1.4.5.3 Applications of IGBTs

(i) AC motor drives, i.e. inverters.

(ii) DC to DC power supplies, i.e choppers.

(iii) UPS systems.

(iv) Harmonic compensators.

1.4.6 Protection Circuits for IGBT [May-2007]

IGBT can be protected against,

i) Gate overvoltage protection ii) Overcurrent protection iii) Snubber circuits.

1.4.6.1 Gate Overvoltage Protection

Answer following question after reading this topic.

1. *Draw the circuit diagram and explain any one protection circuit of IGBT.* **Marks [4], May-2007**

Most likely and **asked in** previous University Exam

- Fig. 1.4.11 shows the circuit diagram of gate overvoltage protection. This circuit consists of two zener diode connected in series back to back.
- Normally the gate overvoltage is ± 20 V. The two zener diodes conduct when overvoltage occurs between gate and source.
- The breakdown voltage of the zener diodes can be adjusted according to Gate-source breakdown voltage of IGBT.

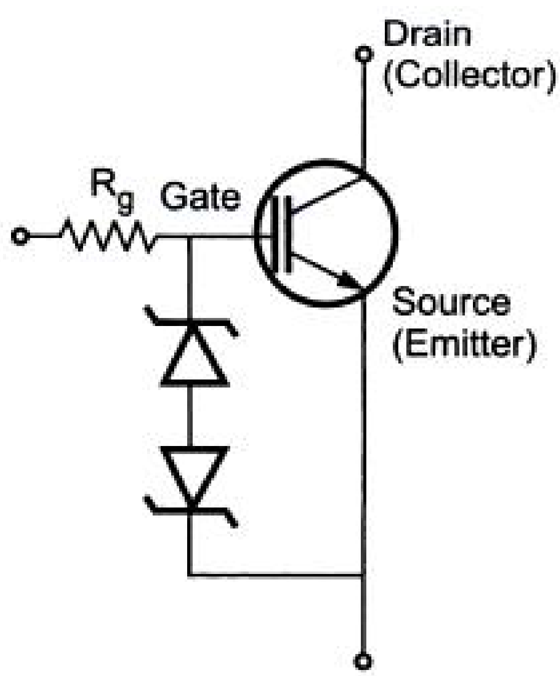


Fig. 1.4.11 Gate overvoltage protection

1.4.6.2 Overcurrent Protection

- The drain overcurrent of IGBT is continuously monitored. If overcurrent is detected, then drive of IGBT is disabled. This is normally incorporated in drive circuit of IGBT. Fig. 1.4.12 shows drive circuit of IGBT with overcurrent protection.

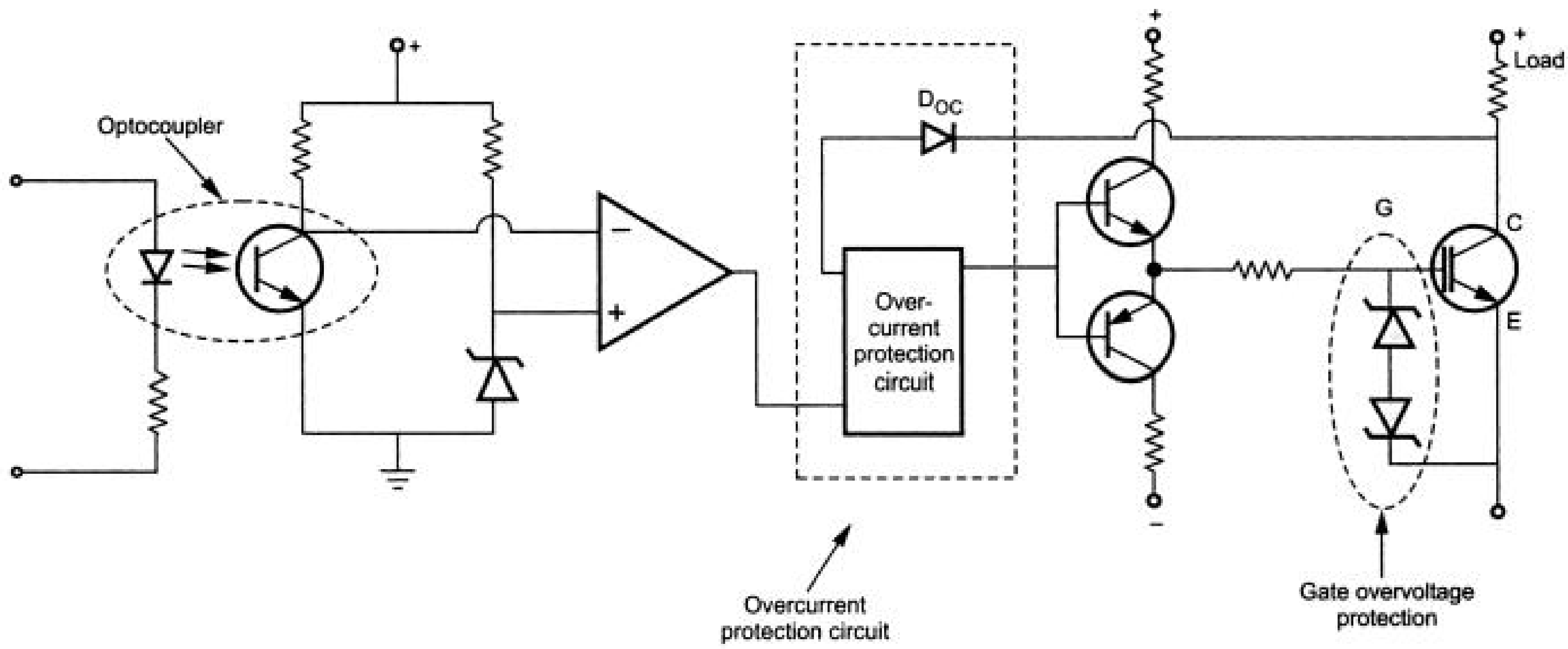


Fig. 1.4.12 Overcurrent protection

Operation

- In this circuit, the turn-on/off signal is given through optocoupler.
- The overcurrent protection circuit receives drive signal from comparator and gives it to gate of IGBT through npn-pnp pair of BJTs.
- The collector voltage of IGBT is sensed through diode D_{OC}. Normally this diode is forward biased, since collector voltage is very small.
- If there is overcurrent, then collector voltage increases and diode D_{OC} is reverse biased. This condition is sensed by overcurrent protection circuit and it simply blocks the drive given to gate of IGBT.

