EEE4117F QUIZ 3 **TOTAL MARKS: 30**
DATE: 25 JUNE 2020 **TIME: 1 HOUR (X2)**

PART A: MACHINES Marks: 15

QUESTION 1 [6 MARKS]

1.1. Draw well-labelled phasor diagrams to highlight the leading power factor, unity power factor and lagging power factor features of a wound field synchronous motor drives. **[3]**

1.2. Briefly explain why a synchronous motor is not self-starting when connected to a 3-phase AC supply and explain any **two** methods of starting up a synchronous motor drive **[3]**

QUESTION 2 [9 MARKS]

A three-phase, 5 kVA, 208 V, four-pole, 60 Hz, wye-connected synchronous machine has negligible stator winding resistance and a synchronous reactance of 8 Ω per phase at rated voltage. The machine is operated as a motor from a three-phase 208 V, 60 Hz supply. Answer the following questions:

2.1. If the field excitation is adjusted so that power factor is unity when the machine draws 3 kW from the supply, determine the excitation voltage E_f and power angle δ. **[3]**

2.2. Draw the phasor diagram for the operation of the motor under the conditions in 2.1 above. **[2]**

2.3. If the field excitation is held constant and the shaft load is slowly increased, determine the maximum torque (pull-out torque) that the motor can deliver. **[4]**

PART B: POWER ELECTRONICS Marks: 15

QUESTION 1 [4 MARKS]

1.1. Why is it advantageous to use a full-bridge instead of half-bridge in case of the high-power applications? **[2]**

1.2. Name two advantages of space vector pulse width modulation over sinusoidal pulse width modulation **[2]**

QUESTION 2 **[11 MARKS]**

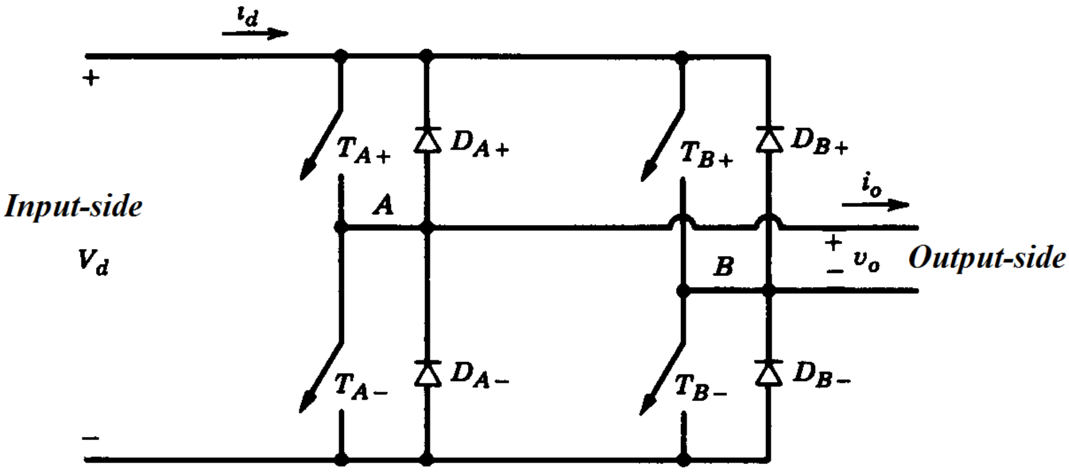


Fig. 1

The output of the voltage source inverter shown in **Fig. 1** is connected across an **RL** load. The RL load has a resistance of R=10 Ω and series inductance L=10 mH. The input of the inverter is connected across a 200 V dc voltage source (V_d). The inverter is controlled using the bipolar PMW switching, where the sinusoidal signal with a peak amplitude of 8 V and frequency of 50 Hz is compared with a triangular signal with a peak amplitude of 10 V and frequency of 1050 Hz. Answer the following questions:

2.1. Name an additional component that can be connected to the input side of the voltage source inverter to improve its performance. **[1]**

