TY. B.Tech. (EE)

Trimester: V **Subject: Power Electronics**

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Experiment No: 08

Name of the Experiment: TYPE A STEP-DOWN MOSFET CHOPPER

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Marks

Teacher's Signature with date

AIM: To study the operation of a type A step-down MOSFET chopper.

APPARATUS: 1) Circuit board.
2) DMM.
3) Ammeter.
4) Dual trace CRO with probes.

NOMENCLATURE:

(i) V_o : average (DC) output (load) voltage

(ii) I_o : average (DC) output (load) current

(iii) $V_{o\,\max}$: maximum (peak) output voltage

(IV) $V_{o\,\min}$: minimum (peak) output voltage

(v) $I_{o\,\max}$: maximum (peak) output current

(vi) $I_{o\,\min}$: minimum (peak) output current

(Vii) V_{DC} : DC supply voltage

(Viii) I_{DC} : average (DC) supply current

(ix) t_{ON} : duration for which the switch is ON

(x) t_{OFF} : duration for which the switch is OFF

(xi) t_{FWD} : duration for which the output current freewheels through the FWD

(xii) $f = 1/T$: chopper frequency

(xiii) K : chopper duty cycle

(Xiv) $\tau = L/R$: load time constant

(xv) L : load inductance

(xvi) R : total resistance of current sensing resistor, ammeter & load (including the winding resistance of the load inductance, for inductive loads)

(Xvii) V_T : ON-state voltage drop of the MOSFET

(xviii) $V_D (V_{FWD})$: ON-state voltage drop of the freewheeling diode

THEORY:

A type A step-down chopper is a fixed DC-to-variable DC convertor whose average output voltage can be continuously varied from zero to the fixed DC supply voltage using pulse width modulation.

The schematic diagram of an ideal step-down chopper circuit is shown in Fig. 1 & consists of a controlled switch S1 and freewheeling diode (FWD) D1. During the ON period of the switch, the output voltage, $v_O(t)$, is given by $v_O(t) = V_{DC}$ ideally, ($v_O(t) = V_{DC} - V_T$ actually). Similarly, during the OFF period for an inductive load, the output voltage is given by $v_O(t) = 0$ ideally, ($v_O(t) = -V_D$ actually, as long as the FWD is conducting). During the OFF period, for a resistive load, $v_O(t) = 0$ for both ideal and actual cases.

Therefore the output voltage waveform, shown in Fig. 5, is a rectangular pulse train of amplitude V_{DC} at a frequency f having a duty cycle K and is practically independent of the type of load. However the output current $i_O(t)$ depends on the load and is also shown in Fig. 5 for resistive, discontinuous & continuous inductive loads. For a resistive load, voltage and current are in phase, and therefore the current waveform is a rectangular pulse train at frequency f and with an amplitude of V_{DC}/R . Further the FWD D1 does not conduct at all and therefore the current is carried only by switch S1. Hence the supply current waveform is identical to the load current waveform.

For an inductive load, the output current cannot change instantaneously and therefore builds-up & decays at a rate governed by the load time constant $\tau = L/R$. In the case of a discontinuous inductive load, the current builds-up from zero to $I_{O\max}$ during the ON period and the supply current equals the load current. When switch S1 turns-off at the beginning of the OFF period, the stored magnetic energy in the inductive load causes the load current to freewheel through D1 by reversing the polarity of the output voltage and forward biasing D1. The current decays exponentially to zero before the start of the next ON period, and during this period the supply current is zero as switch S1 is OFF. Thus the freewheeling duration t_{FWD} is less than the OFF period .

In contrast, for a continuous inductive load in the steady state, the load current never falls to zero but builds up from $I_{O\min}$ to $I_{O\max}$ during t_{ON} and decays from $I_{O\max}$ to $I_{O\min}$ during t_{OFF}. Here the freewheeling duration t_{FWD} is equal to the OFF period.

CIRCUIT DESCRIPTION:

1. Power circuit: The power circuit diagram of the step-down chopper is shown in Fig.3 and consists of power MOSFET T11 (IRF840) acting as switch S1 & power MOSFET D27 (IRF840), with **gate shorted-to-source**, acting as free wheeling diode D1. The DC supply to the chopper is obtained by stepping down the mains supply using 230V/26V step-down transformer TR3, and then full-wave rectifying the output voltage using diodes D41 to D43 in a bridge configuration with capacitor C41 as filter capacitor.