1.4.6.3 Snubber Circuits for IGBT

Purpose : To ensure that IGBT always operates in its safe operating area at the time of turn-on and turn-off.

If IGBT does not operate in its SOA, then it can be damaged. Thus snubber circuits protect IGBT. There are two types of snubbers : i) Turn-off snubber and ii) Turn-on snubber.

i) Turn-off snubber

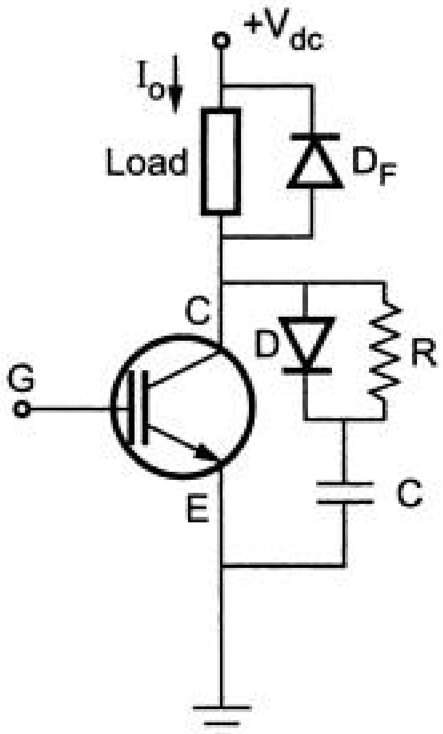


Fig. 1.4.13 Turn-off snubber

Fig. 1.4.13 shows the circuit diagram of turn-off snubber.

Operation

- Turn-off snubber is necessary to limit the voltage across collector-emitter when IGBT turns-off.
- The load current flows through diode D and capacitor C. This changing of capacitor limits the voltage v_{CE} at the time of turn-off.
- The resistance 'R' is used to limit the discharge current of capacitor when IGBT turns-on.

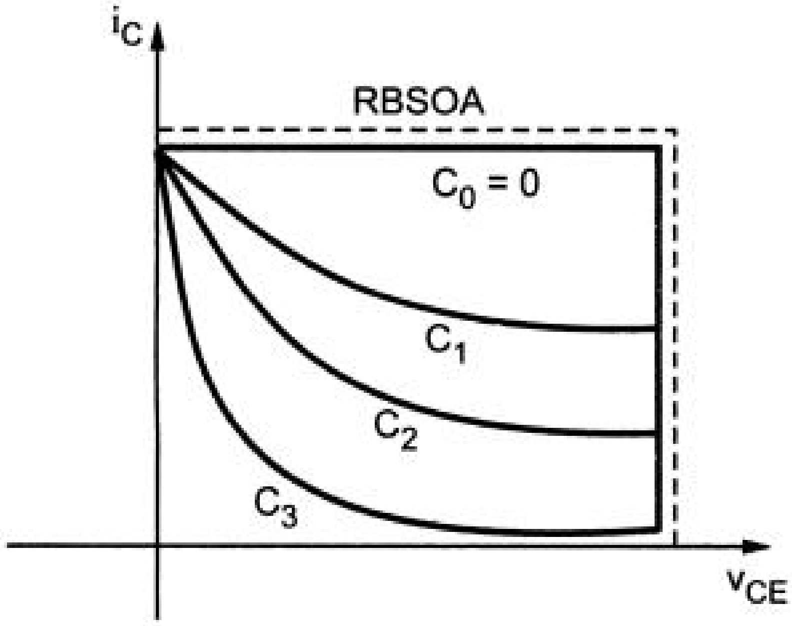


Fig. 1.4.14 Switching trajectory for various values of C

- Fig. 1.4.14 shows the switching trajectory of IGBT for various values of C.
- Here $C_0 < C_1 < C_2 < C_3$. Thus large capacitor value limits the i_C, v_{CE} to considerably small values during switching.

Values of R and C

The values of R and C are given as,

$$R = \frac{V_{dc}}{0.2 I_o}$$

Here V_{dc} is DC supply voltage.

I_o is load current.

$$C_s = \frac{2E_C}{V_{dc}^2}$$

Here E_C is energy stored in capacitor.

ii) Turn-on Snubber

Fig. 1.4.15 shows the circuit diagram of turn-on snubber.

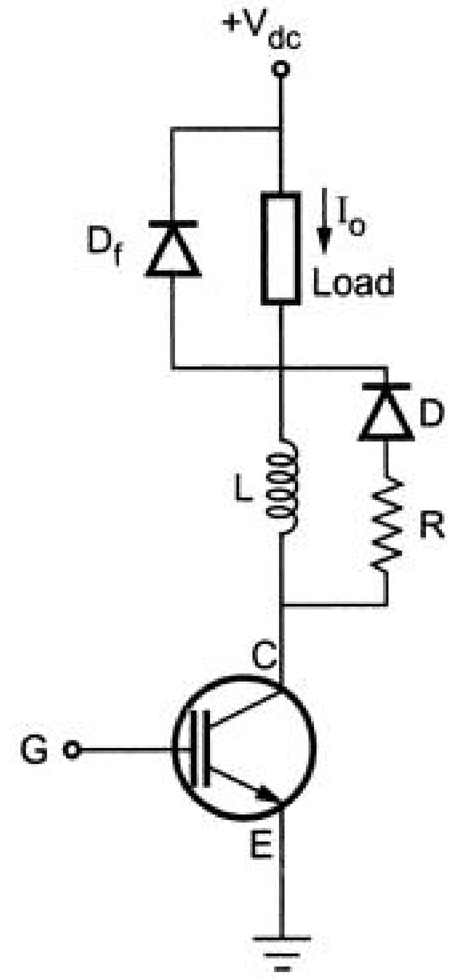


Fig. 1.4.15 Turn-on snubber

Operation

- The turn-on snubber is used to reduce the switching losses during turn-on.
- It reduces the voltage across IGBT when current is rising.
- The voltage drop across inductor L reduces the net voltage across IGBT.
- The energy stored in inductor is dissipated through resistor R and diode D.
- Large value of inductance reduces IGBT voltage during turn-on but also causes high voltages during turn-off. Hence its value must be appropriately selected for turn-on as well as turn-off.