2.2. Determine the maximum amplitude modulation ratio (m_a) **[1]**

2.3. Determine the frequency modulation ratio (m_f) **[1]**

2.4. Determine the amplitude of the fundamental component (50 Hz) of the output voltage **[1]**

2.5. Determine the amplitude of the fundamental component (50 Hz) of the output current **[2]**

The table shown below list the normalised Fourier coefficients (V_n/V_d) for bipolar PWM scheme. V_n is the amplitude value of the harmonic component "**n**". "**m_f**" is the frequency modulation ratio and m_a is the maximum amplitude modulation ratio (m_a).

	m_a=1	0.9	0.8	0.7	0.6	0.5	0.4	0.3	0.2	0.1
$n=1$	1.00	0.90	0.80	0.70	0.60	0.50	0.40	0.30	0.20	0.10
$n=m_f$	0.60	0.71	0.82	0.92	1.01	1.08	1.15	1.20	1.24	1.27
$n=mf\pm2$	0.32	0.27	0.22	0.17	0.13	0.09	0.06	0.03	0.02	0.00

2.6. Determine the voltage amplitudes of the harmonic components of the inverter **[1.5]**

2.7. Determine the current amplitude of the harmonic component of the inverter **[1.5]**

2.8 Determine the THD of the load current **[2]**

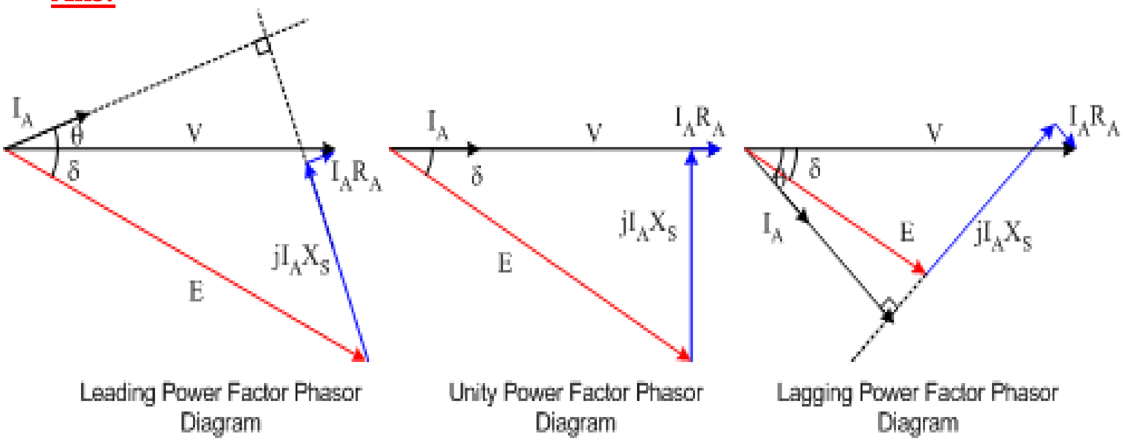
SOLUTIONS

PART A: MACHINES Marks: 15

QUESTION 1 [6 MARKS]

1.1. Draw well-labelled phasor diagrams to highlight the leading power factor, unity power factor and lagging power factor features of a wound field synchronous motor drives. **[3]**

Ans:



[3]

1.2. Briefly explain why a synchronous motor is not self-starting when connected to a 3-phase AC supply and explain any **two** methods of starting up a synchronous motor drive. **[3]**

Ans:

If a synchronous motor is connected directly to the AC supply, it will simply vibrate. The inertia of the rotor prevents it from locking onto the rotating stator field. **[1]**

[Any two of the three starting methods below]

- **Use of damping winding**: Damper windings are made up of non-magnetic material (usually copper) rods embedded in the pole face of the rotor. Damper windings may either be continuous or non-continuous. These conductors are shorted together across each end of the rotor, and thus form a squirrel-cage type winding.

[1]

- **Use of a low power auxiliary motor**: The small motor is either mounted the motor shaft or coupled to the synchronous motor. The auxiliary motor is usually an induction motor. The auxiliary motor should have the same number of poles with the synchronous motor or be one pole less than the synchronous motor. So that it can rotate the rotor merely at synchronous speed. When the rotor of the synchronous speed is close to the synchronous speed, the main switch and DC switch of the main synchronous motor are closed. [1]

- **Use of Variable-Frequency Supply** - The synchronous motor can be started with a frequency converter (variable frequency output) by slowly increasing the frequency of the stator field upon startup. This allows the rotor time to overcome the inertia required for it to follow the stator field as it increases in speed. The primary drawback to this technique is the cost of the frequency converter. **[1]**

