Lab no. 4

CONTROL OF THE POWER BIPOLAR JUNCTION TRANSISTORS

1. Introduction

The ***B****ipolar* ***J****unction* ***T****ransistor* (BJT) is a well known semiconductor device described in detail in the majority of the electronic or semiconductor treaties. These transistors are current-controlled devices. The control current, called ***base current*** (I_B), should be permanently maintained during the transistor on-state. A certain base current imposes a certain ***collector current*** (I_C) if the external circuit does not limit its value. In this situation, the transistor operates in the ***active region*** (active state) where it acts as a variable resistance. The ratio between the power output current I_C and the base control current I_B is defined as transistor amplification factor (***current gain***): $\beta = I_C/I_B$. Because in active state most of the electrical power that flows through the transistor is retained by it (power conduction losses), the full conduction mode of the BJTs is recommended. This particular on-state is called ***saturation*** and can be obtained if an excess base current is used for a certain value of the collector, imposed by the load: $I_B > I_C / \beta$ (***saturation condition***).

The ***power*** **BJTs** are made for high ratings of voltages and currents. Unfortunately, as a tribute to these qualities, the power BJTs can not reach the high switching frequencies of the low-power BJTs because they operate with high power switching losses. In addition, they have a low current gain (typically $\beta<15$), feature that requires a relatively high control power. All of these disadvantages appear because the power BJTs semiconductor structure is different from the low-power BJTs. The structure form, the layer thickness and the doping level directly affects the transistor operating characteristics and parameters.

2. The symbols and the semiconductor structure of the power BJTs

Nowadays the power bipolar junction transistors are almost exclusively made from silicon semiconductor materials. Similar to the low-power devices the power BJTs can be of type *npn* or *pnp*. Also, the symbols and terminal names are identical.

In practice the *npn* power BJTs are preferred, whose structure and symbol are shown in Fig.4.1. Like any controllable device the power BJT has two power terminals, collector (C) and emitter (E), and a control terminal called base (B). The emitter is used as a common terminal by the power circuit and by the control circuit,

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being assimilated as a ground (GND) point (common emitter topology). For a *npn* BJT, (+) on the collector and (-) on the emitter (u_{CE}> 0) means its forward biased.

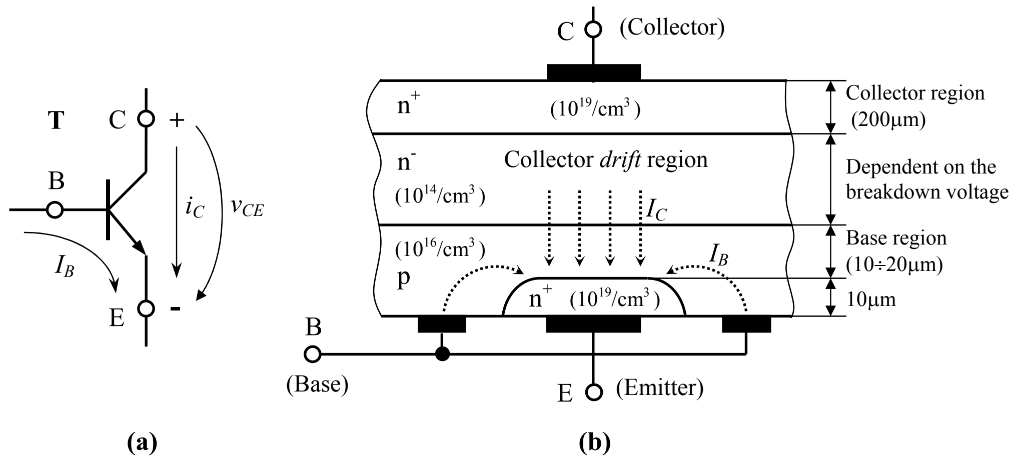

Fig. 4.1 The symbol (a) and the semiconductor structure (b) of a *npn* power BJT.

The main difference between the semiconductor structures of the power BJT and of the low-power BJT is the additional layer that forms the ***collector drift region***. Its role is similar to that of the power diode structure, which is to block high forward voltage through the junction formed with the base layer, the base-collector (B-C) junction. For this reason the drift region is lightly doped (10^{14}electrons/cm^3) and its thickness is relatively high, depending on the forward breakdown voltage for which the device has been manufactured. When the transistor is forward biased and is in off-state (I_B=0) the B-C junction is reverse biased, sustaining all the supply voltage. This lock is possible if the thicknesses of the drift region and the base layer are large enough so that the spatial electric charge has enough space to achieve the required value for the supply voltage counterbalancing.

The turn-on transient of the transistor is initiated if the B-E junction is forward biased and the base current I_B causes the flow of the holes from the base to the emitter and the flow of the electrons from the emitter to the base. Thus, in the base layer, an excess of stored charges appears, formed by the minority carriers (electrons), the amount of which can control the phenomenon of conduction between the collector and emitter terminals. If the power BJT is forward biased, as shown in Fig.4.1(a), the electrons' flux that leaves the n^+ emitter layer is higher than that which flows to the base terminal. Due to the small thickness of the base (less than the electrons diffusion length), due to a large collector area and to the excess carrier density, most of electrons which leave the emitter cross the narrow base layer and diffuse to the drift region, where they recombine with the positive charges which leave the collector terminal. In this way the collector current I_C flows from the collector to the emitter, in the direction given by the arrows shown in Fig.4.1(b). Both negative and positive

charges (the electrons that leave the emitter and the holes that leave the collector) contribute to the collector current flow. For this reason the semiconductor device is called ***bipolar*** transistor.

