Examination	**ENM060 Power Electronic Converters**
Date and time	Monday January 12th, 2015, 14:00 – 18:00
Responsible Teacher:	Andreas Karvonen, tel. 0709-524924
Authorised Aids:	Chalmers-approved calculator (Casio FX82..., Texas Instruments Ti30... and Sharp ELW531...)
Grades:	U, 3, 4 or 5. (The limit for a 3 on the exam is 20p, a 4 is 30p and 5 is 40p. The maximum number of points is 50.)
Solutions:	Course webpage (Ping-Pong), January 13th 2015
Review of Exam	February 5th and February 11th, 12:00-13:00. Uno Lamms Room. Division of Electric Power Engineering (2nd floor). From February 12th 2015, the exams can be picked-up at the student office at the department of Energy and Environment. Location: EDIT building, Maskingränd 2, 3Ö (east) floor, room 3434A. Opening hours during semesters: Monday-Friday 12:30-14:30

Observe that the questions are not arranged in any kind of order.

On the last pages there are some formulas that can be used in the examination. Always assume steady-state conditions in all tasks unless otherwise stated.

Please, read through the exam before you start.

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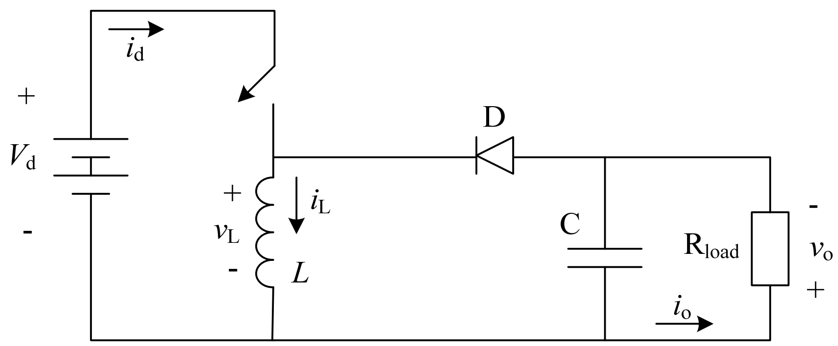
1) **Consider the ideal buck/boost converter below. Derive the input/output voltage ratio for CCM. A complete derivation is needed; just writing down the final expression gives zero points. (2p)**

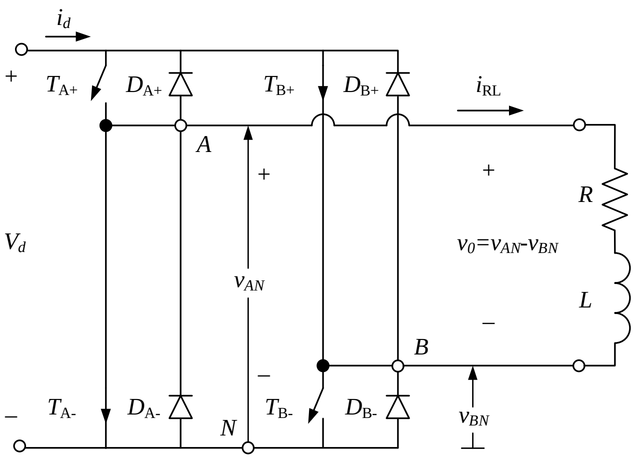


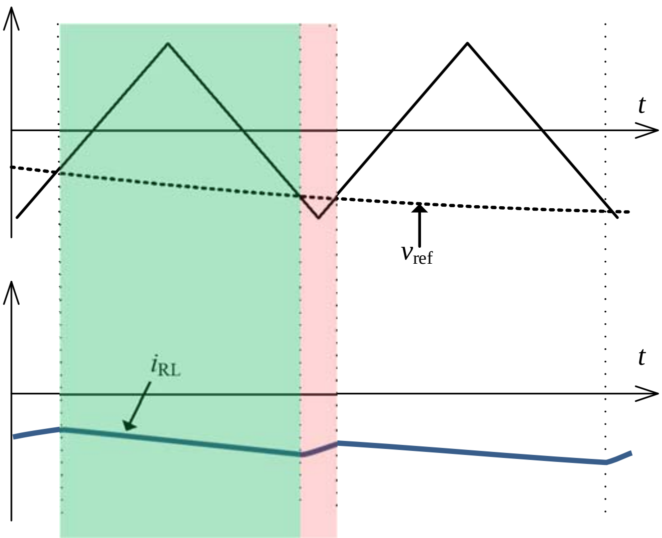
$V_d = 9V$ $\quad V_o = 24V$ $\quad f_{sw} = 100kHz$ $\quad C = 470\mu F$ $\quad I_o = 2.5A$ $\quad L = 63\mu H$

