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APPLICATION NOTE

INSULATED GATE BIPOLAR TRANSISTORS IN HIGH FREQUENCY RESONANT CONVERTERS

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ABSTRACT

IGBT technology produces devices that are easy to drive, are capable of switching at high voltages and currents and operate at high current density.
A common application for this class of device is in off-line motor drives that use them in a "hard" switching mode.
Designs are now begining to be made that use the IGBT in resonant converters with "soft" switching and that operate at higher frequencies.
This paper discusses the operating limits of IGBTs in resonant circuits. In particular, this analysis considers the thermal balance and the maximum current density that can be achieved by IGBTs in this type of application.
The major resonant sub-circuits are highlighted and the duality rules that permit the use of these circuits in place of other configurations, discussed.
Finally, a practical circuit is given for driving and protection of IGBTs.

1. INTRODUCTION

Resonant converters will operate at much higher frequencies than conventional designs of converters. For this reason they are attractive because using a higher operating frequency means that the size of passive components in the circuit will be smaller. The higher frequency is possible because the converter switching losses are lower. The extent of this improvement is dependent on the converter structure and mode of operation. Until recently resonant converters used SCRs, bipolar transistors or Power MOSFETs as switching elements.

The purpose of this paper is to consider the use of IGBTs in resonant converters. IGBTs combine some of the advantages of bipolar transistors and Power MOSFETs. For example easy voltage drive, fast and efficient protection and low on-state dynamic resistance. The paper also analyses IGBT losses and the dependence of their maximum operating frequency on the converter structure and mode of operation. A practical example is discussed that uses a fast IGBT, the STGP10N50, which is rated at 10 Amps/500 volts.

2. RESONANT STRUCTURE

The resonant switch is the basic element of any resonant converter. It is a single tuned sub-circuit that includes a switching component, a diode, an inductor and a capacitor. Depending on the position of the diode, this resonant switch is uni- or bi-directional, thus providing half or full wave operation. The major feature of this type of sub-circuit is its ability to switch at zero current (or zero voltage). This reduces the switching losses as compared to "hard" switching circuits. This means that current and voltage do not occur simultaneously across the switch. As a result the switch will only experience either a voltage or a current.

There are two main resonant converter configurations:

a) A quasi resonant converter which uses one resonant switch excited in discontinuous operating mode by pulse frequency modulation. Because the current (or voltage) wave is whole (the waveform is unbroken) the switching behaviour of the resonant switch is maintained. Evaluation of the losses in the IGBT in these converters is made using the two basic operating modes: zero current mode (ZCM) and zero voltage mode (ZVM).

b) A resonant converter uses a minimum of two resonant switches in a symmetrical structure. It allows continuous operating mode operation which changes the switching conditions of the resonant switch: it is not a whole wave mode and zero current (or zero voltage) switching occurs, depending on the switching frequency, only at turn on or at turn off. So, a large fraction of the IGBT's losses can be deducted from the quasi resonant analysis.

Section 3 gives an accurate analysis of IGBT losses in quasi resonant converters. The overview of switching conditions in resonant converters provides the basis for loss evaluation using the analysis of the previous section.

3. IGBTs IN QUASI RESONANT CONVERTERS

As already stated previously, in quasi resonant converters the IGBT operates as a single tuned resonant switch with a quasi sinusoidal current (or voltage) waveform. This analysis examines each mode.

3.1 IGBTs IN ZERO CURRENT SWITCHING QUASI RESONANT CONVERTERS.

a. Switching: The IGBT's switching behaviour is analysed using the circuit shown in figure 1 - full wave mode zero current switching (ZCS) quasi resonant converter.

Because the collector current is zero during switching (see fig 2 & 3), the only switching losses occuring are due to the internal discharge of the IGBT output capacitance at turn-on. The discharge current is not detectable externally, but the charging current appears in figure 3 when voltage is re-applied to the collector. Integration of the current waveform shows that the energy stored in the output capacitance of this IGBT is about 10μJ at 400V.

b. Conduction: Figure 4 shows that the current factor is low due to the discontinuous operating mode of the quasi resonant converter. For this reason it is important to be able to use the switch at high current density and this is the major characteristic of an IGBT.

