text{ V}}{500\ \Omega} = 0.48\text{ A}$$

From Figure P9-1, this field current would produce an internal generated voltage E_{Ao} of 199 V at a speed n_o of 1200 r/min. At no-load conditions, the maximum internal generated voltage $E_A = V_A$ = 240 V. Therefore, the speed n with a voltage of 240 V would be

$$\frac{E_A}{E_{Ao}} = \frac{n}{n_o}$$

$$n = \frac{E_A}{E_{Ao}} n_o = \frac{240\text{ V}}{199\text{ V}}(1200\text{ r/min}) = 1447\text{ r/min}$$

(b) The minimum speed will occur with the minimum V_A and the minimum R_{adj}. The field current when R_{adj} = 100 Ω is:

$$I_F = \frac{V_T}{R_{adj} + R_F} = \frac{240\text{ V}}{100\ \Omega + 100\ \Omega} = \frac{240\text{ V}}{200\ \Omega} = 1.2\text{ A}$$

From Figure P9-1, this field current would produce an internal generated voltage E_{Ao} of 287 V at a speed n_o of 1200 r/min. At no-load conditions, the minimum internal generated voltage $E_A = V_A$ = 120 V. Therefore, the speed n with a voltage of 120 V would be

$$\frac{E_A}{E_{Ao}} = \frac{n}{n_o}$$

$$n = \frac{E_A}{E_{Ao}} n_o = \frac{120\text{ V}}{287\text{ V}}(1200\text{ r/min}) = 502\text{ r/min}$$

9-21. A 15-hp 120-V 1800 r/min shunt dc motor has a full-load armature current of 60 A when operating at rated conditions. The armature resistance of the motor is $R_A = 0.15\ \Omega$, and the field resistance R_F is 80 Ω. The adjustable resistance in the field circuit R_{adj} may be varied over the range from 0 to 200 Ω and is currently set to 90 Ω. Armature reaction may be ignored in this machine. The magnetization curve for this motor, taken at a speed of 1800 r/min, is given in tabular form below

E_A, V	5	78	95	112	118	126
I_F, A	0.00	0.80	1.00	1.28	1.44	2.88

Note: An electronic version of this magnetization curve can be found in file `prob9_21_mag.dat`, which can be used with MATLAB programs. Column 1 contains field current in amps, and column 2 contains the internal generated voltage E_A in volts.

(a) What is the speed of this motor when it is running at the rated conditions specified above?

(b) The output power from the motor is 7.5 hp at rated conditions. What is the output torque of the motor?

(c) What are the copper losses and rotational losses in the motor at full load (ignore stray losses)?

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

(e) If the motor is now unloaded with no changes in terminal voltage or R_{adj}, what is the no-load speed of the motor?

(f) Suppose that the motor is running at the no-load conditions described in part *(e)*. What would happen to the motor if its field circuit were to open? Ignoring armature reaction, what would the final steady-state speed of the motor be under those conditions?

(g) What range of no-load speeds is possible in this motor, given the range of field resistance adjustments available with R_{adj}?

SOLUTION

(a) If $R_{adj} = 90\ \Omega$, the total field resistance is 170 Ω, and the resulting field current is

$$I_F = \frac{V_T}{R_F + R_{adj}} = \frac{230\text{ V}}{90\ \Omega + 80\ \Omega} = 1.35\text{ A}$$

This field current would produce a voltage E_{Ao} of 221 V at a speed of n_o = 1800 r/min. The actual E_A is

$$E_A = V_T - I_A R_A = 230\text{ V} - (60\text{ A})(0.15\ \Omega) = 221\text{ V}$$

so the actual speed will be

$$n = \frac{E_A}{E_{Ao}} n_o = \frac{221\text{ V}}{221\text{ V}}(1800\text{ r/min}) = 1800\text{ r/min}$$

(b) The output power is 7.5 hp and the output speed is 1800 r/min at rated conditions, therefore, the torque is

$$\tau_{out} = \frac{P_{out}}{\omega_m} = \frac{(15\text{ hp})(746\text{ W/hp})}{(1800\text{ r/min})\left(\frac{2\pi\text{ rad}}{1\text{ r}}\right)\left(\frac{1\text{ min}}{60\text{ s}}\right)} = 59.4\text{ N}\cdot\text{m}$$

(c) The copper losses are

$$P_{CU} = I_A^2 R_A + V_F I_F = (60\text{ A})^2 (0.15\ \Omega) + (230\text{ V})(1.35\text{ A}) = 851\text{ W}$$