Values of R and L

Value of inductance is given as,

$$L = \frac{\Delta V_{CE} t_r}{I_o}$$

Here ΔV_{CE} is reduction in voltage across IGBT.

t_r is rise time of current.

I_o is load current.

Value of resistance is given as,

$$R > \frac{2.3\,L}{t_{off}}$$

Here t_{off} is off state of IGBT or its turn-off time.

Example 1.4.1 : *The Thevenin equivalent of an IGBT gate drive circuit is a DC source of 10 V in series with a resistance R. The IGBT parameters are C_{gs} = 100 pF, C_{gd} = 150 pF and $V_{GS\,(Th)}$ = 3 V. Calculate the value of R so that the turn-on delay, i.e. time taken for V_{GS} to rise from zero to $V_{GS(Th)}$ is 5 ns.* **[May-2006, 6 Marks]**

Solution : Fig. 1.4.16 shows the Thevenin equivalent circuit.

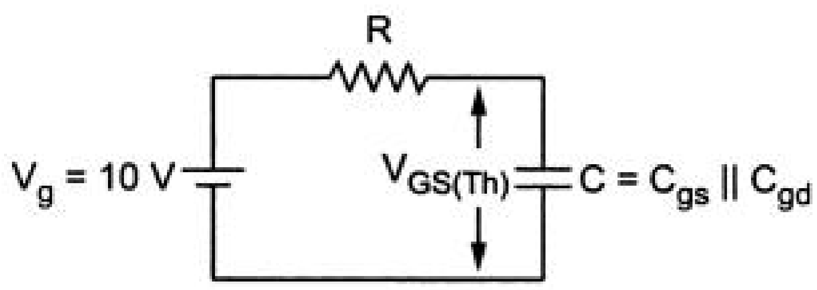


Fig. 1.4.16

Here 'C' is the parallel combination of C_{gs} and C_{gd} hence,

$$C = C_{gs} + C_{gd}$$
$$= 1000 \text{ pF} + 150 \text{ pF}$$
$$= 1150 \text{ pF}$$

The voltage across capacitor will be gate-source voltage. Hence

$$V_{GS} = V_g(1 - e^{-t/RC})$$

Here we have to determine value of 'R' for t = 5 nsec, $V_{GS} = V_{GS(Th)}$ = 3 V, C = 1150 pF and V_g = 10 V. Hence,

$$3 = 10\left(1 - e^{-5\times10^{-9}/(R\times1150\times10^{-12})}\right)$$

$$0.3 = 1 - e^{-4.3478/R}$$

$$0.7 = e^{-4.3478/R}$$

$$\therefore \quad R = 12.19\ \Omega \approx 12\ \Omega$$

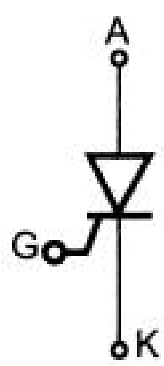
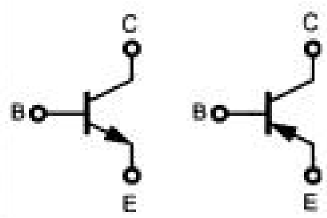
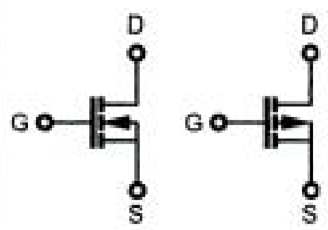
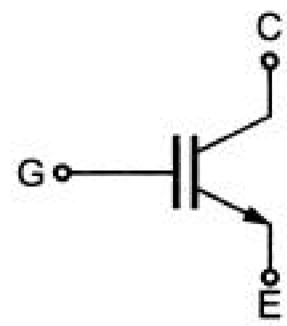
1.5 Comparison of Power Devices

Answer following questions after reading this topic.

1. *Compare BJT, MOSFET and IGBT.*
2. *Compare the MOSFET with other power devices.*
Marks [4] Dec.-2007

Most likely and **asked in** previous University Exam

The power devices can be compared on the basis of switching frequency, gate drive circuit, power handling capacity etc. Table 1.5.1 shows the comparison of SCR, BJT, MOSFET and IGBT.

Sr. No.	Parameter	SCR	BJT	MOSFET	IGBT
1.	Symbol				
2.	Triggered i.e. latching or linear	Triggered or latching device	Linear trigger	Linear trigger	Linear trigger
3.	Type of carriers in device	Majority carrier device	Bipolar device	Majority carrier device	Majority carrier device
4.	Control of gate or base	Gate has no control once turned on	Base has full control	Gate has full control	Gate has full control
5.	On-state drop	< 2 volts	< 2 volts	4-6 volts	3.3 volts
6.	Switching frequency	500 Hz	10 kHz	Upto 100 kHz	20 kHz
7.	Gate drive	Current	Current	Voltage	Voltage
8.	Snubber	Unpolarized	Polarized	Not essential	Not essential
9.	Temperature coefficient	Negative	Negative	Positive	Approximately flat, but positive at high current
10.	Voltage and current ratings	10 kV/ 4 kA	2 kV/1 kA	1 kV/50 A	1.5 kV/400 A

11.	Voltage blocking capability	Symmetric and asymmetric (both)	Asymmetric	Asymmetric	Asymmetric
12.	Applications	AC to DC converters, AC voltage controllers, electronic circuit breakers	DC to AC converters, induction motor drives, UPS, SMPS, Choppers	DC choppers, low powers UPS, SMPS, brushless DC motor drives	DC to AC converters, AC motor drives, UPS, choppers, SMPS etc.

Table 1.5.1 Comparison of power devices

1.6 Need of Gate/Base Drive Circuits

The power devices are controlled with the help of base or gate. The gate or base facilitates the ON or OFF of the power device. Proper gate/base drive circuits are essential for power devices because of following reasons.

(i) The power device can be switched on or switched off quickly with the help of gate/base drive circuit.

(ii) The signal coming from the controllers such as microcontroller or microprocessors is not enough in amplitude/current to drive the power device properly.

(iii) The gate/base drive circuit shapes the drive signal for the device to have efficient switching.

(iv) The gate/base drive circuit offers protection to the device at the time of malfunctioning.

(v) It is necessary to isolate the power device and its control circuit electrically. This is done with the help of gate/base drive circuits.