Figure 5 shows the IGBT saturation at high current and its dependence on gate source voltage. The current saturation threshold is virtually independent of temperature (less than 10% between 85°C and 95°C) and conduction time (unchanged between 1μsec and 5μsec).

An IGBT with a nominal current of 10A can conduct more than 80A without saturation. However, with a ZCS quasi resonant converter, the maximum operating current is limited by conduction losses as follows:

Considering the maximum switching frequency (duty cycle < 50%) and the transfer characteristics given in figure 6, the conduction losses are:

$$P_{cond} < (1.4\ I_{pk}/\pi) + (0.118\ I_{pk}^2/4)\ \text{watts}$$

for a 30A peak P_{cond} < 40W - a maximum realistic value for a TO-220 package.

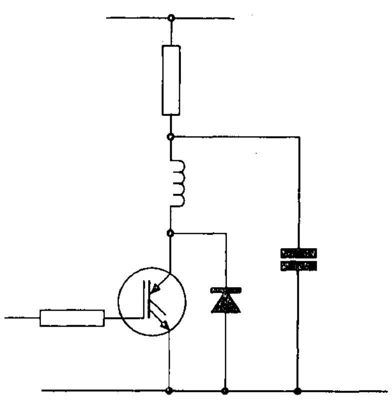


Fig.1: Full-wave mode ZCS quasi resonant converter IGBT STGP10N50 10A/500V.

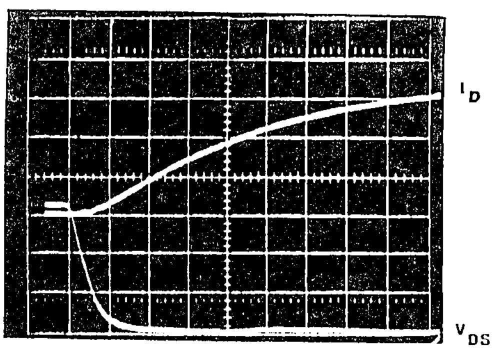


Fig.2:Turn on switching circuit defined in figure 1
V_{DS} = 100V/div R_C = 50 Ohms
I_D = 20A/div t = 100nsec/div

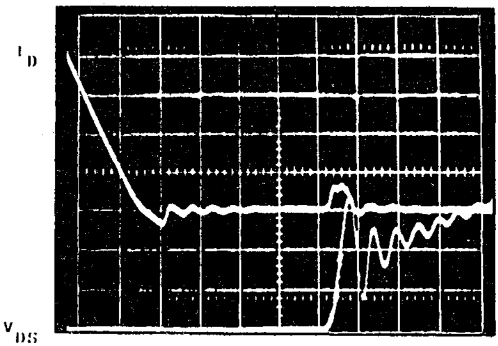


Fig.3:Turn on switching circuit defined in figure 1
V_{DS} = 100V/div T_{case} = 50°C
V_{GS} = 5V/div R_G = 10 Ohms
I_D = 20A/div t = 100nsec/div

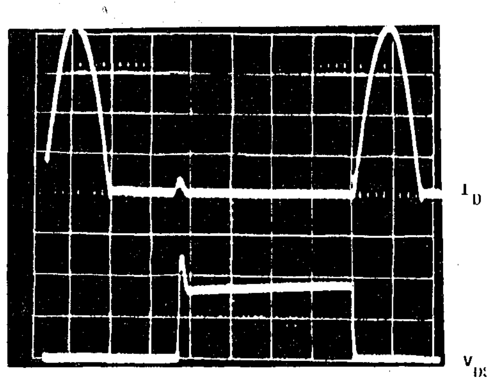


Fig.4: Drain current and voltage wave form. Circuit defined in fig. 1 (a snubber is used in order to avoid voltage oscillations)
I_D = 1A/div V_{DS} = 100V/div t = 5msec/div

