1. You probably figured this one out :)

2. 1 kW, 100 V output step-up converter is to be evaluated. Consider all the components to be ideal. The input voltage is Vd = 48 V, and the switching frequency is $f_{\text{sw}} = 80\,\text{kHz}$

   (a) **Calculate the output capacitor C when the output voltage peak-to-peak ripple is 5% of the output voltage $V_{\text{o}} = 100\,\text{V}$.**

   The duty cycle (D) is given by

$$D = 1 - \frac{V_{\text{d}}}{V_{\text{o}}} = 1 - \frac{48}{100} = \mathbf{0.52}.$$

   The input current (I_{d}) is

$$I_{\text{d}} = \frac{P}{V_{\text{d}}} = \frac{1000}{48} = \mathbf{20.83\,A}.$$

   Since all the components are assumed to be ideal, the input and output powers are identical. Therefore, the output current (I_{o}) is

$$I_{\text{o}} = \frac{P}{V_o} = \frac{1000}{100} = \mathbf{10\,A}$$

   the output capacitor (C) when the output voltage peak-to-peak ripple is 5% of the output voltage $V_{\text{o}} = 100\,\text{V}$ is

$$C = \frac{I_{\text{o}}\,D}{\Delta V_{\text{o}}\,f_{\text{sw}}} = \frac{10 \times 0.52}{0.05 \times 100 \times 80 \times 10^3} = \mathbf{13\,\mu F}.$$

   (b) **Consider filter inductance $L = 40\,\mu\text{H}$, calculate $I_{\mathbf{L(peak)}}$. Is the converter in continuous conduction mode?**

   The peak-to-peak ripple input (or inductor) current is

$$\Delta I_d = \frac{D\,V_{\text{o}}}{L\,f_{\text{sw}}}(1-D) = \frac{0.52 \times 100}{40 \times 10^{-6} \times 80 \times 10^3} \times (1 - 0.52) = \mathbf{7.8\,A}.$$

   The maximum and minimum values of the inductor current ($I_{\text{d}}^{\text{max}}$ and $I_{\text{d}}^{\text{min}}$, respectively) are

$$I_{\text{d}}^{\text{max}} = I_{\text{d}} + \frac{\delta I_{\text{d}}}{2} = \mathbf{24.73\,A}$$
$$I_{\text{d}}^{\text{min}} = I_{\text{d}} - \frac{\delta I_{\text{d}}}{2} = \mathbf{16.93\,A}$$

   Since, $I_{\text{d}}^{\text{min}} > 0$, the converter is in continuous conduction mode.

   (c) **Consider filter inductance $\mathbf{L} = \mathbf{6}\,\mu\mathbf{H}$, calculate $I_{\mathbf{L(peak)}}$. Is the converter in continuous conduction mode?**

   The peak-to-peak ripple input (or inductor) current is

$$\Delta I_d = \frac{D\,V_{\text{o}}}{L\,f_{\text{sw}}}(1-D) = \frac{0.52 \times 100}{6 \times 10^{-6} \times 80 \times 10^3} \times (1 - 0.52) = \mathbf{52\,A}.$$

   The maximum and minimum values of the inductor current ($I_{\text{d}}^{\text{max}}$ and $I_{\text{d}}^{\text{min}}$, respectively) are

$$I_{\text{d}}^{\text{max}} = I_{\text{d}} + \frac{\delta I_{\text{d}}}{2} = \mathbf{46.83\,A}$$
$$I_{\text{d}}^{\text{min}} = I_{\text{d}} - \frac{\delta I_{\text{d}}}{2} = \mathbf{-5.17\,A}$$

   Since, $I_{\text{d}}^{\text{min}} < 0$, the converter is **not** in continuous conduction mode.

   (d) **Determine the conduction losses of the MOSFET if the on-state resistance of the MOSFET is 1 mΩ.**

   The conduction losses of the MOSFET is

$$P_{\text{mos}}^{l} = D\,I_{\text{d}}^2\,R_{\text{ds(on)}} = 0.52 \times (20.83)^2 \times 1 \times 10^{-3} = \mathbf{0.23}\,\text{W}$$

3. An n-channel power MOSFET, IPD023N04NF2S by Infineon, is to be used in a step-down converter (*datasheet is attached*). The MOSFET conducts an RMS current of 100 A. The switching frequency is 10 kHz, the duty cycle (D) is 0.75 and the input voltage of the converter is 20 V.