2) **For the buck/boost converter in question (1), an LC-filter is applied to the input that smoothens the current drawn from the DC-source. Calculate the power dissipation in the input filter capacitor if $R_{ESR} = 120m\Omega$. Assume that the input filter is sufficiently large so that the current from the DC-source is a pure DC-current. (5p)**

3) **For the boost converter in (1), draw a graph of V_o/V_d as a function of the duty-cycle (D) with and without ideal components. Also, explain why the two graphs differ. (3p)**

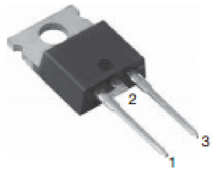
4) **The single phase inverter below is operating with PWM bipolar switching. For the specified time instant below (v_{ref} and i_{RL} are given), draw the resulting voltage over the load (v_0) and the current drawn from the source (i_d). Also mark the current paths during the two shaded time intervals. (4p)**



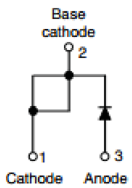


5) **The single phase inverter in (4) is operated in square wave mode ($V_d = 200V$ and 50Hz). Calculate the resulting temperature rise in diode D_{B-} if the load is purely inductive. The output current is assumed to have a peak value of 50A and the diode is mounted to a heat-sink with $R_{thSA} = 4.9°C/W$. The datasheet for the diode is attached below. (5p)**

Fast Soft Recovery Rectifier Diode, 20 A



TO-220AC



FEATURES

- 150 °C max operating junction temperature
- Low forward voltage drop and short reverse recovery time
- Designed and qualified according to JEDEC-JESD47
- Material categorization:
  For definitions of compliance please see www.vishay.com/doc?99912

RoHS COMPLIANT HALOGEN FREE

PRODUCT SUMMARY	
Package	TO-220AC
$I_{F(AV)}$	20 A
V_R	800 V, 1000 V, 1200 V
V_F at I_F	1.31 V
I_{FSM}	320 A
t_{rr}	95 ns
T_J max.	150 °C
Diode variation	Single die
Snap factor	0.6

APPLICATIONS

These devices are intended for use in output rectification and freewheeling in inverters, choppers and converters as well as in input rectification where severe restrictions on conducted EMI should be met.

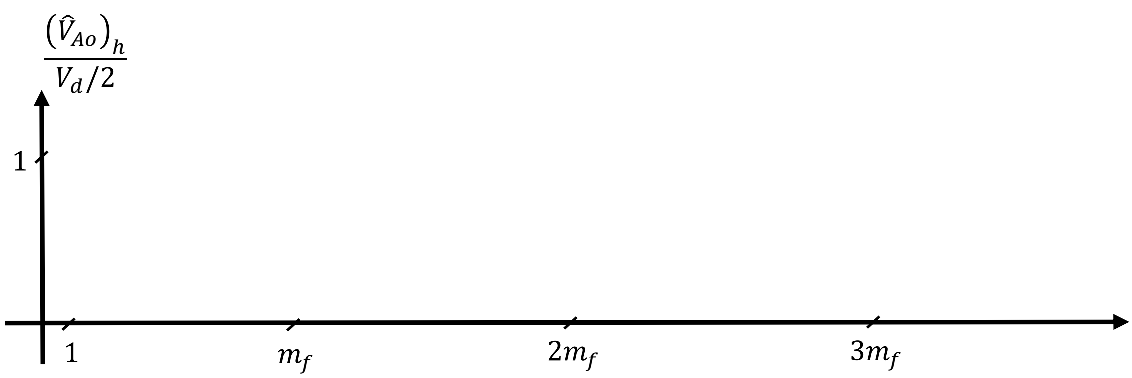
DESCRIPTION

The VS-20ETF... fast soft recovery rectifier series has been optimized for combined short reverse recovery time and low forward voltage drop.