1.7 Drive Circuits for BJT

Answer following questions after reading this topic.

1. *Give different circuit configurations for base drive of BJT.*
2. *What is the need of driver circuit ?* **Marks[2], Dec.-2001**

Most likely and **asked in** previous University Exam

Following points are to be remembered when designing the base drive circuit for transistor.

1. BJT is a current controlled device.
2. Power BJT is used as on/off switch in power converters.
3. Power BJT operates in saturation and cut-off when used as a switch.

4. Sufficient base current is required to drive BJT in saturation.
5. Amount of carrier injected in base region determine storage time of BJT.
6. Storage time determines turn-on and turn-off times of BJT.
7. There should be mechanism to control the amount of saturation so as to control storage time.

There are most important points about BJTs.

Need of Driver Circuit

- It is necessary to operate BJT as a switch in power converters. The drive should be such that BJT is driven in saturation and cut-off with short switching times. This makes operation of BJT faster.
- Also it is necessary to protect the BJT against various faults such as overcurrent, overvoltage etc. The driver circuit takes care of all these faults.
- There should be isolation between control circuit and power circuit. This isolation is provided by driver circuit.

1.7.1 Base Drive Control during Turn-on

Fig. 1.7.1 shows the base drive circuit for turn-on of a transistor. Due to this circuit the 't_{on}' time is reduced.

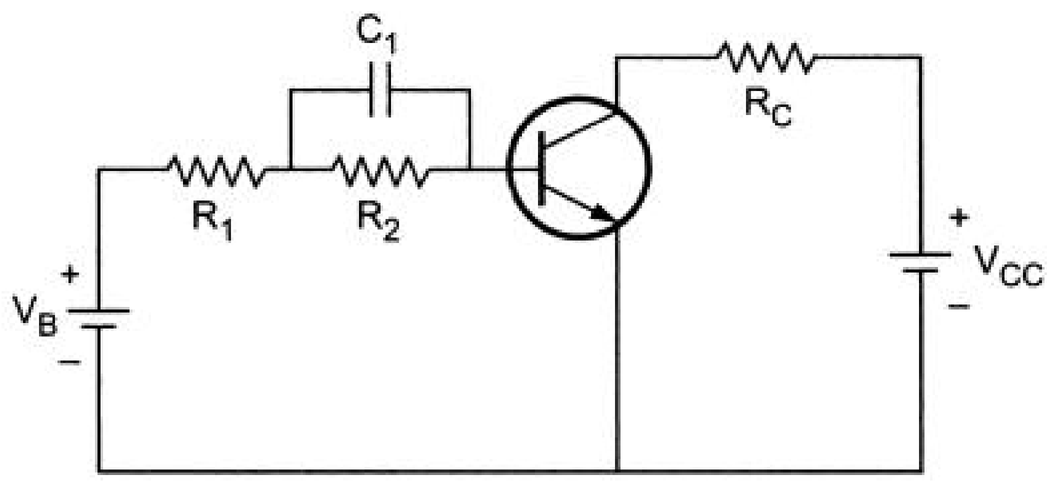


Fig. 1.7.1 Drive circuit to make base current high at beginning of t_{on}

As shown in this circuit, when base drive V_B is applied, the capacitor C_1 acts as a short. Hence R_2 is virtually by passes. Therefore an initial value of base current is only limited by R_1 and it is given as,

$$I_{B(peak)} = \frac{V_B - V_{BE}}{R_1}$$

This heavy base current drives transistor into saturation for quick turn-on. Once the transistor is turned on, there is no need of such large base current. This is taken care-off by R_2C_1 circuit. The capacitor C_1 starts charging and base current starts falling. This is shown in Fig. 1.7.2. Observe that there is peaking of base current at the beginning of turn-on. Then the current reduces to,

$$I_B = \frac{V_B - V_{BE}}{R_1 + R_2}$$

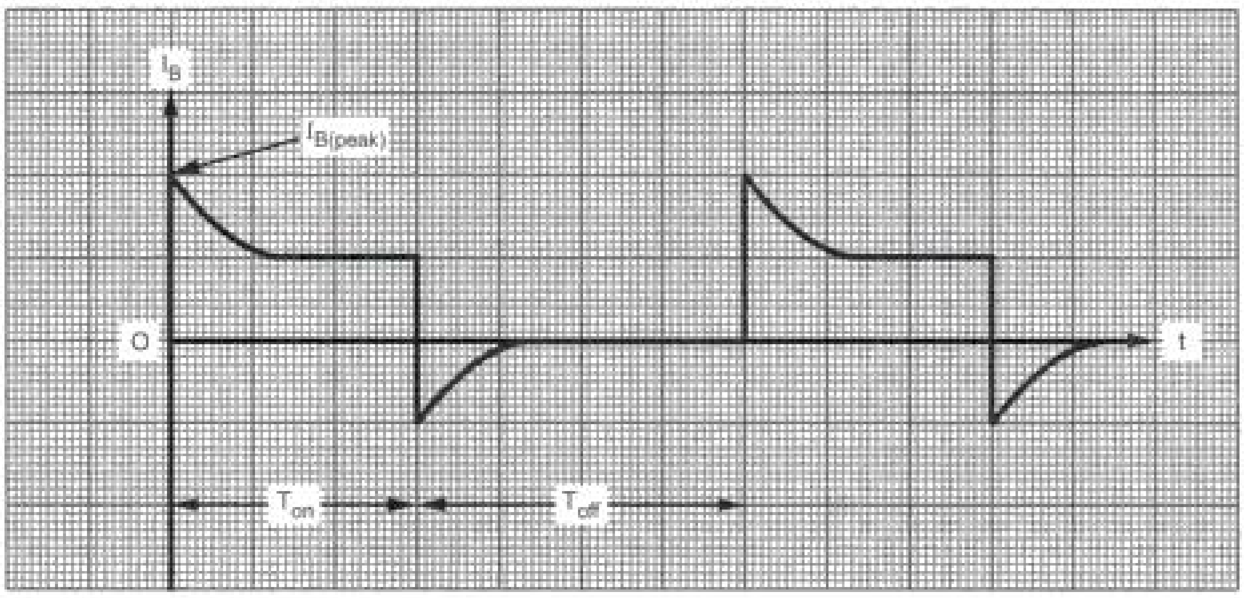


Fig. 1.7.2 Base current peaking at the beginning of turn-on

To turn-off the transistor, base voltage is made zero. Therefore capacitor voltage appears as negative voltage across base-emitter. Hence suddenly base current is reversed as shown in Fig. 1.7.2. This current slowly decays to zero after the stored charge in base region is removed. The capacitor C_1 then discharges through R_2. This discharge time constant is,