QUESTION 2 [9 MARKS]

A three-phase, 5 kVA, 208 V, four-pole, 60 Hz, wye-connected synchronous machine has negligible stator winding resistance and a synchronous reactance of 8 Ω per phase at rated voltage. The machine is operated as a motor from a three-phase 208 V, 60 Hz supply. Answer the following questions:

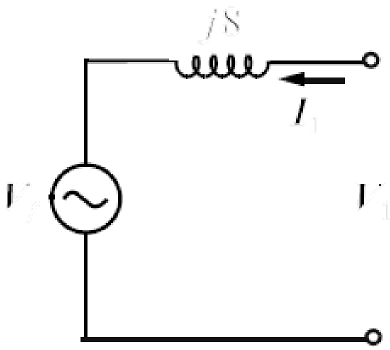
2.1. If the field excitation is adjusted so that power factor is unity when the machine draws 3 kW from the supply, determine the excitation voltage E_f and power angle δ. **[3]**

$$V_1 = 120\angle 0^o \text{ V}$$

$$PF = 1.0 \qquad \theta_v - \theta_i = 0^o$$

$$P = 3V_1 I_1 = 3(120)I_1 = 3 \text{ kW}$$

$$I_1 = \frac{3000}{3(120)} = 8.33 \text{ A} \quad [1]$$



$$V_f = V_1 - I_1 Z_s = 120\angle 0^o - (8.33\angle 0^o)(8\angle 90^o)$$

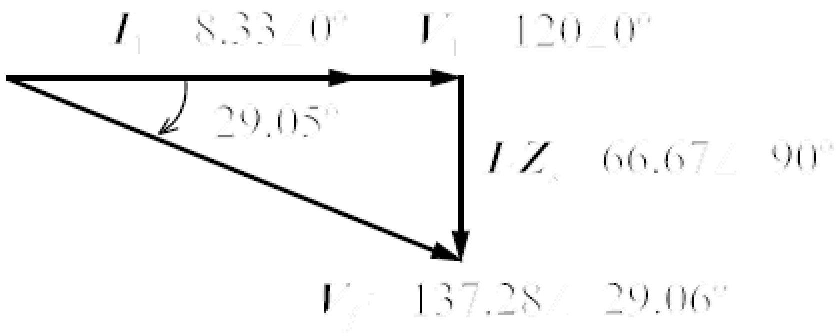
$$= 120\angle 0^o - 66.67\angle 90^o$$

$$= 137.28\angle -29.06^o \text{ V} = V_f\angle\delta$$

$$V_f = 137.28 \text{ V} \quad [1] \qquad \delta = -29.06^o \quad [1]$$

[3]

2.2. Draw the phasor diagram for the operation of the motor under the conditions in 2.1 above. **[2]**



[2]

2.3. If the field excitation is held constant and the shaft load is slowly increased, determine the maximum torque (pull-out torque) that the motor can deliver. **[4]**

$$V_f = 137.28\angle 90^o$$

$$P_{\max} = \frac{3V_1V_f}{X_s} = \frac{3(120)(137.28)}{8} = 6.18\ \text{kW} \quad [1]$$

$$T_{\max} = \frac{P_{\max}}{\omega_s}\ [1] \qquad \omega_s = \frac{n_s}{60}2\pi \qquad n_s = 120\frac{f}{p}$$

$$\omega_s = 4\pi\frac{f}{p} = 4\pi\frac{60}{4} = 188.5\ \text{rad/s} \quad [1]$$

$$T_{\max} = \frac{6180}{188.5} = 32.8\ \text{N-m} \quad [1]$$

[4]

PART B: POWER ELECTRONICS Marks: 15

QUESTION 1 **[4 MARKS]**

1.1. Why is it advantageous to use a full-bridge instead of half-bridge in case of the high-power applications? **[2]**

Ans:

For a given V_d, output voltage of the converter will be double the that a half bridge. Therefore, output current and switch currents are one half of those for a half-bridge inverter. **At high power levels, it requires less paralleling of devices** [2]

1.2. Name two advantages of space vector pulse width modulation over sinusoidal pulse width modulation **[2]**

Ans:

Space vector PWM generates less harmonic distortion in the output compared to sine PWM [1]

Space vector PWM provides more sufficient use of supply voltage compared to sine PWM [1]

QUESTION 2 [11 MARKS]

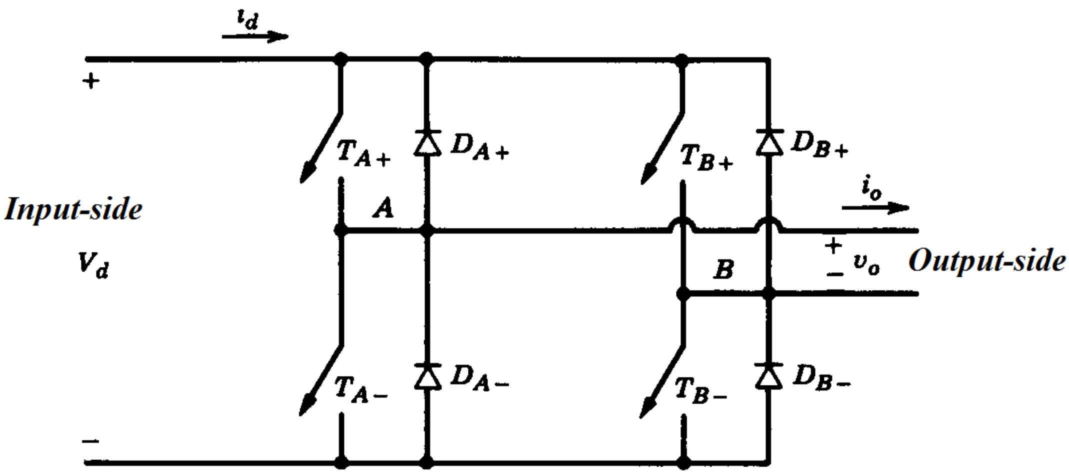


Fig. 1

The output of the voltage source inverter shown in **Fig. 1** is connected across an **RL** load. The RL load has a resistance of R=10 Ω and series inductance L=10 mH. The input of the inverter is connected across a 200 V dc voltage source (V_d). The inverter is controlled using the bipolar PMW switching, where the sinusoidal signal with a peak amplitude of 8 V and frequency of 50 Hz is compared with a triangular signal with a peak amplitude of 10 V and frequency of 1050 Hz. Answer the following questions:

2.1. Name an additional component that can be connected to the input side of the voltage source inverter to improve its performance. **[1]**

Ans: Capacitor [1]

2.2. Determine the maximum amplitude modulation ratio (m_a) **[1]**

Ans:

$m_a = \frac{\hat{V}_{control}}{\hat{V}_{tri}} = \frac{8}{10} = 0.8$ [1]

2.3. Determine the frequency modulation ratio (m_f) **[1]**

Ans:

$m_f = \frac{f_s}{f_1} = \frac{1050}{50} = 21$ [1]

2.4. Determine the amplitude of the fundamental component (50 Hz) of the output voltage **[1]**

Ans:

$V_0 = m_a V_d = 0.8x200 = 160\ V$ [1]

2.5. Determine the amplitude of the fundamental component (50 Hz) of the output current **[2]**

Ans:

Using phasor analysis

$I_n = \frac{V_n}{Z_n} = \frac{V_n}{Z_n} = \frac{V_n}{\sqrt{R^2+(2\pi f_n L)^2}}$ [1] for the correct equation

$I_0 = \frac{160}{\sqrt{10^2+(2\pi(50)(10x10^{-3}))^2}} = 15.26\ A$ [1]

[0.25] each for correct substitution of R and L and [0.5] for the correct answer

The table shown below list the normalised Fourier coefficients (V_n/V_d) for bipolar PWM scheme. V_n is the amplitude value of the harmonic component "**n**". "**m$_f$**" is the frequency modulation ratio and m_a is the maximum amplitude modulation ratio (m_a).

	m_a=1	**0.9**	**0.8**	**0.7**	**0.6**	**0.5**	**0.4**	**0.3**	**0.2**	**0.1**
$n=1$	1.00	0.90	0.80	0.70	0.60	0.50	0.40	0.30	0.20	0.10
$n=m_f$	0.60	0.71	0.82	0.92	1.01	1.08	1.15	1.20	1.24	1.27
$n=mf\pm2$	0.32	0.27	0.22	0.17	0.13	0.09	0.06	0.03	0.02	0.00

2.6. Determine the voltage amplitudes of the harmonic components of the inverter **[1.5]**

Ans:

The first harmonic is at n=m$_f$=21 and other two are at n= (21+2)=23 and n=(21-2)=19.