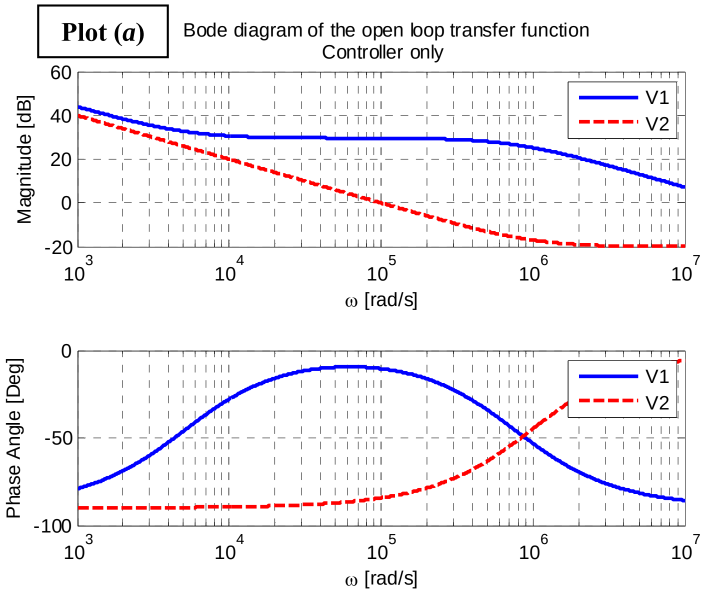
The glass passivation ensures stable reliable operation in the most severe temperature and power cycling conditions.

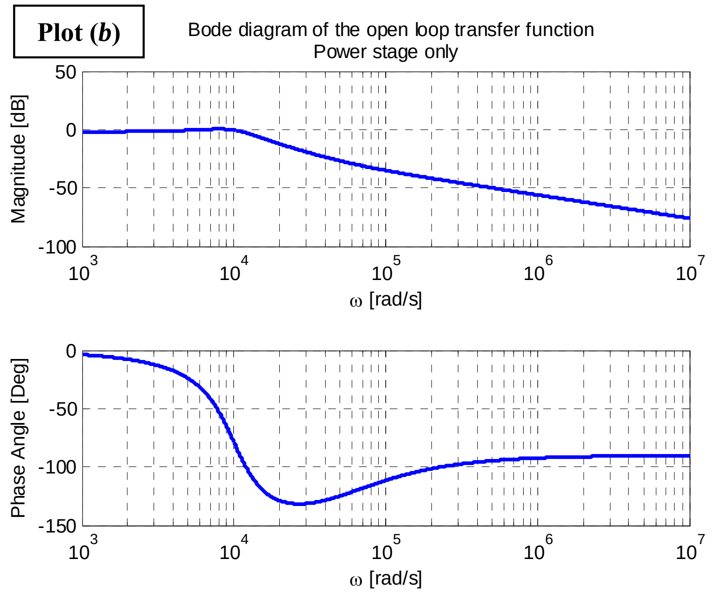
THERMAL - MECHANICAL SPECIFICATIONS					
PARAMETER		SYMBOL	TEST CONDITIONS	VALUES	UNITS
Maximum junction and storage temperature range		T_J, T_{Stg}		- 40 to 150	°C
Maximum thermal resistance, junction to case		R_{thJC}	DC operation	0.9	°C/W
Maximum thermal resistance, junction to ambient		R_{thJA}		62	
Typical thermal resistance, case to heatsink		R_{thCS}	Mounting surface, smooth and greased	0.5	
Approximate weight				2	g
				0.07	oz.
Mounting torque	minimum			6 (5)	kgf · cm (lbf · in)
	maximum			12 (10)	
Marking device			Case style TO-220AC	20ETF08 20ETF10 20ETF12	

6) **For the single phase inverter in (4), sketch the harmonic spectrum of the output voltage for $m_a = 0.8$ and $m_f = 15$. Mark the amplitudes for the specified frequencies (and sidebands) in the diagram. (4p)**

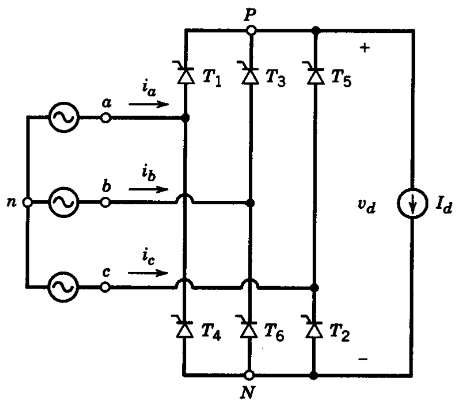


7) **The bode-plots below represent the transfer function of the power stage of a buck converter (plot (*a*)) and the transfer functions of two different controller structures (plot (*b*)). Which controller (V1 or V2) is best to use for the converter in plot (*b*)? Sketch the resulting transfer functions of the controller and the power stage and explain which controller shall be used. Empty bode plots can be found at the end of the exam. (4p)**