   (a) **Calculate the total MOSFET power losses (assume the same time for voltage and current transients, i.e., $t_{\mathbf{ri}} = t_{\mathbf{fv}} = t_{\mathbf{r}}$ and $t_{\mathbf{fi}} = t_{\mathbf{rv}} = t_{\mathbf{f}}$).**

   From the MOSFET datasheets, the on-state resistance of the MOSFET ($r_{ds(\text{on})}$) and the switching transient times are

$$r_{ds(\text{on})} = 2.3\,\text{m}\Omega \qquad t_{ri} = t_{fv} = 15\,\text{ns}, \qquad t_{rv} = t_{fi} = 15\,\text{ns}.$$

   The conduction losses of the MOSFET (P_c^l) is

$$P_c^l = D\,I_{\text{mos}}^2\,r_{ds(\text{on})} = 0.5 \times 100^2 \times 2.3 \times 10^{-3} = \mathbf{11.5\,W}.$$

   In the DC-DC converter the peak MOSFET current ($\hat{I}_{\text{mos}}$) is

$$\hat{I}_{\text{mos}} = \frac{I_{\text{mos}}}{D} = \frac{100}{0.75} = \mathbf{133.33\,A}.$$

   The switching losses of the MOSFET (P_s^l) is

$$\begin{aligned} P_s^l &= \frac{1}{2}\,V_{\text{d}}\,\hat{I}_{\text{mos}}\,t_{\text{sw}}\,f_{\text{sw}} = \frac{1}{2}\,V_{\text{d}}\,\hat{I}_{\text{mos}}\,(t_{ri} + t_{fv} + t_{rv} + t_{fi})\,f_{\text{sw}} \\ &= \frac{1}{2} \times 20 \times 133.33 \times \left(2 \times 15 \times 10^{-9} + 2 \times 15 \times 10^{-9}\right) \times 10 \times 10^3 = \mathbf{80\,mW}. \end{aligned}$$

   The total losses in the MOSET (P^l) is

$$P^l = P_c^l + P_s^l = 11.5 + 0.08 = \mathbf{11.58\,W}.$$

   (b) **If the internal junction temperature is not to exceed 100°C and the maximum ambient temperature is 35°C, specify the thermal resistance of the required heat sink.**

   The thermal resistance of the required heat sink is

$$\begin{aligned} \Delta T_{\text{ja}} = P^l\,(R_{\theta\text{jc}} + R_{\theta\text{ca}}) \implies R_{\theta\text{ca}} = \frac{\Delta T_{\text{ja}}}{P^l} - R_{\theta\text{jc}} \\ \implies R_{\theta\text{ca}} = \frac{100 - 35}{11.5} - 1 = \mathbf{4.61\,K/W}. \end{aligned}$$

   (c) **Determine the peak MOSFET drain-to-source voltage during the turn-off transient if the parasitic inductance between the input voltage source and the MOSFET drain-terminal is 3 nH.**

   The voltage across the MOSFET during the turn-off transient is

$$V_{\text{ds}}^{\max} = V_{\text{d}} - L\,\frac{dV_{\text{ds}}}{dt} = 20 - 3 \times 10^{-9} \times \frac{0 - 100}{15 \times 10^{-9}} = \mathbf{40\,V}.$$

1 Maximum ratings

at T_A=25 °C, unless otherwise specified

Table 2 Maximum ratings

Parameter	Symbol	Values			Unit	Note / Test Condition
		Min.	Typ.	Max.		
Continuous drain current[1]	I_D	- - -	- - -	143 110 27	A	V_{GS}=10 V, T_C=25 °C V_{GS}=10 V, T_C=100 °C V_{GS}=10 V, T_A=25 °C, R_{THJA}=50 °C/W[2]
Pulsed drain current[3]	$I_{D,pulse}$	-	-	572	A	T_A=25 °C
Avalanche energy, single pulse[4]	E_{AS}	-	-	167	mJ	I_D=70 A, R_{GS}=25 Ω
Gate source voltage	V_{GS}	-20	-	20	V	-
Power dissipation	P_{tot}	- -	- -	150 3.0	W	T_C=25 °C T_A=25 °C, R_{THJA}=50 °C/W[2]
Operating and storage temperature	T_j, T_{stg}	-55	-	175	°C	-