$$\tau_2 = R_2 C_1$$

The charging time constant of the capacitor is,

$$\tau_1 = \frac{R_1 R_2 C_1}{R_1 + R_2}$$

The T_{on} period of the transistor must be at least five times of τ_1. Similarly the T_{off} period must be five times of τ_2. The switching frequency of the BJT will then be,

$$f_s = \frac{1}{T_{on} + T_{off}}$$

We know that,

$$T_{on(min)} > 5\,\tau_1 \quad \text{and} \quad T_{off(min)} > 5\,\tau_2$$

This gives the maximum switching frequency of,

$$f_{s(max)} = \frac{1}{T_{on(\min)} + T_{off(\min)}}$$

$$= \frac{1}{5\tau_1 + 5\tau_2} = \frac{1}{5(\tau_1 + \tau_2)}$$

1.7.2 Base Drive Control During Turn-off

For quick turn-off, the stored charge in the base region must be removed fast. This can be done by applying negative base drive for turn-off. Due to $-V_B$, the base-emitter voltage becomes negative during turn-off. The voltage on capacitor C_1 also adds to this negative voltage. Therefore the negative peaking of base current (see Fig. 1.7.3) at the beginning of turn-off is increased. This removes the stored charge fast, and the transistor is turned-off quickly.

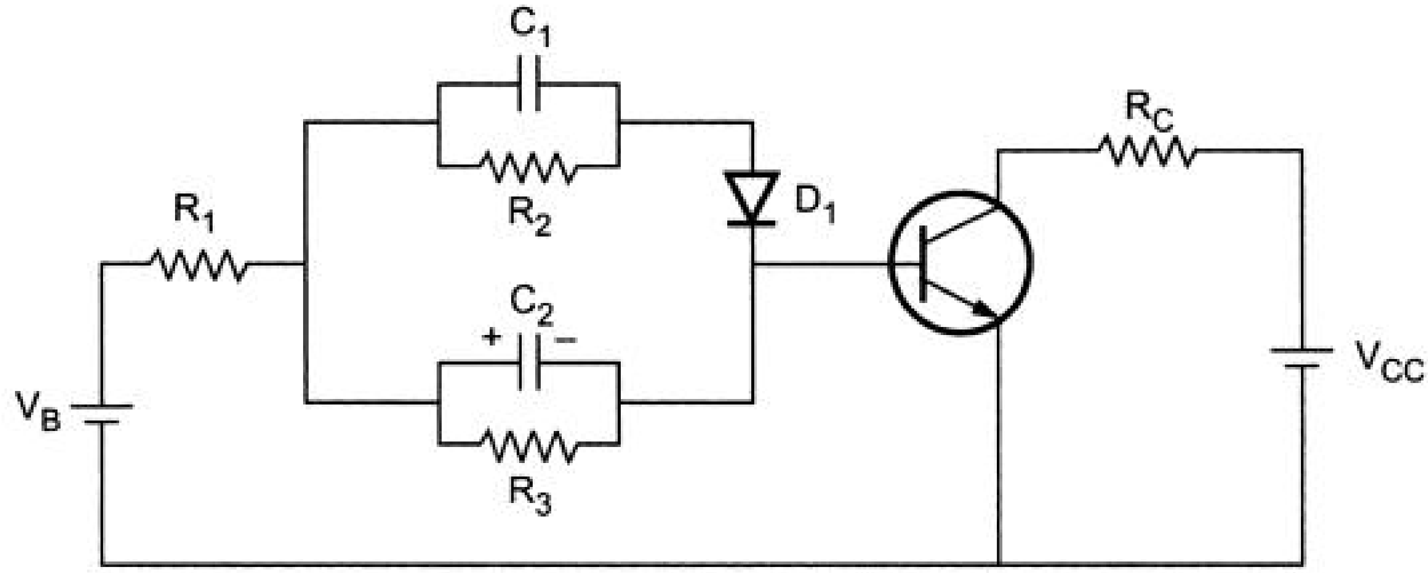


Fig. 1.7.3 Base drive circuit for positive and negative peaking of base current

It is possible to design the different turn-on and turn-off circuits for base current peaking. Fig. 1.7.3 shows one of such circuit. In this circuit, R_2C_1 is used for positive peaking of base current as discussed earlier. The diode D_1 acts as short when V_B is positive. Capacitor C_2 charges to the polarity as shown in above figure when V_B is positive. Normally R_3 is much higher than R_2, hence base current flows through R_2. The base voltage V_B is made negative to turn-off the transistor. Therefore the voltage of C_2 imposes additional negative input to the base. The negative base current flows through C_2, R_1 and V_B. Thus R_3C_2 becomes effective at the time of turn-off. No current flows through R_2C_1 during turn-off since diode D_1 is reverse biased. Once the base current is zero, then C_2 discharges through R_3. Similarly C_1 discharges through R_2. Thus it is possible to design separate peaking characteristics for turn-on and turn-off.

1.7.3 Proportional Base Control

The collector current changes as the load changes. If the load is reduced, then collector current reduces. Then the base current should also be reduced to avoid excess carries in the base region. Hence proportional base control can be used. Fig. 1.7.4 shows the circuit diagram of proportional base drive.