8) **A three-phase thyristor rectifier (inverter) is loaded with a constant DC-side current ($I_d = 75A$). The phase voltages are $260V_{(RMS)}$ and the resulting average DC-side voltage is $V_d = 370V$. Draw the phase voltage (v_a), the resulting line current (i_a) and calculate its RMS-value. (3p)**



9) **For the thyristor rectifier in (7), derive an expression for the resulting DC-link voltage as a function of known quantities. Also, calculate the needed delay angle (α) to obtain the specified DC-link voltage (5p)**

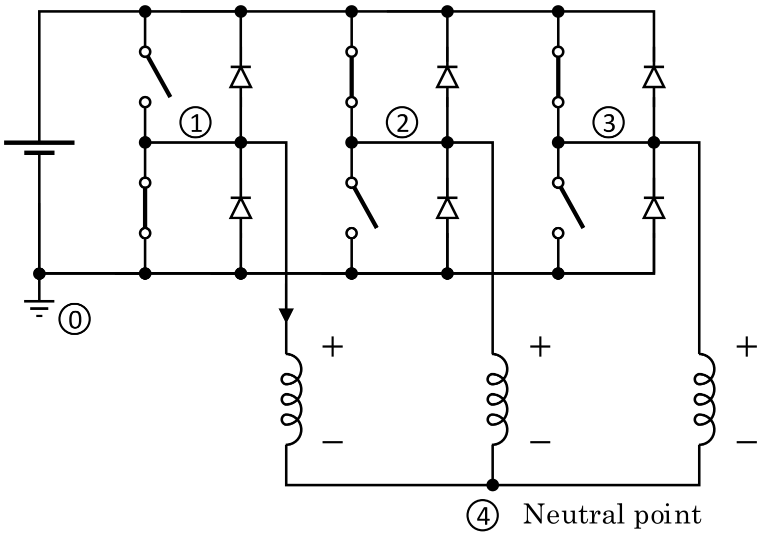
10) **If the thyristor rectifier in (7) is operated with zero delay angle ($\alpha = 0°$), calculate the fundamental frequency component in the line current and the resulting power factor (PF). Why does the rectifier consume reactive power? (4p)**

11) If the source inductance is taken into account in the rectifier in (7), draw the line currents in two phases during the commutation, e.g. phase c (i_5) and phase a (i_1). How will the commutation affect the PF and/or the DPF of the rectifier? (3p)

12) In a flyback converter, the transformer has a primary magnetizing inductance of $100\mu H$. Calculate the air-gap length needed to decrease the inductance to $50\mu H$. Explain also why an air-gap is needed in the transformer. (4p)

Mean path length (l_m): $2\pi\ cm$
Cross sectional area (A_m): $1cm^2$
Turns ratio: $N_1 : N_2 : N_3 = 40 : 40 : 40$ turns.

13) The three phase inverter below is operating with square wave mode. Draw the resulting voltages in the midpoint of each phase leg (v_{1-0}, v_{2-0} and v_{3-0}) and the neutral point voltage (v_{4-0}). (4p)



Formulas for Examination in Power Electronic Converters (ENM060)

Table 3-1 Use of Symmetry in Fourier Analysis

Symmetry	*Condition Required*	a_h and b_h
Even	$f(-t) = f(t)$	$b_h = 0 \quad a_h = \frac{2}{\pi}\int_0^{\pi} f(t)\cos(h\omega t)\, d(\omega t)$
Odd	$f(-t) = -f(t)$	$a_h = 0 \quad b_h = \frac{2}{\pi}\int_0^{\pi} f(t)\sin(h\omega t)\, d(\omega t)$
Half-wave	$f(t) = -f(t + \frac{1}{2}T)$	$a_h = b_h = 0$ for even h $a_h = \frac{2}{\pi}\int_0^{\pi} f(t)\cos(h\omega t)\, d(\omega t)$ for odd h $b_h = \frac{2}{\pi}\int_0^{\pi} f(t)\sin(h\omega t)\, d(\omega t)$ for odd h
Even quarter-wave	Even and half-wave	$b_h = 0$ for all h $a_h = \begin{cases} \frac{4}{\pi}\int_0^{\pi/2} f(t)\cos(h\omega t)\, d(\omega t) & \text{for odd } h \\ 0 & \text{for even } h \end{cases}$
Odd quarter-wave	Odd and half-wave	$a_h = 0$ for all h $b_h = \begin{cases} \frac{4}{\pi}\int_0^{\pi/2} f(t)\sin(h\omega t)\, d(\omega t) & \text{for odd } h \\ 0 & \text{for even } h \end{cases}$