2 Thermal characteristics

Table 3 Thermal characteristics

Parameter	Symbol	Values			Unit	Note / Test Condition
		Min.	Typ.	Max.		
Thermal resistance, junction - case	R_{thJC}	-	-	1.0	°C/W	-
Thermal resistance, junction - ambient, 6 cm² cooling area[2]	R_{thJA}	-	-	50	°C/W	-
Thermal resistance, junction - ambient, minimal footprint	R_{thJA}	-	-	75	°C/W	-

[1] Rating refers to the product only with datasheet specified absolute maximum values, maintaining case temperature as specified. For other case temperatures please refer to Diagram 2. De-rating will be required based on the actual environmental conditions.
[2] Device on 40 mm x 40 mm x 1.5 mm epoxy PCB FR4 with 6 cm² (one layer, 70 µm thick) copper area for drain connection. PCB is vertical in still air.
[3] See Diagram 3 for more detailed information
[4] See Diagram 13 for more detailed information

3 Electrical characteristics

at T_j=25 °C, unless otherwise specified

Table 4 Static characteristics

Parameter	Symbol	Values			Unit	Note / Test Condition
		Min.	Typ.	Max.		
Drain-source breakdown voltage	$V_{(BR)DSS}$	40	-	-	V	V_{GS}=0 V, I_D=1 mA
Gate threshold voltage	$V_{GS(th)}$	2.2	2.8	3.4	V	V_{DS}=V_{GS}, I_D=81 µA
Zero gate voltage drain current	I_{DSS}	- -	0.1 10	1 100	µA	V_{DS}=40 V, V_{GS}=0 V, T_j=25 °C V_{DS}=40 V, V_{GS}=0 V, T_j=125 °C
Gate-source leakage current	I_{GSS}	-	10	100	nA	V_{GS}=20 V, V_{DS}=0 V
Drain-source on-state resistance	$R_{DS(on)}$	- -	1.9 2.2	2.3 3.1	mΩ	V_{GS}=10 V, I_D=70 A V_{GS}=6 V, I_D=35 A
Gate resistance	R_G	-	3.0	-	Ω	-
Transconductance[1]	g_{fs}	125	-	-	S	$\lvert V_{DS}\rvert \geq 2\lvert I_D\rvert R_{DS(on)max}$, I_D=70 A

Table 5 Dynamic characteristics

Parameter	Symbol	Values			Unit	Note / Test Condition
		Min.	Typ.	Max.		
Input capacitance	C_{iss}	-	4800	-	pF	V_{GS}=0 V, V_{DS}=20 V, f=1 MHz
Output capacitance	C_{oss}	-	1800	-	pF	V_{GS}=0 V, V_{DS}=20 V, f=1 MHz
Reverse transfer capacitance	C_{rss}	-	98	-	pF	V_{GS}=0 V, V_{DS}=20 V, f=1 MHz
Turn-on delay time	$t_{d(on)}$	-	16	-	ns	V_{DD}=20 V, V_{GS}=10 V, I_D=70 A, $R_{G,ext}$=1.6 Ω
Rise time	t_r	-	15	-	ns	V_{DD}=20 V, V_{GS}=10 V, I_D=70 A, $R_{G,ext}$=1.6 Ω
Turn-off delay time	$t_{d(off)}$	-	35	-	ns	V_{DD}=20 V, V_{GS}=10 V, I_D=70 A, $R_{G,ext}$=1.6 Ω
Fall time	t_f	-	15	-	ns	V_{DD}=20 V, V_{GS}=10 V, I_D=70 A, $R_{G,ext}$=1.6 Ω

Table 6 Gate charge characteristics[2]

Parameter	Symbol	Values			Unit	Note / Test Condition
		Min.	Typ.	Max.		
Gate to source charge	Q_{gs}	-	21	-	nC	V_{DD}=20 V, I_D=70 A, V_{GS}=0 to 10 V
Gate charge at threshold	$Q_{g(th)}$	-	13.5	-	nC	V_{DD}=20 V, I_D=70 A, V_{GS}=0 to 10 V
Gate to drain charge	Q_{gd}	-	13	-	nC	V_{DD}=20 V, I_D=70 A, V_{GS}=0 to 10 V
Switching charge	Q_{sw}	-	20	-	nC	V_{DD}=20 V, I_D=70 A, V_{GS}=0 to 10 V
Gate charge total[1]	Q_g	-	68	102	nC	V_{DD}=20 V, I_D=70 A, V_{GS}=0 to 10 V
Gate plateau voltage	$V_{plateau}$	-	4.3	-	V	V_{DD}=20 V, I_D=70 A, V_{GS}=0 to 10 V
Gate charge total, sync. FET	$Q_{g(sync)}$	-	61	-	nC	V_{DS}=0.1 V, V_{GS}=0 to 10 V
Output charge	Q_{oss}	-	76	-	nC	V_{DS}=20 V, V_{GS}=0 V