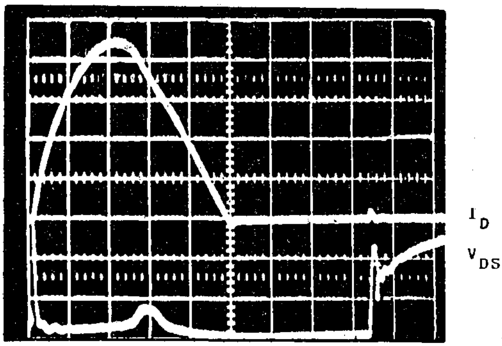


Fig.5: Saturation test circuit defined in figure 1
I_D = 20A/div V_{DS} = 5V/div V_{DS} = 100V/div
t = 1msec/div

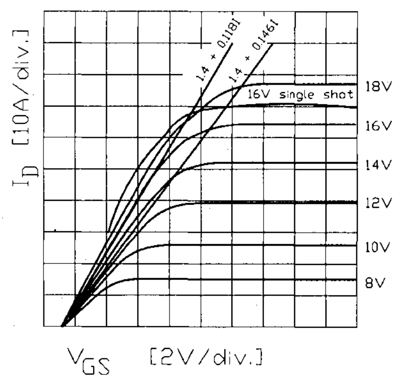


Fig.6: Characteristics of STCP10N50
Tj = 100°C
$V_{DS(on)}$ = 1.4 + (0.118 x 1) for V_{GS} = 15V

c. Operating range and limits: When the STGP10N50 operates over its full frequency range the peak current in this converter should be limited to 30A by the conduction losses. In any case the RMS current is compatible with die bonding:

$$I_{RMS} = \sqrt{d}\, I_{pk} / \sqrt{2} = I_{pk} / 2$$

at maximum frequency with 30A peak I_{RMS} < 15A.
As there are no major switching losses (10 µJ), a ZCS converter is able to operate at several hundred kilohertz.

3.2 IGBTs IN ZERO VOLTAGE SWITCHING RESONANT CONVERTERS.

a. Switching: The IGBT's switching behaviour is analysed using the circuit in figure 7, a half-wave zero voltage switch (ZVS) quasi resonant converter.

The intrinsic properties of an IGBT create specific losses due to the current tail induced by stored minority carriers, in spite of the "soft" voltage switching. Contrary to bipolar transistors, these carriers are not discharged rapidly as there is no access to the base and they induce losses when voltage is re-applied after current turn-off.

Figure 8 shows current and voltage waveforms in the IGBT during conduction and after current turn-off. Figure 9 shows an example of the evaluation of the turn-off energy (E_{ct}) by integration of the current, time and voltage.

Current tail losses were measured with respect to temperature, switched current and re-applied voltage. The results of these measurements are shown in figures 10 to 15. They show that turn-off losses are proportional to dV/dt when current and temperature are constant and proportional to the square of the current when temperature and dV/dt are constant.

- Current tail losses = $P_{ct} = K_{(dv/dt,Tj)} \cdot I^2 \cdot f$
- As K is proportional to dV/dt (ref: figures 13, 14, 15 - gradients of the curves) and dV/dt is proportional to I in such an inverter, the losses can be expressed as:

$$P_{ct} = K'_{(Tj)} \cdot I^3 \cdot f$$

where I = switched current.

As K' increases rapidly compared to T_j, the maximum switched current must be strictly limited and the heatsink sufficiently sized to avoid thermal runaway.

