Chapter-2: Common Aspects of Power Equipment

Problem Solutions

Problem 2.1: Determine the rms value of voltage induced in a 80-turn coil on a 30 cm × 25 cm cross section core with peak flux density of 1.7 tesla alternating at 60 Hz.

Solution:

Flux density of 1.7 tesla (weber/m^2) gives the peak flux in the core = 1.7 × (0.30 m × 0.25 m) = 0.1275 weber .

Then, Equation (2.2) gives

$V_{rms} = 4.444 \times 60 \times 80 \times 0.1275 = 2720$ V

Problem 2.2: Two parallel 1-phase rectangular bus bars 2 cm apart at center lines experience 30,000 A_{rms} current when a load gets short circuited. Determine the peak mechanical force per meter length of the bus bars. Assume the bus bar shape factor K = 0.85.

Solution:

In 1-phase power circuits, the currents in two parallel bus bars are equal and opposite.

$\therefore I_1 = - I_2 = \sqrt{2} \times 30{,}000$ in Equation 2.4 gives the peak force

$$F = \frac{200\, x\, 0.85\, x\, (\sqrt{2} x 30{,}000)\, x\, (-\sqrt{2} x 30{,}000)}{2} x 10^{-7} = -15{,}300 \;\; newtons / meter$$

The – sign indicates repulsive force.

The bars must be accordingly braced to avoid mechanical damage due to bending stresses or deflections between supports.

Problem 2.3: A transformer has no-load loss of 30 kW and full load loss of 90 kW when delivering 3 MW power. Determine its (i) full load efficiency, and (ii) maximum efficiency with the corresponding loading level in % of the full load and in kW.

Solution:

Using power in kW, full load efficiency = 3000 ÷ (3000 + 90) = 0.9709

The no-load power loss of 30 kW remains constant as long as the machine remains connected to the lines, regardless of its level of loading. Therefore, the I^2R power loss in conductor at 100 % load = 90 – 30 = 60 kW, which varies with load-squared.

As per Equation (2.9), the efficiency is maximum when conductor loss is equal to the fixed loss, i.e. when 30 = 60 × load^2. This gives load = $(30 \div 60)^{½}$ = 0.7071 or 70.71 % of the full load, or 3000 × 0.7071 = 2121 kW.

Maximum efficiency at 70.71 % load = 2121 ÷ (2121 + 30 + 30) = 0.9725

Problem 2.4: A dc source with open circuit voltage of 120 V drops to 105 V under 15 A load. Determine its Thevenin parameters, i.e. the source voltage V_s and the source resistance R_s.

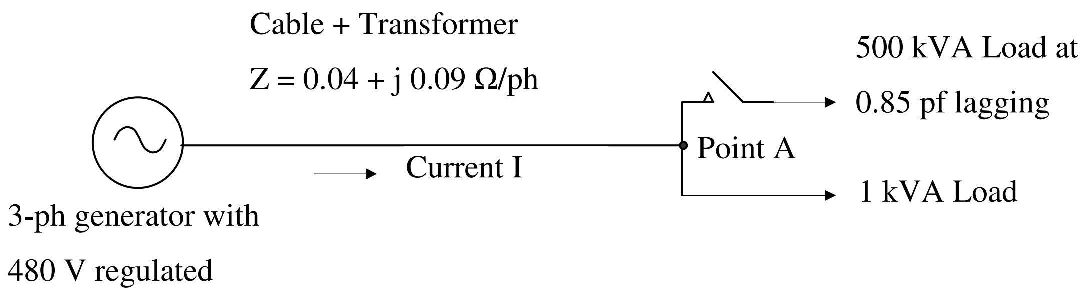
Solution:

The open circuit voltage is the Thevenin source voltage, i.e. $V_s = 120$ V.

Since the voltage drop of 120 – 105 = 15 volts at 15 A load current must be in the internal source resistance,

Thevenin source resistance $R_s = 15\text{ V} \div 15\text{ A} = 1.0\ \Omega$.

Problem 2.5: From 3-phase, 480-V generator switchboard, a feeder takes 3-phase power to two equipments at the other end – similar to figure in Example 2.5 – via a cable and transformer with combined Z = 0.04 + j 0.09 Ω/phase. The voltage at point A at the receiving end rises and falls as a large 3-phase, 500-kVA load varies over time. The small 1-kVA load, also connected at point A, remains on line continuously, and must accommodate the voltage variations at point A with 500-kVA load fully on or fully off. Determine the voltage range that the 1-kVA load will see, over which it must perform within its specifications.



Solution:

The 500-kVA load current I = 500 kVA × 1000 ÷ (√3 × 480) = 601 A/ph

For 0.85 pf lagging (i.e. $\cos\theta = 0.85$ and $\sin\theta = 0.5268$), Equation (2.15) gives the voltage drop in the cable

$V_{drop} = 601\,(0.04 \times 0.85 + 0.09 \times 0.5268) = 49$ V/ph $= 49\sqrt{3} = 85\ V_{LL}$

∴ Line voltage at point A when 500-kVA load is fully on = 480 – 85 = 395 V_{LL}

Voltage at point A when 500-kVA load is fully off = 480 V_{LL} (since there is negligible current and hence negligible voltage drop in the cable).