[1] Defined by design. Not subject to production test.
[2] See ″Gate charge waveforms″ for parameter definition

4. The output voltages and current of a single-phase full-bridge inverter are shown in Figure 1.

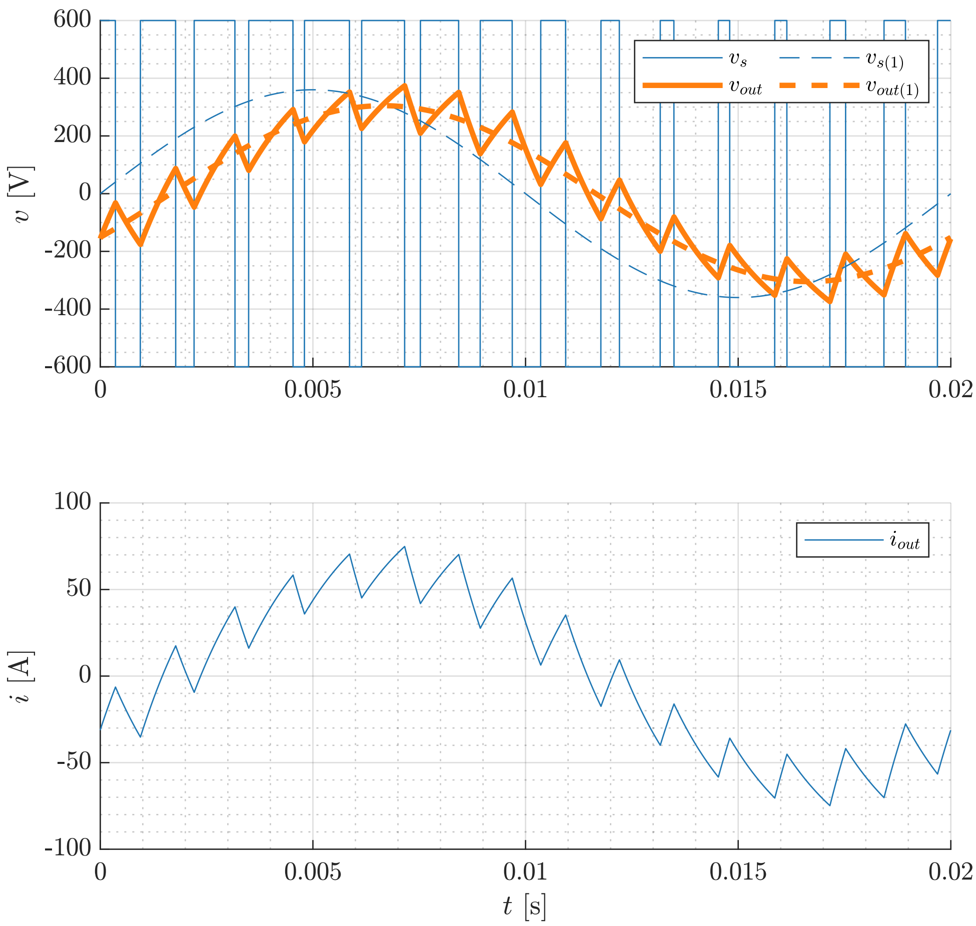


Figure 1: full-bridge inverter output waveforms.

(a) **Type of modulation (unipolar or bipolar).**
Bipolar modulation.