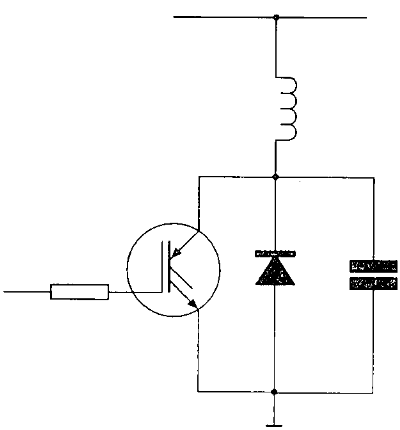


Fig. 7: Half wave mode ZVS quasi resonant converter

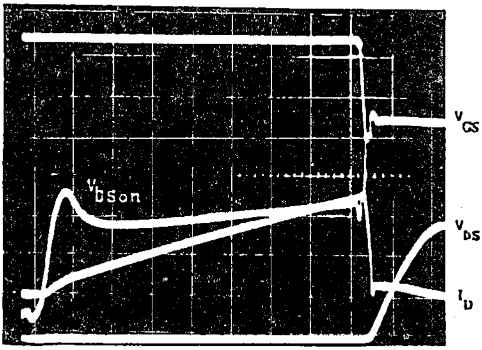


Fig. 8: Drain current and voltage wave form. Circuit defined in figure 7.
I_D = 5A/div V_{DSon} = 1V/div
V_{DS} = 100V/div V_{GS} = 10V/div

b. Conduction. In this type of converter, IGBT conduction losses are not a constraining factor due to the low average current. They can easily be calculated by integration, (current x voltage) figure 8.

c. Thermal balance. The circuit shown in figure 7 is used where:

switched current = I_p = 20A

dV/dt = 1500V/sec

t_{on} = 9.5 msec

The losses due to the current tail can be calculated by subtracting the conduction losses from the total measured losses (thermal balance). An alternative method is to use the numerical integration as shown in figures 9 to 15:

As the results are similar, the numerical integration allows easy calculation of the losses.

d. Operating range and limits. Considering the IGBT switching its normal current, the

Frequency	E_{ct} (Thermal balance)	E_{ct} (numerical integration)
6kHz	566mJ	420mJ
8kHz	725mJ	600mJ

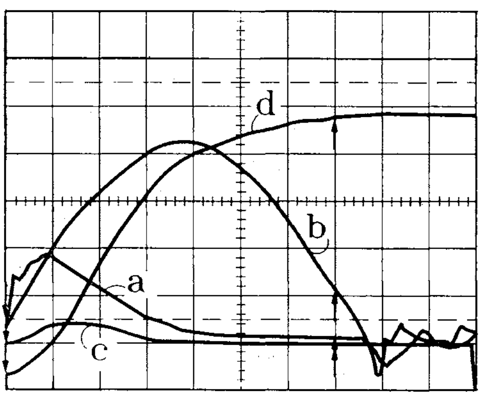


Fig. 9: Energy evaluation circuit defined in fig. 7.
curve a: current tail (1A/div)
curve b: drain voltage (100V/div)
curve c: (curve a) x (curve b)
curve d: curve c x dt