2. Control circuit: The control circuit is shown in Fig. 2, while the control circuit waveforms are shown in Fig. 4.

The control circuit delivers a rectangular gate pulse train of duration t_{ON} from $t = 0$ to $t = t_{ON}$ in each cycle to the power MOSFET switch S1, with t_{ON} being settable, ideally, from 0 to T corresponding to a duty cycle variation of 0 to 1.

2.1. Triangular waveform generator: A triangular wave oscillator is formed by VCO U1 (LM566) with resistors R1, R2, R3, capacitor C1 and frequency setting potentiometer R3. The frequency f of the triangular voltage waveform (pin 4) $v_A(t)$, can be calculated using following formulae:

$$f = \frac{2(V_{CC} - V_5)}{(R_3 + R_4)C_1} \text{ where } V_5 = \frac{R_2}{(R_1 + R_2)} V_{CC} \text{ is the voltage at pin 5 of U1} \tag{1}$$

This frequency can be adjusted by potentiometer R3.

2.2. Pulse train generator: The triangular voltage waveform $v_A(t)$ is compared with a reference DC voltage v_B in comparator U2 (LF356), which produces a rectangular waveform of frequency f and duty cycle K. The duty cycle can be adjusted by varying the reference voltage by means of potentiometer R6.

2.3. Driver & isolation circuits: In power electronics isolation between the control and power circuits is essential and is usually provided either by pulse transformers or opt couplers. In the present case this isolation is achieved using opt couplers.

Since opt couplers require driving currents of the order of 10mA, the output of the pulse train generator is buffered by a complementary symmetry transistor driver circuit consisting of transistors T1 (BC547), T2 (BC557) and base current control resistor R9, and is then used to drive the opto-diode of opt coupler U3 (MCT2E) via resistors R11 & R12.

Owing to the finite bandwidth of the opt coupler, the output pulses delivered by it to the power circuit have relatively large rise and fall times which are unacceptable. Hence Schmitt comparator U6 (4093), along with pull-up resistor R21, is used to ‘sharpen’ these pulses which are then given to hex non-inverting buffer U7 (4050) with paralleled inputs and outputs. The turn-on and turn-off times of the MOSFET can be controlled by the current limiting resistance R22 // R23 in series between the buffer output and MOSFET gate terminal, which essentially controls the rate of charge and discharge of C_{GS}, the MOSFET gate-source capacitance.

Switch SW2, along with transistor switch T3 (BC547) and resistors R13, R14 & R15, is used to enable or disable the control circuit.

2.4. Test points:

2.4.1. Control circuit:

TP1: triangular voltage $v_A(t)$	**A**
TP2: reference DC voltage v_B	**B**
TP3: pulse train output	**C**

2.4.2. Driver circuit:

TP4: gate pulses for MOSFET switch S1	**D**

FORMULAE:

1. Output voltage (ideal):

$$V_o = KV_{DC} \quad \text{where } K = \frac{t_{ON}}{T} = f\, t_{ON} = \frac{t_{ON}}{t_{ON} + t_{OFF}} \qquad 0 \le K \le 1 \tag{1}$$

$$V_{o\,\max} = V_{DC} \tag{2}$$

$$V_{o\,\min} = 0 \tag{3}$$

2. Output voltage (actual):

2.1 R load:

$$V_o = KV_{DC} - KV_T \qquad 0 \le K \le 1 \tag{4}$$

$$V_{o\,\max} = V_{DC} - V_T \tag{5}$$

$$V_{o\,\min} = 0 \tag{6}$$

2.2 Discontinuous inductive load:

$$V_o = KV_{DC} - KV_T - \frac{t_{FWD}}{T} V_D \qquad 0 \le K \le 1 \tag{7}$$

$$V_{o\,\max} = V_{DC} - V_T \tag{8}$$

$$V_{o\,\min} = -V_D \tag{9}$$

2.3 Continuous inductive load:

$$V_o = KV_{DC} - KV_T - \frac{t_{OFF}}{T} V_D \qquad 0 \le K \le 1 \tag{10}$$

$$V_{o\,\max} = V_{DC} - V_T \tag{11}$$

$$V_{o\,\min} = -V_D \tag{12}$$

3. Average (DC) output current (for all cases):

$$I_o = \frac{V_o}{R} \tag{13}$$

4. Maximum, minimum and p-p ripple current for continuous inductive load:

$$I_{o\,\max} = \frac{V_{o\,\max}}{R} \left(\frac{1 - e^{-KT/\tau}}{1 - e^{-T/\tau}} \right) \tag{14}$$