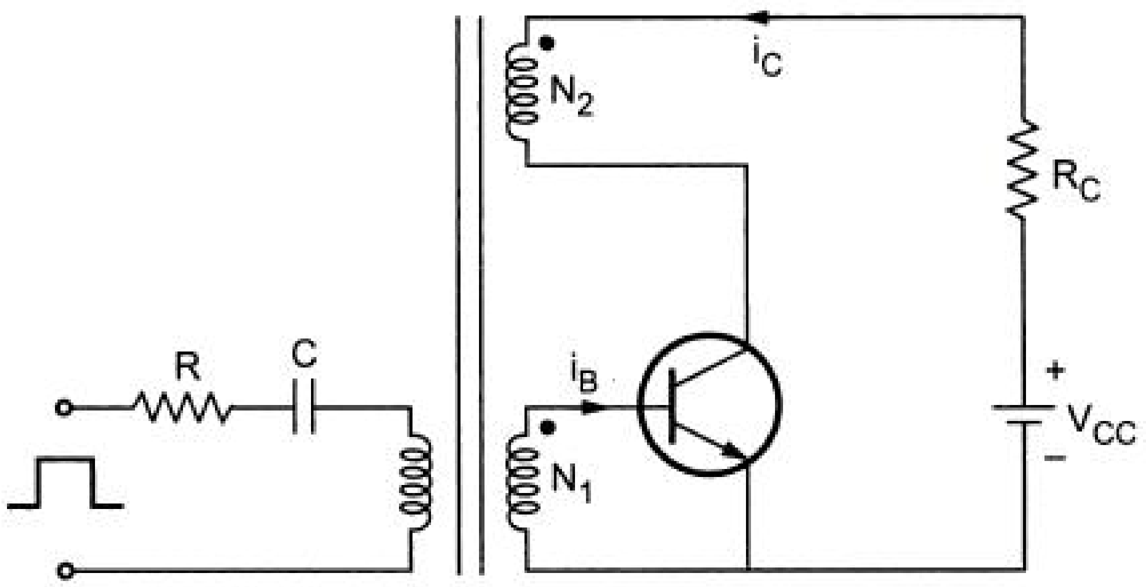


Fig. 1.7.4 Proportional base drive control

A short duration pulse is applied to turn-on the transistor. The transistor turns-on and collector current starts flowing. The collector current passes through the coil which is magnetically coupled to base coil. Hence collector current induces the current in the base coil also. This current acts as base drive to the BJT. The RC time constant determines the duration of the pulse to be applied externally to drive BJT into saturation. The turns ratio must be,

$$\frac{N_2}{N_1} = \frac{I_C}{I_B} = \frac{\beta I_B}{I_B} = \beta$$

The base current then varies according to variations in the collector current. The transistor can be turned off by applying negative pulse through RC circuit. This makes base current negative and BJT turns-off.

1.7.4 Anti-saturation Control

Answer following question after reading this topic.

1. *Draw the drive circuit for BJT. What is anti-saturation control ?*

Most likely and **Important** Question

We know that excess base current increases storage time of the BJT. Hence the turn-off time increases. Such excess or heavy base drive is called hard saturation. Therefore transistor must be operated in soft saturation. This means base must be given the carriers which are sufficient to drive the transistor in just saturation (quasi-saturation).

Fig. 1.7.5 shows the circuit diagram to achieve quasi-saturation. In this circuit the base drive is applied at terminals a-b. We can write following equation for loop consisting of $a - D_1 - B - E - b$,

$$v_{a\text{-}b} = v_{D1} + v_{BE}$$

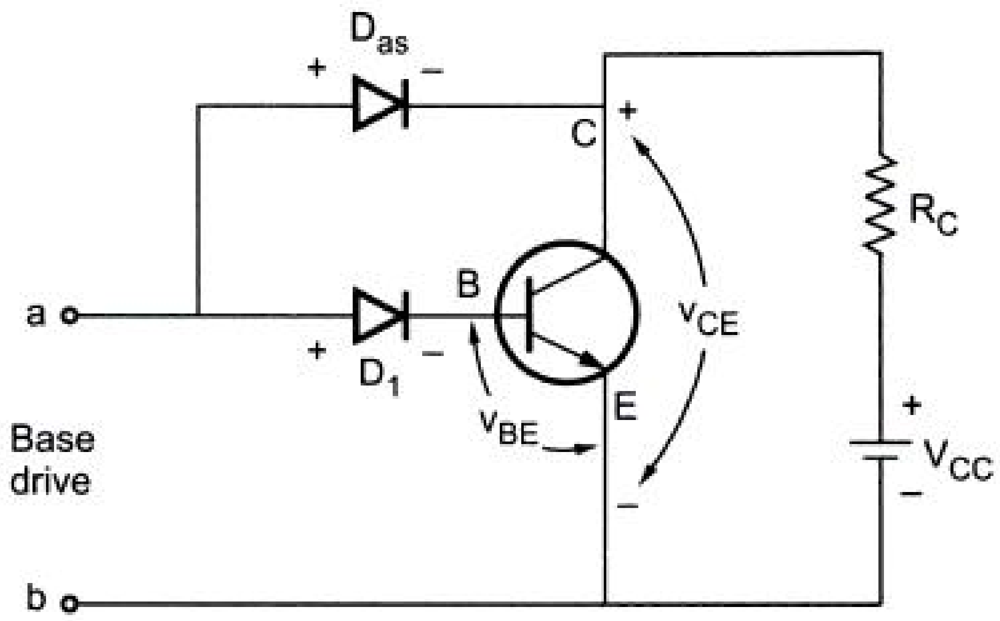


Fig. 1.7.5 Base drive with anti-saturation diode

Similarly for loop a - D_{as} - C - E we can write,

$$v_{a\text{-}b} = v_{D_{as}} + v_{CE}$$

Hence equating the two equations,

$$v_{D1} + v_{BE} = v_{D_{as}} + v_{CE}$$

Normally $v_{D_{as}} = v_{D1}$. Hence above equation becomes,

$$v_{CE} = v_{BE}$$

This shows that the collector-emitter voltage will be equal to base-emitter voltage. When BJT turns on, the base-emitter voltage is nearly 0.7 and collector-emitter saturation voltage is 0.3. Because of anti-saturation diode $\left(v_{D_{as}}\right)$, the collector-emitter voltage is raised to v_{BE}, i.e. 0.7 V. Hence the BJT is no longer in saturation. It is just above saturation. This effect takes place because of anti-saturation diode $v_{D_{as}}$. Since BJT is above saturation, there are no excess carriers in base and its storage time is reduced. This reduces 't_{off}' and hence switching time. The collector-emitter voltage can be further increased by putting additional diode in series of D_1.

Disadvantages of anti-saturation diode

The collector-emitter voltage is increased. This increases the on-state losses in BJT.

1.7.5 Typical Driver Circuit for Power BJT with Isolation

Answer following question after reading this topic.

1. *Draw an isolated base drive circuit for a power BJT and explain how over current protection can be achieved.*
Marks [3], Dec.-2001; Marks[6], Dec.-2004

Most likely and **asked in** previous University Exam

Fig. 1.7.6 shows the typical driver circuit for power BJT that takes into consideration all the earlier requirements.