The power converted from electrical to mechanical form is

$$P_{conv} = E_A I_A = (221\text{ V})(60\text{ A}) = 13{,}260\text{ W}$$

The output power is

$$P_{OUT} = (15\text{ hp})(746\text{ W/hp}) = 11{,}190\text{ W}$$

Therefore, the rotational losses are

$$P_{rot} = P_{conv} - P_{OUT} = 13{,}260\text{ W} - 11{,}190\text{ W} = 2070\text{ W}$$

(d) The input power to this motor is

$$P_{IN} = V_T (I_A + I_F) = (230\text{ V})(60\text{ A} + 1.35\text{ A}) = 14{,}100\text{ W}$$

Therefore, the efficiency is

$$\eta = \frac{P_{OUT}}{P_{IN}} \times 100\% = \frac{11{,}190\text{ W}}{14{,}100\text{ W}} \times 100\% = 79.4\%$$

(e) The no-load E_A will be 230 V, so the no-load speed will be

$$n = \frac{E_A}{E_{Ao}} n_o = \frac{230\text{ V}}{221\text{ V}} (1800\text{ r/min}) = 1873\text{ r/min}$$

(f) If the field circuit opens, the field current would go to zero $\Rightarrow \phi$ drops to $\phi_{res} \Rightarrow E_A \downarrow \Rightarrow I_A \uparrow \Rightarrow \tau_{ind} \uparrow \Rightarrow n \uparrow$ to a *very* high speed. If $I_F = 0$ A, $E_{Ao} = 8.5$ V at 1800 r/min, so

$$n = \frac{E_A}{E_{Ao}} n_o = \frac{230\text{ V}}{8.5\text{ V}} (1800\text{ r/min}) = 48{,}700\text{ r/min}$$

(In reality, the motor speed would be limited by rotational losses, or else the motor will destroy itself first.)

(g) The maximum value of $R_{adj} = 200\ \Omega$, so

$$I_F = \frac{V_T}{R_F + R_{adj}} = \frac{230\text{ V}}{200\ \Omega + 80\ \Omega} = 0.821\text{ A}$$

This field current would produce a voltage E_{Ao} of 153 V at a speed of $n_o = 1800$ r/min. The actual E_A is 230 V, so the actual speed will be

$$n = \frac{E_A}{E_{Ao}} n_o = \frac{230\text{ V}}{153\text{ V}} (1800\text{ r/min}) = 2706\text{ r/min}$$

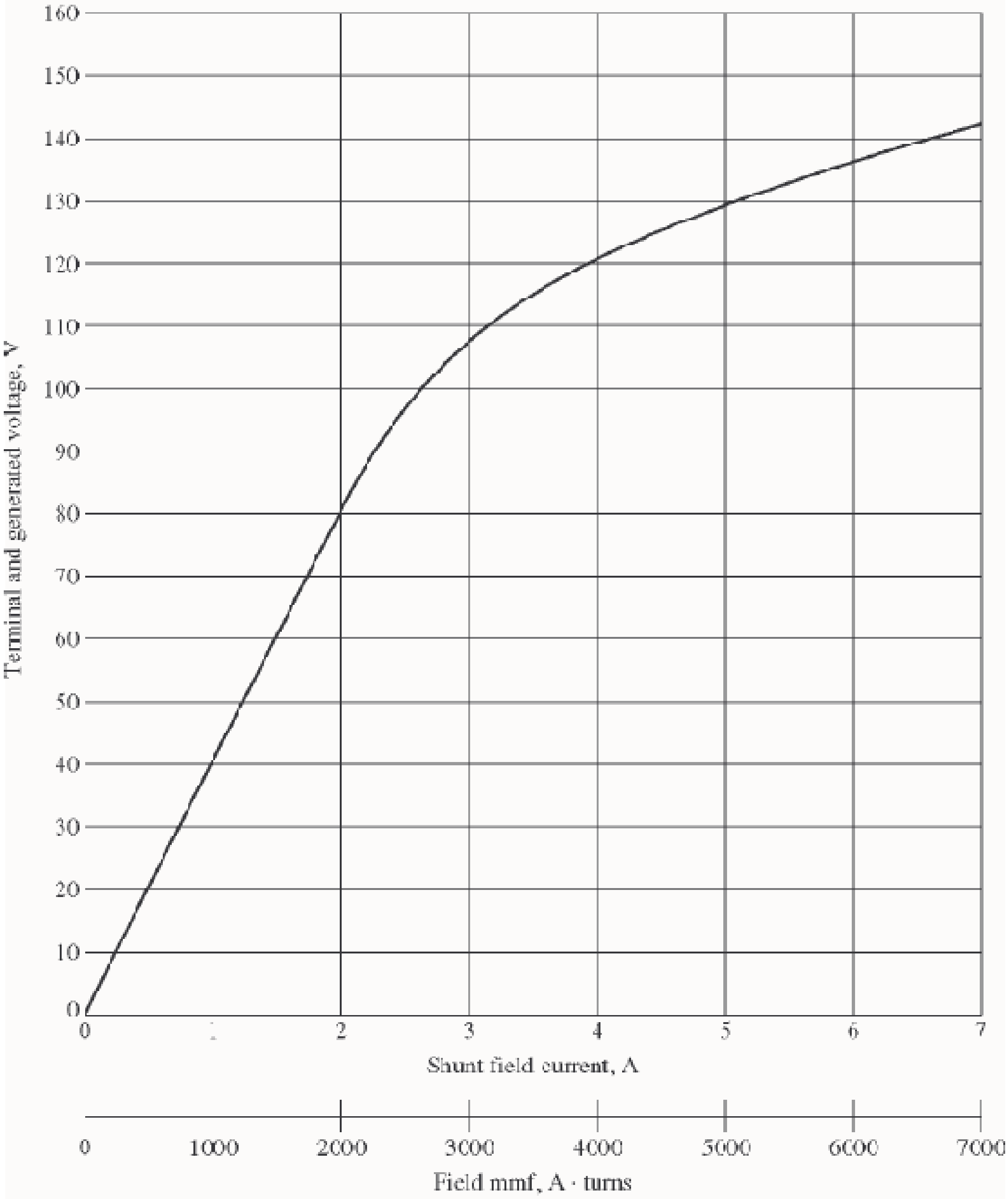
The minimum value of $R_{adj} = 0\ \Omega$, so