Definition of RMS-value:

$$F_{RMS} = \sqrt{\frac{1}{T}\int_{t_o}^{t_o+T} f(t)^2 dt}$$

Definition of RMS-value with Fourier-series:

$$F_{RMS} = \sqrt{F_0^2 + \sum_{n=1}^{\infty} F_n^2} = \sqrt{\left(\frac{a_0}{2}\right)^2 + \sum_{n=1}^{\infty}\left(\frac{\sqrt{a_n^2 + b_n^2}}{\sqrt{2}}\right)^2}$$

$$\sin^2(\alpha) + \cos^2(\alpha) = 1$$

$$\sin(\alpha+\beta) = \sin(\alpha)\cos(\beta) + \cos(\alpha)\sin(\beta) \qquad \sin(\alpha-\beta) = \sin(\alpha)\cos(\beta) - \cos(\alpha)\sin(\beta)$$

$$\cos(\alpha+\beta) = \cos(\alpha)\cos(\beta) - \sin(\alpha)\sin(\beta) \qquad \cos(\alpha-\beta) = \cos(\alpha)\cos(\beta) + \sin(\alpha)\sin(\beta)$$

$$\sin(\alpha)\sin(\beta) = \frac{1}{2}\left(\cos(\alpha-\beta) - \cos(\alpha+\beta)\right) \qquad \sin(\alpha)\cos(\beta) = \frac{1}{2}\left(\sin(\alpha-\beta) + \sin(\alpha+\beta)\right)$$

$$\cos(\alpha)\cos(\beta) = \frac{1}{2}\left(\cos(\alpha-\beta) + \cos(\alpha+\beta)\right)$$

$$\int \sin(ax)dx = -\frac{1}{a}\cos(ax), \quad \int x\sin(ax)dx = \frac{1}{a^2}\left(\sin(ax) - ax\cos(ax)\right), \quad \int \cos(ax)dx = \frac{1}{a}\sin(ax)$$

$$\int x\cos(ax)dx = \frac{1}{a^2}\left(\cos(ax) + ax\sin(ax)\right)$$

$$PF = \frac{P}{S} = \frac{V_s I_{s1}\cos\phi_1}{V_s I_s}, \quad DPF = \cos\phi_1, \quad \%THD_i = 100\frac{I_{dis}}{I_{s1}} = 100\frac{\sqrt{I_s^2 - I_{s1}^2}}{I_{s1}} = 100\sqrt{\sum_{h\neq 1}\left(\frac{I_{sh}}{I_{s1}}\right)^2}$$

Electromagnetics

$$e = \frac{d}{dt}\psi \qquad \psi = N\phi \qquad \phi = BA \qquad R = \frac{l}{A\mu_r\mu_0} \qquad L = \frac{\Psi}{i}$$

$$NI = R\phi = mmf \qquad N\phi = LI \qquad L = A_L N^2 \qquad W = \frac{1}{2}LI^2$$