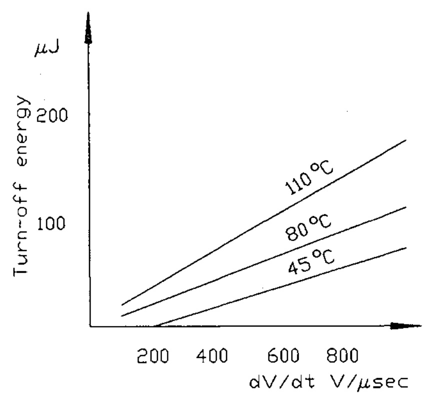


Fig. 10: Turn-off energy E_{ct} 10A switching

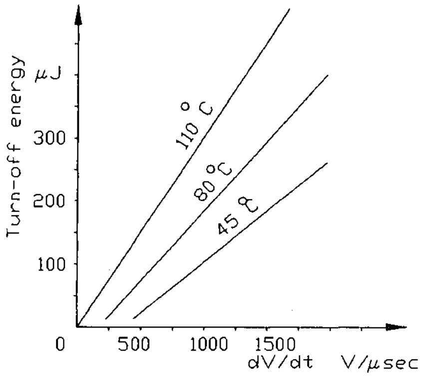


Fig. 11: Turn-off energy E_{ct} 15A switching

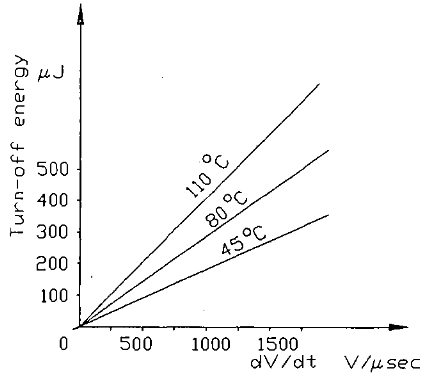


Fig. 12: Turn-off energy E_{ct} 20A switching

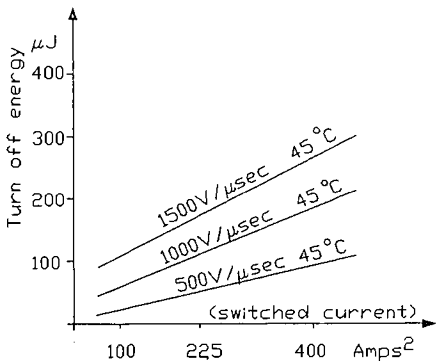


Fig. 13: Turn-off energy E_{ct} - T_j = 45°C

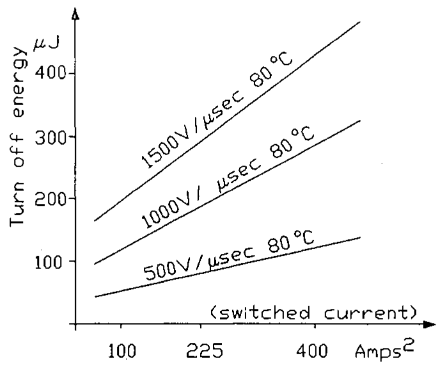


Fig. 14: Turn-off energy E_{ct} - T_j = 80°C

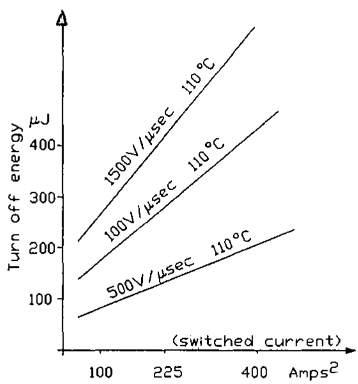


Fig. 15: Turn-off energy E_{ct} - T_j=110°C

maximum switching frequency can be evaluated with, for example, the following conditions:

I_{peak} = 10A dV/dt = 500V/msec

Switching losses = 10W
(Safety margin = 33%) ref:- figures 10-15

T_j = 80°C operating frequency = 110kHz

T_j = 110°C operating frequency = 80kHz

This shows that using IGBTs in this configuration is possible up to 80kHz with fast IGBTs .

4. IGBTs IN RESONANT CONVERTERS.

The switching conditions of this type of converter are dependent on the switching frequency because they work in the continuous operating mode. For this reason, close to the resonant frequency, the constraints on the IGBT are similar to those of the quasi resonant converter in the ZCS or ZVS mode, whereas above or below the resonant frequency, a different switching mode occurs.

4.1 Voltage excited resonant converter.

An example of a voltage excited resonant converter circuit is shown in figure 16. Voltage excitation requires a current load, i.e. a series resonant circuit.

a. Operating above the resonant frequency
At switch-on: IGBTs operate in the ZCS mode without dV/dt and therefore have negligible losses.
At switch-off: Current and voltage are switched together; as dV/dt is generally reduced by using an external capacitor, the turn-off losses are limited to current tail losses. Consequently, in this situation, the results of the ZVS quasi resonant converter analysis can be applied again.
Conduction in the on-state: The maximum conduction losses occur close to the resonant frequency. They can be calculated using the ZCS quasi resonant converter analysis.