$$I_{o\,\min} = \frac{V_{o\,\max}}{R} \left(\frac{1 - e^{KT/\tau}}{1 - e^{T/\tau}} \right) \tag{15}$$

$$\Delta I_{o\,p-p} = I_{o\max} - I_{o\min} = \frac{V_{o\max}}{R}\left(\frac{\sinh(KT/\tau) + \sinh((1-K)T/\tau) - \sinh(T/\tau)}{1-\cosh(T/\tau)}\right) \tag{16}$$

$$\Delta I_{o\,p-p\max} = \frac{V_{o\max}}{R}\tanh\left(\frac{R}{4fL}\right) \quad \text{for } K = 0.5 \text{ (50\% duty cycle)} \tag{17}$$

PROCEDURE:

1. Keeping power circuit switch SW3 OFF, switch ON control circuit switch SW1. Connect channel 1 of the CRO to observe the triangular output voltage $v_A(t)$ (live of probe to **TP1** & common to control ground **X5**) and channel 2 to observe the pulse train output voltage (live of probe to **TP3** & common to **X5**). Vary **frequency control potentiometer R3** and **duty cycle control potentiometer R6** and observe the variation of and **draw to scale** both these waveforms.

Measure minimum and maximum frequencies f_{min} & f_{max}, respectively, and minimum and maximum duty cycles K_{min} & K_{max}, respectively.

2. Disconnect both live & common of probe connected to channel 1 and then connect it to observe the gate pulses given to the MOSFET switch (live of probe to **TP4** & common to isolated (power) ground **X8**). **Draw to scale** and compare the gate pulse waveform with the pulse train output waveform in the control circuit.

3. R load:

3.1. Switch OFF SW1 and disconnect both channels of the CRO. Put SW2 in 'R' position and switch ON SW3and then SW1. Connect channel 1 of the CRO to observe the output voltage $v_o(t)$ (live of probe to **X14** & common to **X18**). Also connect channel 2 to observe the output current $i_o(t)$ by sensing the voltage across 1 Ω current-sensing resistor R_S (live of probe to **X17** & common to **X18)**. Note that $i_o(t) = v_{R_S}(t)/R_S = v_{R_S}(t)$ algebraically.
Observe and **draw to scale** both these waveforms.

3.2. Adjust the output frequency to f_1 and duty cycle to K_1 and measure the following parameters:

(i) DC output voltage V_o

(ii) DC output current I_o

(iii) Maximum (peak) output voltage $V_{o\max}$

(iv) Maximum (peak) output current $I_{o\max}$

(v) Period T

(vi) ON period t_{ON}

(vii) DC supply voltage V_{DC}

(viii) DC supply current I_{DC}

Repeat these measurements for output frequency f_2 and duty cycle to K_2.

4. Discontinuous inductive load:

4.1. Switch OFF SW1 and then SW3. Put switch SW2 in L position and switch ON SW3 & then SW1. Connect both channels of the CRO to measure output voltage & current as given in **3.1** above.

4.2. Adjust the output frequency to f_3 and duty cycle to K_3 such that the output current is discontinuous (Fig. 5). Observe and **draw to scale** both the output voltage & current waveforms. Measure the following parameters:

(i) DC output voltage V_o

(ii) DC output current I_o

(iii) Maximum (peak) output voltage $V_{o\,\max}$

(iv) Maximum (peak) output current $I_{o\,\max}$

(v) freewheeling output voltage V_{FWD}

(vi) Period T

(vii) ON period t_{ON}

(viii) freewheeling duration t_{FWD}

(ix) DC supply voltage V_{DC}

(x) DC supply current I_{DC}

Repeat these measurements for another output frequency f_4 and another duty cycle to K_4 (discontinuous conduction).

5. Continuous inductive load:

5.1. Adjust the output frequency to f_5 and duty cycle to K_5 such that the output current is continuous (Fig. 5). Observe and **draw to scale** both the output voltage & current waveforms. Measure the following parameters:

(i) DC output voltage V_o

(ii) DC output current I_o

(iii) maximum (peak) output voltage $V_{o\,\max}$

(iv) maximum (peak) output current $I_{o\,\max}$

(v) minimum output current $I_{o\,\min}$

(vi) freewheeling output voltage V_{FWD}

(vii) period T

(viii) ON period t_{ON}

(ix) freewheeling duration t_{FWD}

(x) DC supply voltage V_{DC}

(xi) DC supply current I_{DC}

Repeat these measurements for another output frequency f_6 and 50% duty cycle i.e. K_6 = 0.5 (continuous conduction).