$V_{21} = (0.82)(200) = 164\ V$ [0.5]

$V_{19} = (0.22)(200) = 44\ V$ [0.5]

$V_{23} = (0.22)(200) = 44\ V$ [0.5]

2.7. Determine the current amplitude of the harmonic component of the inverter **[1.5]**

Ans:

f=950 Hz

$I_{19} = \frac{V_{21}}{\sqrt{R^2+(2\pi f_{21} L)^2}} = \frac{44}{\sqrt{10^2+(2\pi(950)(10x10^{-3}))^2}} = 0.727$ [0.5]

f=1050 Hz

$I_{21} = \frac{V_{21}}{\sqrt{R^2+(2\pi f_{21} L)^2}} = \frac{164}{\sqrt{10^2+(2\pi(1050)(10x10^{-3}))^2}} = 2.458$ [0.5]

f=1150 Hz

$I_{21} = \frac{V_{21}}{\sqrt{R^2+(2\pi f_{21} L)^2}} = \frac{44}{\sqrt{10^2+(2\pi(1150)(10x10^{-3}))^2}} = 0.603$ [0.5]

2.8 Determine the THD of the load current **[2]**

Ans:

$$THD_i = \frac{\sqrt{\sum_{n=2}^{\infty} I_{n,rms}^2}}{I_{1,rms}} = \frac{\sqrt{(0.727/\sqrt{2})^2+(2.458/\sqrt{2})^2+(0.603/\sqrt{2})^2}}{(15.26/\sqrt{2})} = \frac{1.862}{10.79} = 0.173 = 17.26\%$$

[0.25] mark identifying each rms component – [0.25]x4 = [1] mark
[1] mark for the correct answer.

A variable dc voltage source (V_d) is connected to the buck-boost converter as shown in Fig.1. The output voltage across the resistive load R is maintained at -12 V by varying the duty cycle (D) of the converter between 0.46 and 0.545. The power rating of the resistor (R) is 15 W. The inductance of L is 1.25 times the value of the inductance required to ensure the converter's continuous conduction. The switching frequency of the converter is 50 kHz. The output voltage ripple (ΔV_o) must be less than 1 percent of the output voltage. Answer the following questions:

1.1. Determine the voltage range of the variable dc voltage source (V_d) **[1]**

Ans:

$$D = \frac{|V_0|}{V_d+|V_0|}$$

$$0.545 = \frac{12}{V_d+12}$$ [0.5]

$$V_d = 10\ V$$

$$0.46 = \frac{|V_0|}{V_d+|V_0|} = \frac{12}{V_d+12}$$ [0.5]

$$V_d = 14\ V$$

$$10 \leq V_d \leq 14$$

1.2. Determine all the possible values of inductors and propose the best inductor for the buck-boost converter. **[3]**

Ans:

$$R = \frac{V^2}{P} = \frac{(-12)^2}{15} = 9.6\ \Omega$$ [0.5]

$$(\mathrm{L})_{\mathrm{D_1 min}} = \frac{(1-\mathrm{D})^2\mathrm{R}}{2\mathrm{f}} = \frac{(1-0.545)^2 9.6}{2(50000)} = 19.87\ \mu\mathrm{H}$$ [0.5]

$$(\mathrm{L})_{\mathrm{D_1}} = 1.25(\mathrm{L})_{\mathrm{D_1 min}} = 24.84\ \mu\mathrm{H}$$ [0.5]

$$(\mathrm{L})_{\mathrm{D_2 min}} = \frac{(1-\mathrm{D})^2\mathrm{R}}{2\mathrm{f}} = \frac{(1-0.46)^2 9.6}{2(50000)} = 27.99\ \mu\mathrm{H}$$ [0.5]

$$(\mathrm{L})_{\mathrm{D_2}} = 1.25(\mathrm{L})_{\mathrm{D_2 min}} = 34.99\ \mu\mathrm{H}$$ [0.5]