An example:

Conditions: Device STGP10N05 IGBT

T_j = 110°C maximum
dV/dt = 1000V/msec

maximum peak current = 16A (close to f_r)
maximum switched current ≈ 8A ($f \approx 2f_r$)

Considering that the maximum conduction losses = maximum switching losses

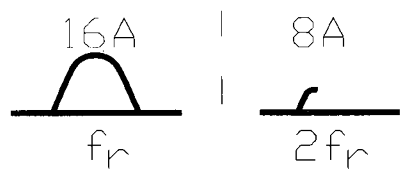
maximum conduction losses =

$(0.445 \cdot I) + (0.0295 \cdot I)^2 = 15W$ (for 16A)

maximum switching losses = $E_{ct} \cdot f$

(for 8A see the curve in figure 15)

The corresponding operating frequency is from 30kHz (f_r) to 60kHz ($2f_r$). As in the case of the ZVS quasi resonant converter, the maximum switched current must be strictly limited and the heatsink sufficiently sized in order to avoid thermal runaway.



b. Operating below the resonant frequency:
At switch-on: Current and voltage are switched together. The losses are due to the discharge of the IGBT's output capacitance and to the recovery of the diode on the other IGBT.

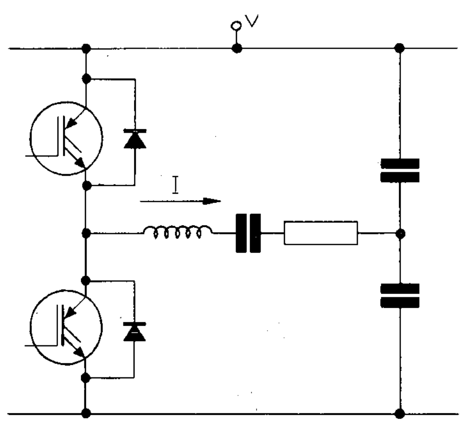


Fig. 16: Voltage excited resonant converter

The maximum losses can be evaluated as:

$$1/2\ Vf(I_{peak\ max}/2 + I_{RM})^2\ dt/dI$$

I_{RM} = diode peak reverse current

At switch off the IGBT is operating in ZCM without switching losses.
Conduction: the maximum conduction losses can be evaluated as for the ZCS quasi resonant converters because it is operating in full wave mode close to the resonant frequency.

An example:
Conditions IGBT = STGP10N50

dI/dt = 300A/sec
V = 300V
T_j = 110°C
I_{RM} = 16A
maximum peak current = 20A
maximum switched current ≈ 10A

Considering:

maximum conduction losses = maximum switching losses

maximum turn-on losses = 338J

maximum conduction losses = 24W

The corresponding operating frequency is from 70kHz ($f_r/2$) to 140 kHz (f_r). Contrary to the previous mode, there is no risk of thermal runaway and the IGBT seems to be a good alternative to SCRs in this type of high frequency converter.

4.2 CURRENT EXCITED RESONANT CONVERTER.

An example of a current excited resonant circuit is shown in figure 17. It is the duality of the previous circuit shown in figure 16. The current excitation requires a voltage load giving a parallel resonant circuit. The switching behaviour depends on the operating frequency.

a. Operating above resonant frequency:
When one IGBT is switched on there is reverse recovery current from the diode of the second IGBT through the capacitor. This means both current and voltage are switched. The maximum losses can be evaluated as:

$$1/2\ f.V(I_{RM} + I_D)^2\ dt/dI$$

where:

V = maximum switched voltage
I_{RM} = diode recovey current
I_D = maximum switched current

At switch-off: the serial diode recovery current reverses the IGBTs current and its collector-emitter voltage. Because of this the reverse recovery charge, Qrr, of the series diode must be kept lower than that of the internal P/N diode of the IGBT as this would cause the IGBT's diode to exceed its breakdown voltage, and conduct the leakage current of the series diode.
However, current tail losses can occur when re-applying voltage during the off state, and depend on the minority carrier lifetime versus the delay between the diode recovery and the positive collector voltage rise. The maximum turn-off losses occur close to the resonant frequency and are similar to those of ZVS quasi resonant converters.
Conduction: The current flowing is continuous and the duty cycle is 50%. The losses are:

$$\approx 1/2\ I_D \cdot V_{DS(on)}$$

b. Operating below resonant frequency.
At switch-on: The IGBTs operate in ZVS mode giving negligible switching losses.
At switch-off: Current and voltage are

switched-off. Consequently, losses can be evaluated using the ZVS quasi resonant converter results.
Conduction: The duty cycle is not dependent on the frequency so the losses are similar to those above.