$$I_F = \frac{V_T}{R_F + R_{adj}} = \frac{230\text{ V}}{0\ \Omega + 80\ \Omega} = 2.875\text{ A}$$

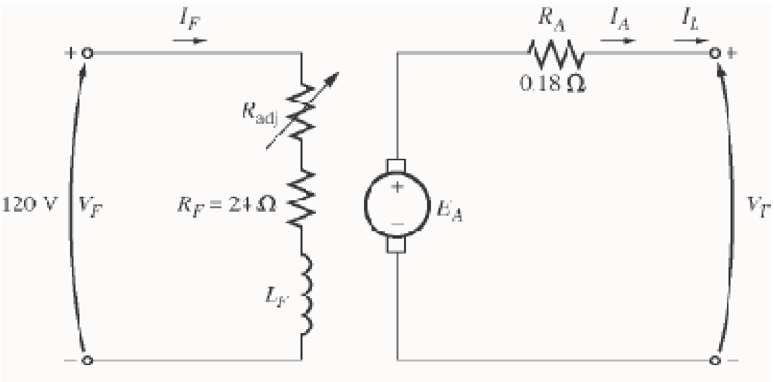
This field current would produce a voltage E_{Ao} of about 242 V at a speed of $n_o = 1800$ r/min. The actual E_A is 230 V, so the actual speed will be

$$n = \frac{E_A}{E_{Ao}} n_o = \frac{230\text{ V}}{242\text{ V}} (1800\text{ r/min}) = 1711\text{ r/min}$$

9-22. The magnetization curve for a separately 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 circuit is rated at 5A. The following data are known about the machine:



Note: An electronic version of this magnetization curve can be found in file p97_mag.dat, which can be used with MATLAB programs. Column 1 contains field current in amps, and column 2 contains the internal generated voltage E_A in volts.



$R_A = 0.18\ \Omega$ $\qquad V_F = 120\ \text{V}$

$R_{adj} = 0$ to $30\ \Omega$ $\qquad R_F = 24\ \Omega$

$N_F = 1000$ turns per pole

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?

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 $R_{adj} = 0\ \Omega$. The current is

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

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 $R_{adj} = 30\ \Omega$. The current is

$$I_{F,max} = \frac{V_F}{R_F + R_{adj}} = \frac{120\ \text{V}}{24\ \Omega + 30\ \Omega} = 2.22\ \text{A}$$

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 $R_{adj} = 0\ \Omega$. The current is

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

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

$$\frac{E_A}{E_{Ao}} = \frac{n}{n_o}$$

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

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

$$I_{F,\max} = \frac{V_F}{R_F + R_{\text{adj}}} = \frac{120 \text{ V}}{24\ \Omega + 30\ \Omega} = 2.22 \text{ A}$$

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 maximum no-load voltage is

$$\frac{E_A}{E_{Ao}} = \frac{n}{n_o}$$

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