∴ Voltage for 1-kVA load will vary from 395 to 480 V. This is a rather large variation the small 1-kVA load must accommodate while meeting the specified performance.

Problem 2.6: Two batteries have their terminal voltage vs. load current droop lines shown in the figure below. Determine analytically the load current shared by each battery and the battery bus voltage if they share a total load current of (i) 500 A and (ii) 800 A. In case of 500 A total load, verify your answers by one-step method with Battery-2 line redrawn as needed.

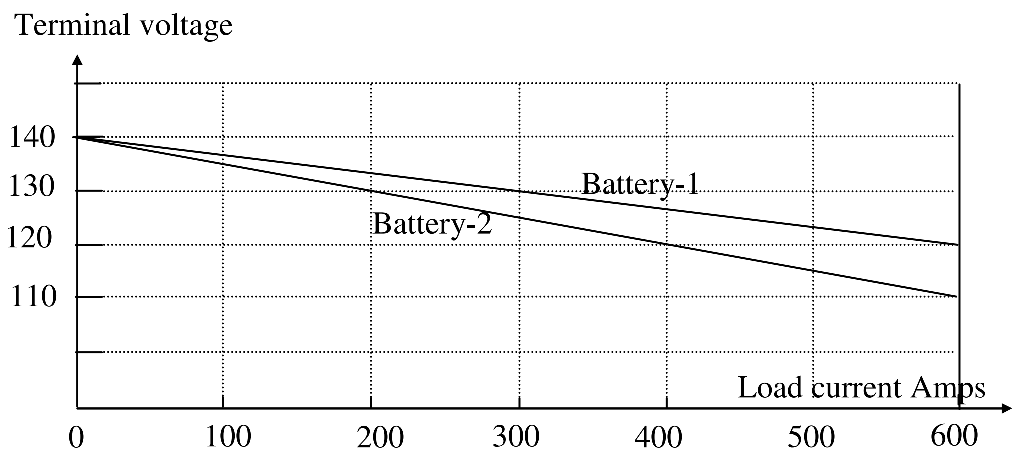


Figure P3.6

Solution:

We first determine the droop line equations from the figure,

Battery-1 voltage drops from 140 V at zero load to 120 V at 600 A, which gives

$$V_{T1} = 140 - \frac{140-120}{600} I_1 = 140 - 0.0333 I_1$$

Similarly, we have $V_{T2} = 140 - \frac{140-110}{600} I_2 = 140 - 0.05 I_2$

For 500 A total load at common bus voltage V_{bus}, we write

$V_{bus} = V_{T1} = 140 - 0.0333\ I_1 = V_{T2} = 140 - 0.05\ I_2$ (a)

And the total load current $I_1 + I_2 = 500$ A (b)

Simultaneous solution of Equations (a) and (b) gives

$I_1 = 300$ A, $I_2 = 200$ A, and $V_{bus} = 140 - 0.05 \times 200 = 130$ V

(ii) For 800 A total current, we repeat the above procedure, which leads to

$I_1 = 480$ A, $I_2 = 320$ A, and $V_{bus} = 140 - 0.05 \times 320 = 124$ V

As the load current increases from 500 A to 800 A, we note that the battery bus voltage decreases from 130 V to 124 V, as expected.

These answers can also be derived graphically in one step by plotting the Battery-2 line backward starting from the right hand side and drooping as we increase its load current from 0 to total value towards the left hand side (a graphical exercise for the student to complete).

Problem 2.7: A electrical equipment is designed for 25-year life with 70˚ C rise in 40˚ C ambient air at rated load. If it is continuously overloaded by 10 %, determine its new expected life.

Solution:

The power loss in conductor is due to resistance only, which varies as the load current squared. Denoting the rated and overload conditions by suffix 1 and 2, respectively,

Power loss at 10 % overload is given by $W_2 = 1.10^2 \times W_1 = 1.21\ W_1$

With the same heat dissipation area, Equation (2.23) in the ratio gives

$$\frac{\Delta T_2}{\Delta T_1} = \left(\frac{W_2}{W_1}\right)^{0.8} = 1.21^{0.8} = 1.165$$

Since $\Delta T_1 = 70˚$ C, we have $\Delta T_2 = 1.165 \times 70 = 81.5˚$ C, and $\Delta T_2 - \Delta T_1 = 81.5 - 70 = 11.5˚$ C. The coil, therefore, operates 11.5˚ C hotter than the design temperature. If this continues until end, its life gets reduced by the 10˚ C rule in Equation (2.24), i.e.

$$Actual\ life\ at\ overload = \frac{25}{2^{\left(\frac{11.5}{10}\right)}} = 11.27 \text{ years.}$$

Problem 2.8: A 500-hp, 460-V motor winding insulation resistance was measured to be 15 MΩ when sitting idle in normal room temperature of 25˚ C. Determine whether this motor is worthy of continuing service as per the IEEE Standard.

Solution:

To be worthy of connecting to the line voltage, the winding insulation must have R_{min} = 5 MΩ at 40˚ C.