OBSERVATIONS:

1. Minimum output frequency f_{min} = Hz

2. Maximum output frequency f_{max} = Hz

3. Minimum output duty cycle K_{min} =

4. Maximum output duty cycle K_{max} =

5. R load:

R = Ω

Sr. No.	Parameter	f_1 = Hz, K_1 =	f_2 = Hz, K_2 =
1.	V_o V		
2.	I_o A		
3.	$V_{o\,\max}$ V		
4.	$I_{o\,\max}$ A		
5.	T ms		
6.	t_{ON} ms		
7.	V_{DC} V		
8.	I_{DC} A		

6. Discontinuous inductive load:

R = Ω

L = mH

Sr. No.	Parameter	f_3 = Hz, K_3 =	f_4 = Hz, K_4 =
1.	V_o V		
2.	I_o A		
3.	$V_{o\,\max}$ V		
4.	$I_{o\,\max}$ A		
5.	V_{FWD} V		
6.	T ms		
7.	t_{ON} ms		
8.	t_{FWD} ms		
9.	V_{DC} V		
10.	I_{DC} A		

7. Continuous inductive load:

R = Ω

L = mH

Sr. No.	Parameter	f_5 = Hz, K_5 =	f_6 = Hz, K_6 = 0.5
1.	V_o V		
2.	I_o A		
3.	$V_{o\,\max}$ V		
4.	$I_{o\,\max}$ A		
5.	$I_{o\,\min}$ A		
6.	V_{FWD} V		
7.	T ms		
8.	t_{ON} ms		
9.	t_{FWD} ms		
10.	V_{DC} V		
11.	I_{DC} A		

CALCULATIONS & VERIFICATIONS:

1. Output voltage (ideal):

For all loads calculate V_o as per equation (1) above.

2. Output voltage (actual):

For the R load make verifications as per equations (4) to (6) above, for the discontinuous inductive load as per equations (7) to (9) above and for the continuous inductive load as per equations (10) to (12) above.

3. Output current (actual):

For all loads make verifications as per equation (13) above.

4. Maximum, minimum and p-p ripple current

For the continuous inductive load make verifications as per equations (14) to (17) above.

RESULT TABLES:

1. Output voltage (ideal):

Parameter	R load		Discont. inductive load		Cont. inductive load	
	f_1 , K_1	f_2 , K_2	f_3 , K_3	f_4 , K_4	f_5 , K_5	f_6 , K_6
V_o V						

2. Output voltage (actual):

Parameter	R load				Discont. inductive load				Cont. inductive load			
	Measured		Calculated		Measured		Calculated		Measured		Calculated	
	f_1 ,K_1	f_2 ,K_2	f_1 ,K_1	f_2 ,K_2	f_3 ,K_3	f_4 ,K_4	f_3 ,K_3	f_4 ,K_4	f_5 ,K_5	f_6 ,K_6	f_5 ,K_5	f_6 ,K_6
V_o V												
$V_{o\,\max}$ V												
$V_{o\,\min}$ V												