(b) **Switching frequency**
Counting the number of positive/negative pulses (or, rising/falling edges) for v_s in Figure 1, gives

$$m_f = 15.$$

Since m_f is defined as

$$m_f = \frac{f_{sw}}{f_1} \qquad \Longrightarrow \; f_{sw} = m_f \, f_1,$$

where f_1 is the fundamental frequency, and from Figure 1

$$f_1 = \frac{1}{0.02\,\text{s}} = 50\,\text{Hz}.$$

Therefore,

$$f_{sw} = m_f \, f_1 = 15 \times 50 = \mathbf{750\,Hz}.$$

(c) **Inductance.**
From Figure 1, during the time interval $t \in [0.005, 0.006]\,\mathrm{s}$, the $v_s = 600\,\mathrm{V}$ and for simplicity the voltage after the inductor v_{out} is about 275 V. Then the voltage drop across the inductor is

$$V_L = (v_{out}(t) - v_s(t))\Big|_{t\in[0.005,0.006]} = L\frac{di(t)}{dt}\Big|_{t\in[0.005,0.006]}$$

$$\implies L = \frac{v_{out}(t) - v_s(t)}{\frac{di}{dt}}\Big|_{t\in[0.005,0.006]}.$$

$dt = 0.006\,\mathrm{s} - 0.005\,\mathrm{s}$, and from Figure 1, $di = 70\,\mathrm{A} - 38\,\mathrm{A} = 32\,\mathrm{A}$. Therefore the inductance, L is

$$L = \frac{600 - 275}{\frac{32}{0.001}} = \mathbf{10.2\,mH}.$$

(d) **Peak fundamental current.**
The peak fundamental output current occurs at $0.006\,\mathrm{s} \le t \le 0.007\,\mathrm{s}$. The average current in this interval is the peak Fundamental output current ($\hat{i}_{out(1)}$)

$$\hat{i}_{out(1)} = \frac{45 + 75}{2} = \mathbf{60\,A}.$$

(e) **Pole-to-pole DC-link voltage (V_d) and modulation index (m_a).**
In the full-bridge inverter, the pole-to-pole DC-link voltage (V_d) is

$$V_d = \hat{v}_s = 600\,\mathrm{V}.$$

The modulation index (m_a) is

$$m_a = \frac{\hat{v}_{s(1)}}{V_d} = \frac{360}{600} = \mathbf{0.6}.$$

(f) **Active power on the load at the fundamental frequency.**
The active power on the load (P_{out}) at the fundamental frequency is

$$P_{out} = \frac{\hat{v}_{out(1)}\,\hat{i}_{out(1)}}{2} = \frac{300 \times 60}{2} = \mathbf{9}\,\mathrm{kW}.$$

(g) **Phase angle of the fundamental current with respect to the inverter side voltage.**
At time $t = 0\,\mathrm{s}$ the reference signal (fundamental converter output voltage) is 0 V thus the converter output voltage (v_s) is also assumed to be 0 V. However, the fundamental load current (or voltage) is 0 A (or 0 V) at $t = 0.0017\,\mathrm{s}$. The time delay (δt) is

$$\delta t = 0.0017\,\mathrm{s}.$$

If time $t = T = 0.02\,\mathrm{s}$ is 2π, then at time $t = \delta t$, the phase angle (ϕ) is

$$\phi = \frac{\delta t}{T}\,2\,\pi = \frac{0.0017}{0.02} \times 2 \times \pi = \mathbf{30.6^\circ}.$$

(h) **Active and reactive power on the converter at the fundamental frequency.**
The active power (P_s) on the converter side is

$$P_s = \frac{\hat{v}_{s(1)}\,\hat{i}_{out(1)}}{2}\,\cos(\phi) = \frac{360 \times 60}{2}\,\cos(30.6^\circ) = \mathbf{9.3\,kW}.$$

The reactive power (Q_s) on the converter side is

$$Q_s = \frac{\hat{v}_{s(1)}\,\hat{i}_{out(1)}}{2}\,\sin(\phi) = \frac{360 \times 60}{2}\,\sin(30.6^\circ) = \mathbf{5.5\,kVar}.$$

5. For a full-bridge inverter with unipolar modulation, the RMS fundamental (at 150 Hz) output voltage and current are 1 kV and 180 A respectively. The inverter incorporates a filter inductor with inductance 100 μH and it operates with a modulation index of 0.8 with a switching frequency of 10 kHz.

Table 1: Generalized harmonics of a half-bridge inverter output voltage for a large m_f.