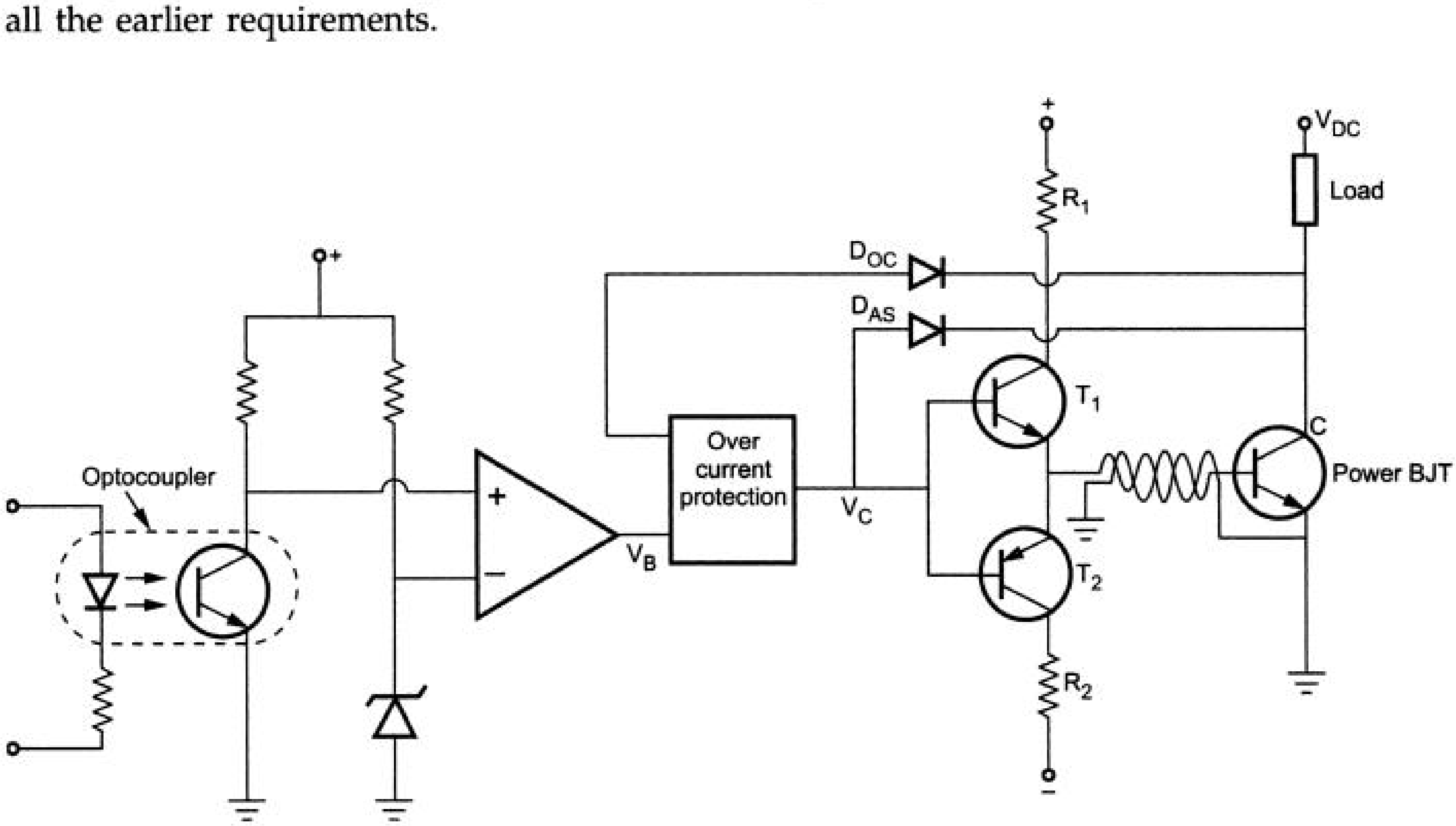


Fig. 1.7.6 Typical driver circuit for Power BJT

- The drive from control circuit is given to driver circuit through optocoupler.
- **Overcurrent Protection :** The signal is amplified, buffered by the comparator and then given to overcurrent protection circuit. The collector voltage of main transistor is sensed through diode D_{OC}. If the collector current increases, then collector voltage will rise. This rise is sensed by overcurrent protection circuit to disable the drive of BJT.
- The output from overcurrent protection circuit is given to pair of pnp-npn transistors T_1 and T_2. These transistors provide the required base current to power BJT to drive it in saturation.
- **Anti-saturation Control :** Note that the collector voltage of power BJT is monitored through diode D_{AS}. This provide anti-saturation control. It is called backer's clamp. It ensures that BJT always operates in quasi-saturation.
- Transistor T_1 provides large positive voltage and current to drive BJT in saturation of quasi-saturation. and transistor T_2 provides large negative voltage and current for faster turn-off of BJT.
- The base-emitter wires of power BJT are twisted to minimize stray inductance.

1.8 Drive Circuit for MOSFET

Answer following question after reading this topic.

1. *Explain the typical gate drive circuit for MOSFET.*

Most likely and **Important** Question

The gate drive circuit for MOSFET should satisfy the following requirements :

(i) The gate-source input capacitance should be charged quickly.

(ii) MOSFET turns on when gate-source input capacitance is charged to sufficient level.

iii) To turn-off MOSFET quickly, the negative gate current should be sufficiently high to discharge gate-source input capacitance.

Fig. 1.8.1 shows the gate drive as per above requirements. The gate drive is applied across the terminals a-b. Initially the resistance R_1 is bypassed by C_1 and full drive voltage is applied to the gate. This charges the gate-source capacitance quickly. As the capacitor C_1 charges, the gate current reduces. Once the MOSFET is turned on required gate current is very small. When MOSFET is to be turned off, the voltage v_{a-b} is made zero. This applies capacitor voltage across gate-source in negative direction. Therefore charge on the gate-source capacitance is removed quickly. C_1 then discharges through R_1. The resistance R_2 provides additional discharge path for gate-source capacitance.