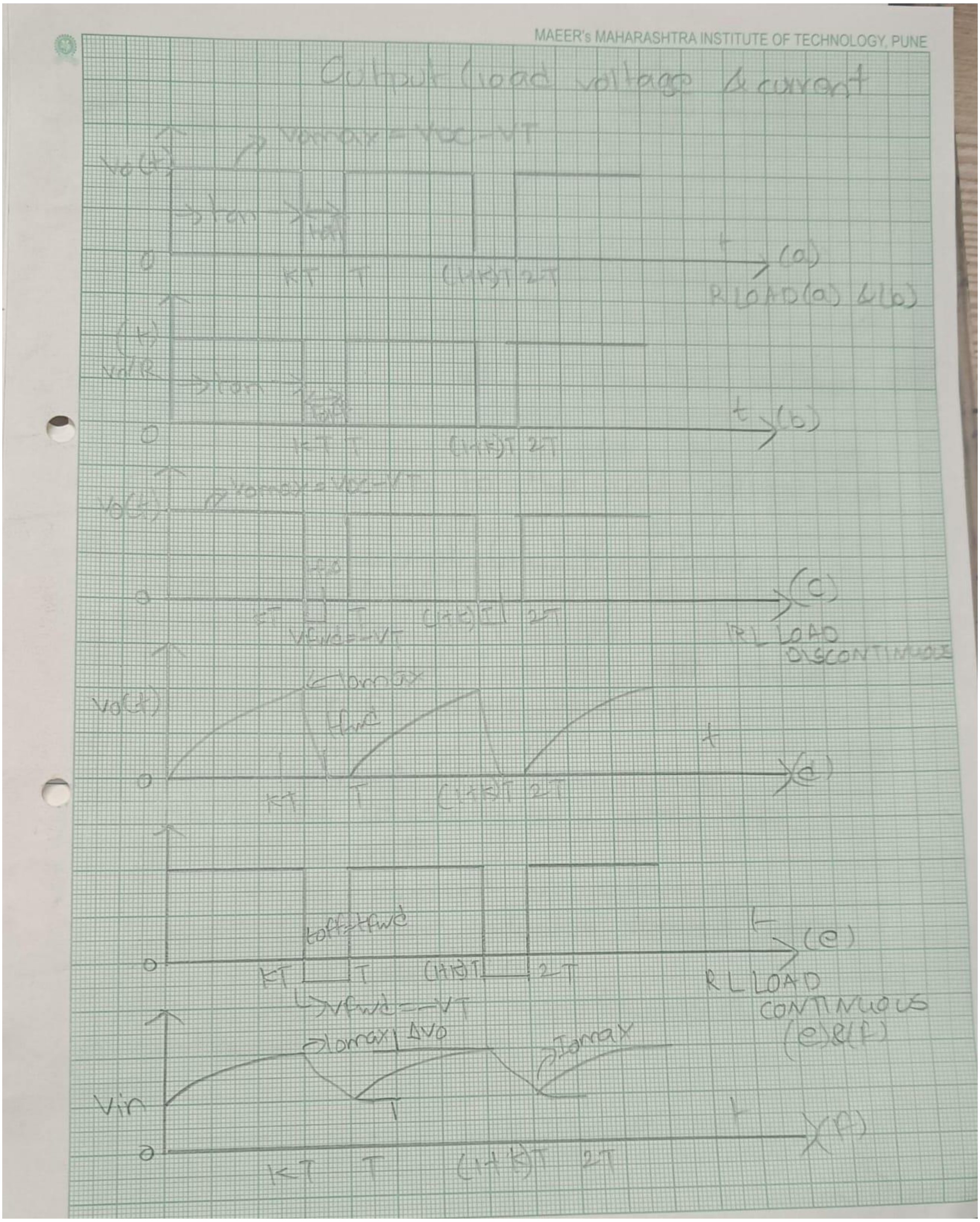
3. Output current (actual):

Parameter	R load				Discont. inductive load				Cont. inductive load			
	Measured		Calculated		Measured		Calculated		Measured		Calculated	
	f_1, K_1	f_2, K_2	f_1, K_1	f_2, K_2	f_3, K_3	f_4, K_4	f_3, K_3	f_4, K_4	f_5, K_5	f_6, K_6	f_5, K_5	f_6, K_6
I_o A												

4. Maximum, minimum and p-p ripple current:

Parameter	Cont. inductive load			
	Measured		Calculated	
	f_5, K_5	f_6, K_6	f_5, K_5	f_6, K_6
$I_{o\max}$ A				
$I_{o\min}$ A				
$\Delta I_{o\,p-p}$ A				
$\Delta I_{o\,p-p\max}$ A				