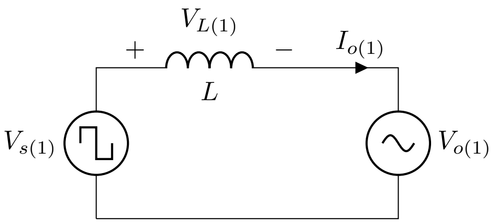
$h \downarrow \quad m_a \rightarrow$	0.2	0.4	0.6	0.8	1
1 Fundamental	0.2	0.4	0.6	0.8	1
m_f	1.242	1.15	1.006	0.818	0.6023
$m_f \pm 2$	0.061	0.061	0.131	0.22	0.318
$m_f \pm 4$					0.018
$2m_f \pm 1$	0.19	0.326	0.37	0.314	0.181
$2m_f \pm 3$		0.024	0.071	0.139	0.212
$2m_f \pm 5$				0.013	0.033
$3m_f$	0.335	0.123	0.083	0.171	0.133
$3m_f \pm 2$	0.044	0.139	0.203	0.176	0.062
$3m_f \pm 4$		0.012	0.047	0.104	0.157
$3m_f \pm 6$				0.016	0.044
$4m_f \pm 1$	0.163	0.157	0.088	0.105	0.068
$4m_f \pm 3$	0.012	0.070	0.132	0.115	0.009
$4m_f \pm 5$			0.034	0.084	0.119
$4m_f \pm 7$				0.017	0.05

Note: output voltage ($\hat{V}_o$) is $\hat{V}_o = m_a\, V_d/2$.

Note: Ripple here is referred to as distortion, which is the alteration of the original shape of a signal. Here ripple means the alteration of the waveform from an ideal sinusoidal signal.

(a) **Determine the dc-link voltage of the inverter**

The equivalent circuit at the fundamental frequency is given as



The peak fundamental converter voltage ($V_{s(1)}$) is determined using KVL, i.e.,

$$V_{s(1)} = V_{o(1)} + I_{o(1)}\,\omega_1\,L = 1000 - 180 \times 2 \times \pi \times 150 \times 100 \times -6 = \mathbf{1094.2\,V}$$

The peak fundamental converter output votlage ($\hat{V}_{s(1)}$) is

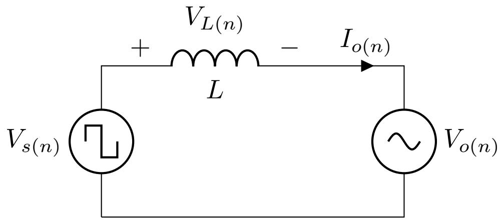
$$\hat{V}_{s(1)} = \sqrt{2}\,V_{s(1)} = \sqrt{2} \times 1094.2 = \mathbf{1547.4\,V}.$$

The DC-link voltage is calculated as

$$V_{\text{d}} = \frac{\hat{V}_{s(1)}}{m_a} = \frac{1547.5}{0.8} = \mathbf{1934.4\,V}.$$

(b) **Calculate the magnitude (in RMS) and frequency of the largest component of the output current for a modulation index of 0.8. Assume that the magnitude of all the other components of the output voltage is zero.**

The equivalent circuit at the n^{th} harmonic, where $n \neq 1$ is



The RMS output output voltage at the n^{th} harmonic ($V_{o(n)}$) is

$$V_{o(n)} = V_{s(n)} - I\,\omega_n\,L. \tag{1}$$

From Table 1, the highest harmonic component for uni-polar modulation is at $2\,m_f \pm 1$, i.e.,

$$V_{s(2\,m_f \pm 1)} = 0.314\,\frac{V_{\text{d}}}{\sqrt{2}} = 0.314 \times \frac{1934.4}{\sqrt{2}} = \mathbf{429.5\,V},$$

and

$$m_f = \frac{f_{\text{sw}}}{f_1} = \frac{10 \times 10^3}{150} = \mathbf{66.67}.$$

The output current at the n^{th} harmonic ($I_{o(n)}$), from (1) is

$$I_{o(n)} = \frac{V_{s(n)} - V_{o(n)}}{\omega_n\,L} = \frac{429.5 - 0}{2\pi \times (n) \times 150 \times 1 \times 100^{-6}}$$

. Substituting, $n = 2\,m_f \pm 1$,

$$I_{o(2\,m_f+1)} = \mathbf{33.92\,A}, \qquad \text{and,}\ I_{o(2\,m_f-1)} = \mathbf{34.44\,A}.$$

The highest harmonic component of the output current occurs at $2\,m_f - 1$, i.e., at **19.85 kHz** with a magnitude of **34.44 A**.