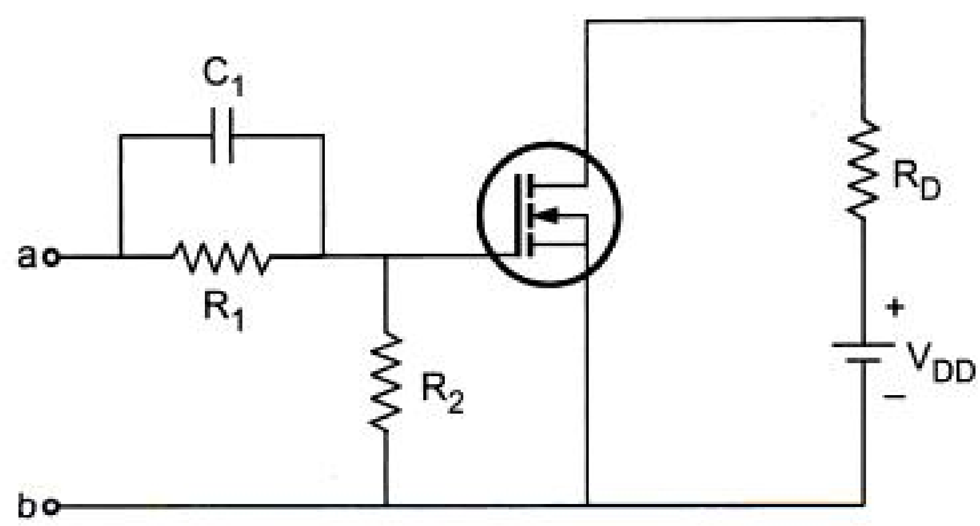


Fig. 1.8.1 Gate drive circuit

1.9 Driver Circuit for IGBT and MOSFET with Isolation

Answer following questions after reading this topic.

1. *Draw the typical isolated gate drive circuit for a MOSFET and explain its operation.*
   Marks [8], Dec.-2002; Marks [6], May-2003, Dec.-2003
2. *Draw the typical driver circuit for the IGBT.*
   Marks [4], May-2000, Dec.-2000; Marks [5], May-2002

Most likely and **asked in** previous University Exam

Fig. 1.9.1 shows the driver circuit for IGBT which uses IR 2125 IC.

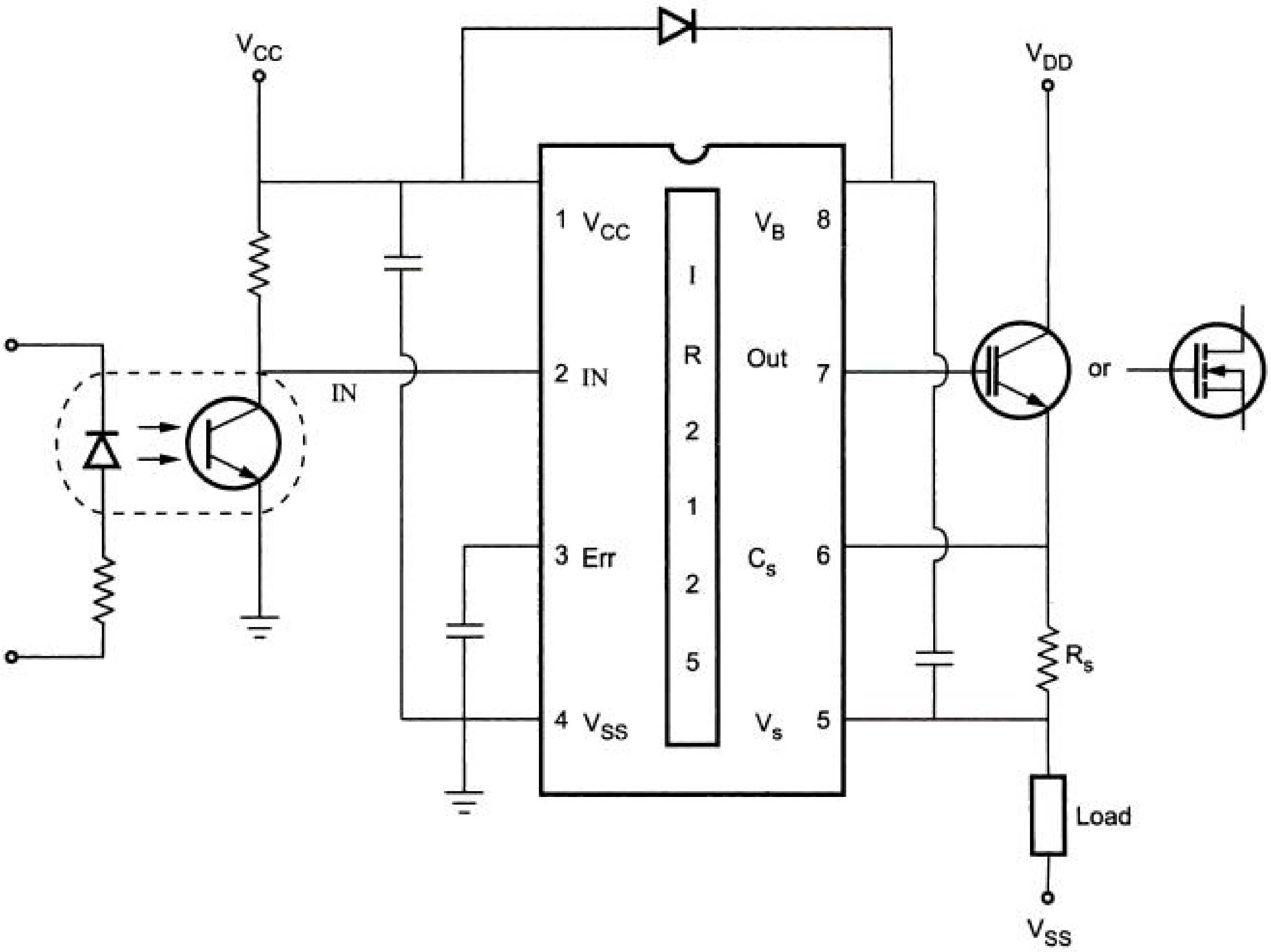


Fig. 1.9.1 Driver circuit for IGBT

- Here IR 2125 is the high voltage, fast switching MOS gate driver with single floating gate driver channel. This IC can be used to drive N-channel power MOSFET or IGBT.
- Overcurrent flowing through the IGBT is detected through R_s and C_s terminal of the IC.
- The error pin of the IC indicates fault conditions.