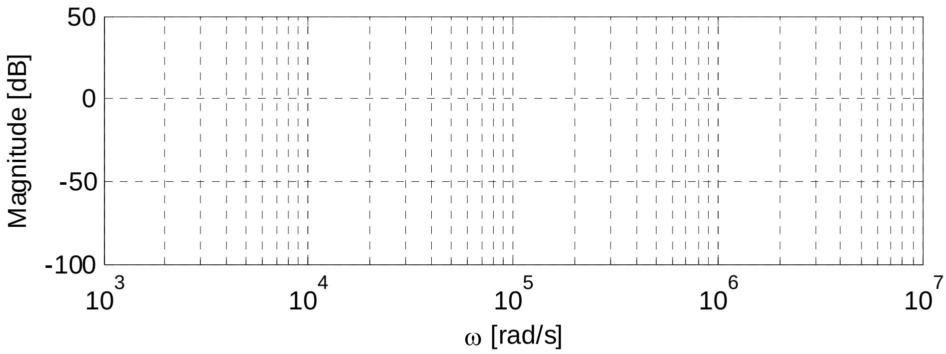
Simpson's rule

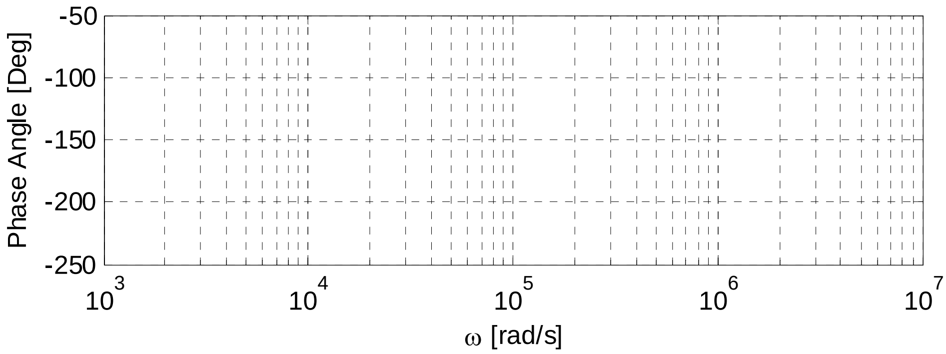
Let $f(x)$ be a polynomial of maximum third degree, this means

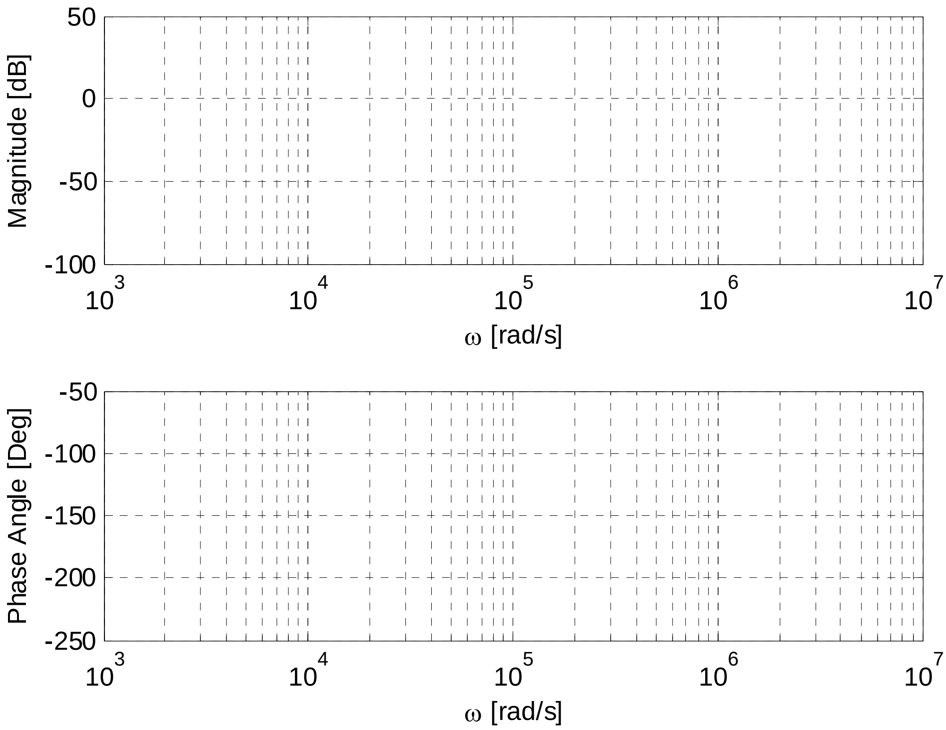
$$f(x) = a_1 + a_2 x + a_3 x^2 + a_4 x^3$$

For this function the integral can be calculated as

$$\frac{1}{T}\int_{t_0}^{t_0+T} f(x)dx = \frac{1}{6}\left(f(t_0) + 4f(t_0 + \frac{T}{2}) + f(t_0 + T)\right)$$


50
0
-50
-100
Magnitude [dB]
10^3
10^4
10^5
10^6
10^7
ω [rad/s]


-50
-100
-150
-200
-250
Phase Angle [Deg]
10^3
10^4
10^5
10^6
10^7
ω [rad/s]



50
0
-50
-100
Magnitude [dB]
10^3
10^4
10^5
10^6
10^7
ω [rad/s]
-50
-100
-150
-200
-250
Phase Angle [Deg]
10^3
10^4
10^5
10^6
10^7
ω [rad/s]