The measured value of 15 MΩ at 25˚ C must be first adjusted to 40˚ C before comparing with the required R_{min} and making judgment about its service worthiness. Using Equation (2.27), the temperature correction factor

$K_T = 2^{\frac{25-40}{10}} = 2^{-1.5} = 0.35$, which gives $R_{40^\circ C}$ = 0.35 × 15 = 5.3 MΩ.

Since this is greater than 5 MΩ minimum required in service, the motor winding insulation meets the IEEE standard, and can be connected to the line.

Problem 2.9: A 75-kVA, 1-phase, 60-Hz transformer primary coil with 100 turns is connected to 265-V source. Determine the peak flux in the core. If the magnetomotive force of 500 ampere-turns is needed to establish this flux, determine the core excitation current.

Solution:

Using Equation (2.2), we have

$265 = 4.444\times 60 \times 100 \times \phi_m$

which gives the steady state peak flux $\phi_m = 0.01$ weber.

Core excitation current drawn from the primary coil of 100 turns is

$$I_{ex} = \frac{500\ amp.turns}{100\ turns} = 5\ \ A$$

Problem 2.10: A feeder transformer delivers full load current at its output voltage of 460 V. When the load is removed, the output voltage rises to 480 V. Determine the voltage regulation of this transformer.

Solution:

Voltage regulation by definition

$$VR = \frac{480 - 460}{460} = 0.0435 \;\; pu = \;\; 4.35\ \% \;\; \text{pu}$$

Problem 2.11: A generator winding delivering rated load of 1000 kVA rises to 50˚C above 40˚C ambient air, making its operating temperature 40 + 50 = 90˚C. If the generator is overloaded by 30 %, determine its operating temperature. If always operated at 30 % overload, determine the generator life if the rated design life is 25 years.

Solution:

Power loss in winding at 30 % overloads = $1.3^2 = 1.69\times$ loss at rated load

$$\frac{\Delta T_{over.load}}{\Delta T_{rated.load}} = (1.69)^{0.8} = 1.52$$

$\therefore\ \Delta T_{over.load} = 1.52 \times 50 = 76$ ˚C rise above 40˚ C ambient

The winding is running 76 – 50 = 26˚ C hotter than the design temperature at rated load.

From Equation (2.24)

$$Actual\ life\ at\ 30\%\ overload = \frac{25}{2^{\frac{26}{10}}} = \frac{25}{6.06} = 4.12$$ years (very short)

Problem 2.12: A 4160-V generator phase coil insulation resistance is 20 MΩ measured at 70˚ C soon after it was tripped. Compare this with the minimum required by the industry standard, and state whether this generator is good to continue in operation.

Solution:

As per IEEE standard, required R_{min} = 100 MΩ at 40˚ C

Measured value = 20 Ω at 70˚ C

If measured at 40˚ C, it would be $20\,x\,2^{\frac{70-40}{10}} = 20\,x\,8 = 160\,M\,\Omega$

Since this is greater than the R_{min} required, the generator is good to continue in operation.

Problem 2.13: A 1-phase, 500-kVA, 440/120-V service transformer feeds service loads via bus duct with two bus bars each ½ x 3 inches in cross section, spaced ½ inch apart. An electrical system study has concluded that the worst-case fault current in the bus is 30,000 A at the first peak. Determine the peak mechanic force between the bus bars that will cause defection and bending stress between the supports. Assume the bus bar shape factor K = 0.7.

Solution:

For 1-phase bus bars, $I_1 = -I_2 = 30{,}000$ A peak

Using Equation (2.3), we have

$$F = \frac{5.4x0.7x(30{,}000)x(-30{,}000)}{0.5}x10^{-7} = -680.4 \ \ Lbf\ /\ ft$$

The negative sign indicates the repulsive force.

Problem 2.14: A power electronics component designed to last 25 years under rated load is always operated 5˚C above the design temperature limit. Determine its expected life if 8˚C rule for ½ life is found applicable to electronics components.

Solution:

Life at 5˚ C hotter operation with 8˚ C half-life-rule can be derived by a modified version of Equation (2.24), i.e.

Actual life at 5˚ C hotter operation = $\frac{25}{2^{\frac{5}{8}}} = 16.21$ years

Problem 2.15: A 1000-kVA, 1-phase transformer operating at 85 % power factor lagging at full rated load has conductor power loss of 10 kW and core loss of 5 kW. Determine its maximum possible efficiency and the corresponding load level as % of the rated load.

Solution:

We know from Equation (2.9) that the maximum efficiency results when the equipment has conductor loss, which varies with load squared, equals the core loss which remains fixed at all loads as long as the voltage remains constant (which is usually the case and is implied unless stated otherwise).

Therefore, for maximum efficiency, 10 kW × Load ^{2} = 5 kW

$\therefore$ Loading level at maximum efficiency = $\sqrt{(5/10)}$ = 0.707 or 70.7 % of rated load.

At 70.7 % load, output power = 0.707 × 1000 kVA × 0.85 pf = 601 kW, and

Maximum efficiency = 601 / (601 + 5 + 5) = 0.9836 or 98.36 %.