5. DRIVE AND PROTECTION CIRCUIT.

The analysis of IGBTs in resonant converters shows that many different switching conditions can occur. The circuit shown in figure 18 is suitable for driving an IGBT gate as it provides the following functions:
- Short circuit protection and current limiting.
- Adjustable sinking and sourcing output current.
- Very low output impedence after turn-off, masking the Miller effect.

6. CONCLUSION

This analysis shows that IGBTs are perfectly suited to resonant converters when the turn off switching is zero current mode. In this situation the switching frequency can rise to several hundred k Hertz giving a controlled current several times its own nominal current. IGBT's are an attractive replacement for more traditional switching components already in use in resonant converters. They offer the following advantages when replacing:

SCRs: the IGBT provides high dV/dt immunity and virtually no dI/dt limit, no t_q and very fast dynamic behaviour. It is very easy to protect under both dynamic and static conditions.

Bipolar Transistors: the IGBT offers very easy gate drive.

Power MOSFETs: IGBTs have a higher current density.

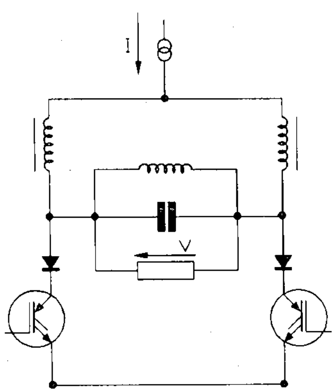


Fig. 17: Current ecited resonant converter

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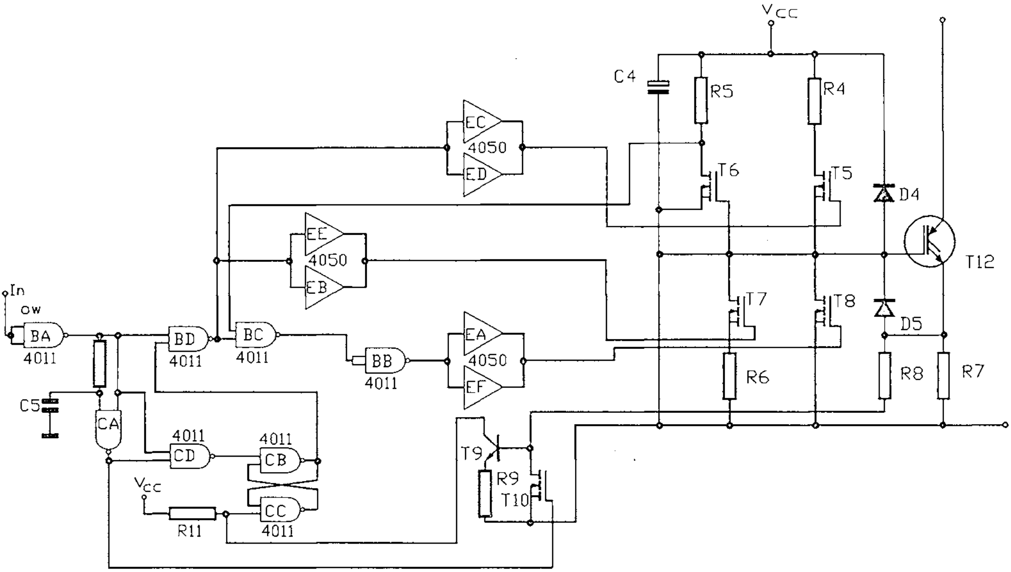

Fig. 18: Gate drive circuit.

APPENDIX .

DUALITY CONSIDERATIONS OF AN ELECTRIC CIRCUIT

1. Every voltage source (or load) has a capacitive nature.
   Every current source (or load) has an inductive nature.
2. Connected source and load must always have opposing natures:
   - Capacitive source with inductive load
   - Inductive source with capacitive load.
3. A voltage source becomes inoperative when the output is open.
   A current source becomes inoperative when the output is shorted.
4. Every circuit has duality. The duality rules are set out below.