CONCLUSIONS: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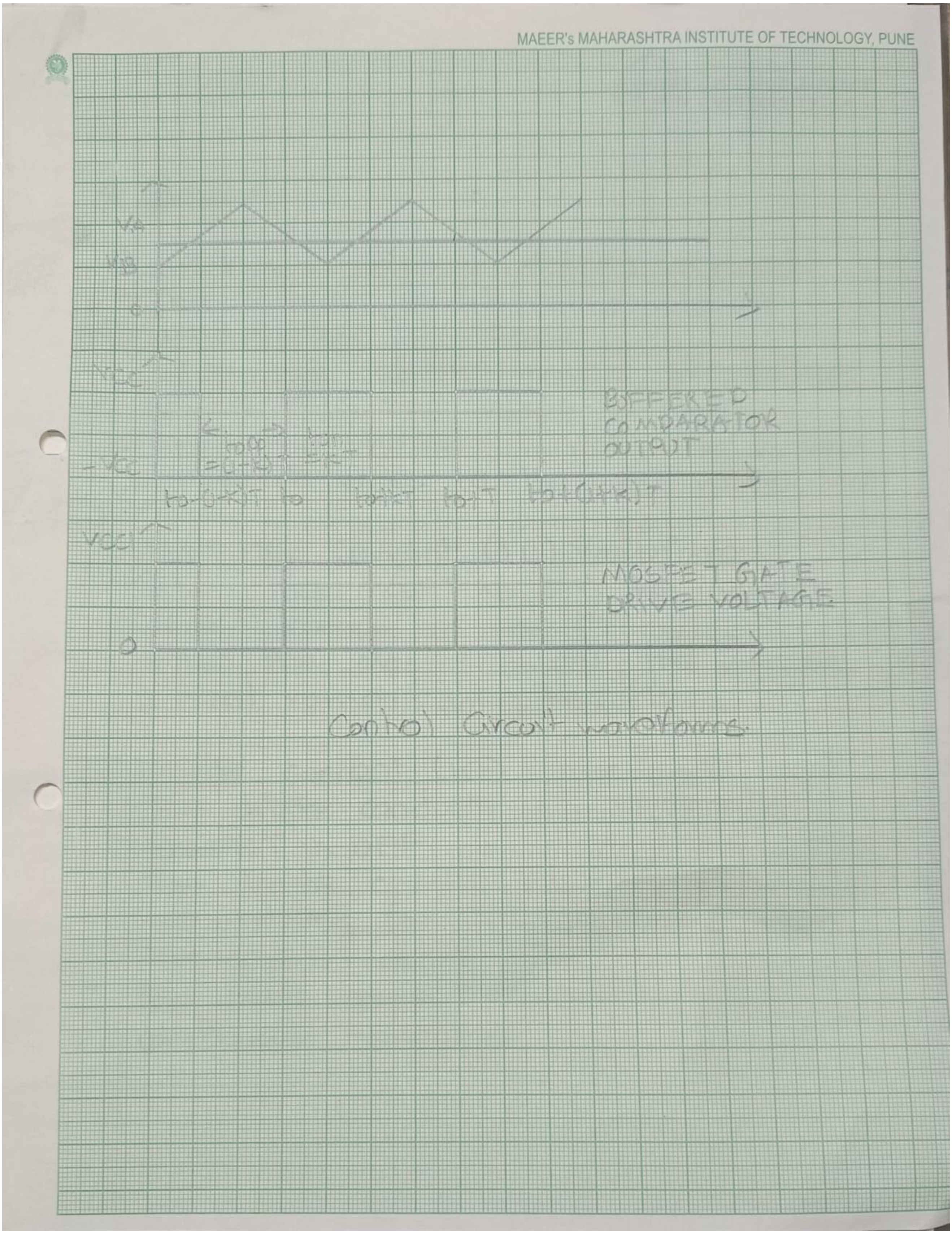
Output (load voltage & current
Vomax = Vdc − VT
Vo(t)
ton
toff
KT
T
(1+K)T
2T
(a)
R LOAD (a) & (b)
Vo/R
(b)
(c)
Vfwd = −VT
RL LOAD
DISCONTINUOUS
Iomax
tfwd
(d)
toff = tfwd
(e)
RL LOAD
CONTINUOUS
(e) & (f)
ΔVo
Vin
(f)


MAEER's MAHARASHTRA INSTITUTE OF TECHNOLOGY, PUNE
VCC
-VCC
BUFFERED COMPARATOR OUTPUT
VCC
MOSFET GATE DRIVE VOLTAGE
0
Control Circuit waveforms

* Explanation -

① switching waveform (MOSFET voltage) -
- The MOSFET switch has a square wave voltage waveform
- when the MOSFET is ON, the voltage across it is low (close to zero).
- when the MOSFET is OFF, the voltage across it rises to the input voltage level.

② Inductor Current (IL) waveform:
- when the MOSFT is ON, the indicator current ramps up linearly.
- when the MOSFT is OFF, the indicator current ramps down linearly.

③ Diode current (ID) waveform:
- The diode conducts only when the MOSFET is OFF.
- The diode current waveform is a freewheeling for inductor current when the MOSFET is OFF.
- The diode current waveform is a continuous waveform.

④ Output Voltage (vout) waveform:
- The output voltage is a relatively constant level with a small ripple.
- The ripple is ~~dute~~ due to the switching action and is smoothed by the output capacitor.

⑤ Control Signal (Duty Cycle):
- The duty cycle of the switching waveform determines the average output voltage.
- Duty cycle = ON time / (ON time + OFF time).