The best inductor for the above circuit should have an inductance greater than $34.99\ \mu H$. [0.5]

1.3. Determine the possible values of capacitors and propose the best capacitor for the buck-boost converter. **[2]**

Ans:

$\Delta V_0 = 1\% * 12 = 0.12$ V [0.5]

$C_{D_1} = \frac{D}{R\left(\frac{\Delta V_0}{V_0}\right)f} = \frac{0.545}{9.6\left(\frac{0.12}{12}\right)50000} = 113.5\ \mu F$ [0.5]

$C_{D_1} = \frac{D}{R\left(\frac{\Delta V_0}{V_0}\right)f} = \frac{0.46}{9.6\left(\frac{0.12}{12}\right)50000} = 95.8\ \mu F$ [0.5]

The best capacitor for the above circuit should have a capacitance greater than 113.5 μF. [0.5]

1.4. Name one similarity between the buck-boost converter and the Cuk converter. **[1]**

Ans:

The output voltage is negative with respect to the input voltage. [1]

QUESTION 2 [8 MARKS]

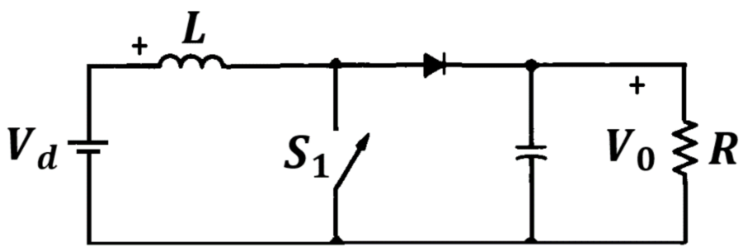


Fig. 2

The boost converter in **Fig. 2** is required to have an output voltage of 8V and supply a load current of 1A through the R. The switching frequency of the converter is 100 kHz. The input voltage varies from 2.7 to 4.2 V. A control circuit adjusts the duty ratio (**D**) to keep the output voltage constant.

2.1. Determine a value for the inductor indicating reasons for your selection to ensure the variation in inductor current is no more than 45 percent of the average inductor current for all operating conditions. Assume continuous conduction mode of operation. **[6]**

Ans:

For $V_s = 2.7$

$D = 1 - \frac{V_s}{V_0} = 1 - \frac{2.7}{8} = 0.663$ [0.5]

Average inductor current

$I_L = \frac{V_0 I_0}{V_s} = \frac{8(1)}{2.7} = 2.96\ A$ [0.5]

Variation of inductor current to meet 45% specification is

$\Delta i_L = 0.45(2.96) = 1.332\ A$ [0.5]

Determine the inductance

$$L = \frac{V_S D}{\Delta i_L f} = \frac{2.7(0.663)}{1.332(100{,}000)} = 13.44\mu H \qquad [1]$$

Repeating the calculations for $V_s = 4.2$

$$D = 1 - \frac{V_s}{V_0} = 1 - \frac{4.2}{8} = 0.475 \qquad [0.5]$$

Average inductor current

$$I_L = \frac{V_0 I_0}{V_s} = \frac{8(1)}{4.2} = 1.90\ A \qquad [0.5]$$

Variation of inductor current to meet 45% specification is

$$\Delta i_L = 0.45(1.90) = 0.855\ A \qquad [0.5]$$

Determine the inductance

$$L = \frac{V_S D}{\Delta i_L f} = \frac{4.2(0.475)}{0.855(100{,}000)} = 23.33\mu H \qquad [1]$$

Inductor must be at least $23.33\mu H$ to satisfy the specification for the total range of input voltages. [1]

2.2. Determine a value for an ideal capacitor such that the output voltage ripple is no more than 1 percent. **[2]**

The highest duty cycle must be selected! D=0.663 [1/2] mark

$$C = \frac{D}{R(\Delta V_0/V_0)f} = \frac{D}{(V_0/I_0)(\Delta V_0/V_0)f} = \frac{0.663}{(8/1)(0.01)100000} = 82.88\ \mu F$$

[1/2] mark for the calculation of R in the above equation and [1] mark for the value of C.