When the excess electron charge is present only in the base layer the transistor is in the active conduction state in which the collector current value can be controlled through the base current. Once the base current is increased and the stored charge expands into the drift region the transistor is fully open, ***saturated***. In turn, the saturation can be: ***quasi-saturation*** near the limit between active and full conduction and the ***hard saturation*** achieved when the base current exceeds a certain value and the stored charge areas extends to the entire collector drift region.

In the '70s compact modules containing two or three power transistors connected in Darlington configuration, started to be manufactured in order to reduce the control power for the BJTs. Thus, were achieved the ***M****onolithic* ***D****arlington* (MD) structures whose current gain is higher because it contains, as principal term, the current gains multiplication of the MD transistors. Fig.4.2 shows two MD variants with two and three transistors, respectively.

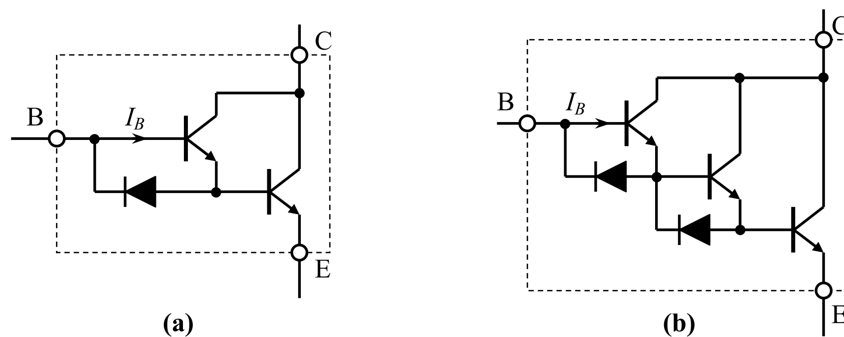

Fig. 4.2 Monolithic Darlington modules obtained with:
(a) two BJTs; (b) three BJTs.

3. Static characteristics of the power BJTs

After the semiconductor structure optimization, the power BJTs result without reverse blocking capability. This feature is a consequence of the high level doping of the base and emitter layers which causes a low reverse breakdown voltage for the B-E junction, around 20V. It is a value that must be taken into consideration when a negative voltage is chosen to accelerate the turn-off transient of the power BJT. However, the lack of the reverse blocking capability is not a major drawback for the power BJTs because, usually, they are used in anti-parallel configuration with a recovery diode which excludes a reverse bias possibility.

In Fig.4.3(a) the BJT static volt-ampere (*i-v*) characteristics are presented for different values of the I_B control parameter. If the transistor's base-emitter circuit is open ($I_B = 0$) the device is in off-state and the collector current can be considered zero ($I_C = 0$). Thus, the operation point is on the forward blocking characteristic for any C-E voltage less than the ***C****ollector-****E****mitter* ***B****reakdown* ***V****oltage* ($v_{CE} < BV_{CE}$).

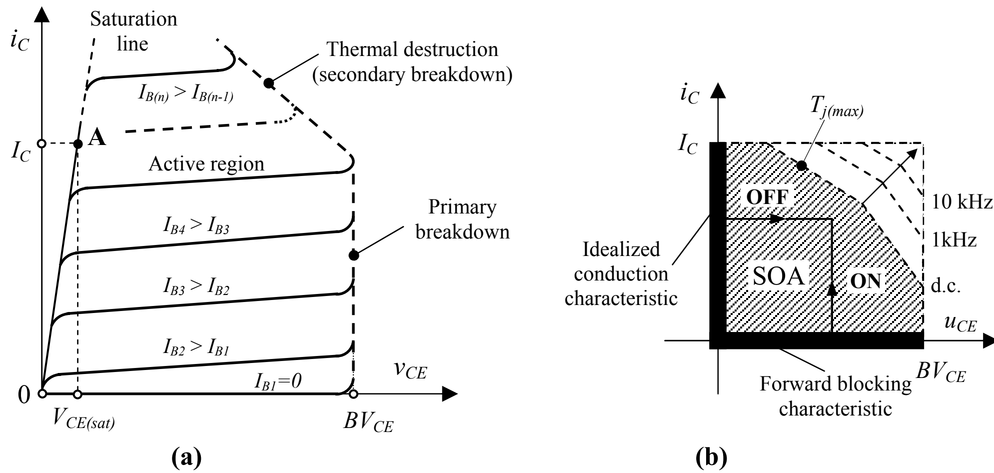

Fig. 4.3 (a) Real *i-v* characteristics of the power BJTs; (b) Idealized *i-v* characteristics with the ***S****afe* ***O****peration* ***A****rea* (*SOA*).

When the power BJT is turned on with the help of the base currents $0 < I_{B1} < I_{B2} < I_{B3} < ..... < I_{B(n-1)} < I_{B(n)}$ the operating point is placed on the static *i-v* characteristics, in the active region or in the saturation region.

If the external load circuit allows a sufficient value for the collector current, the operating point is placed on the *i-v* characteristics in active region, where the on-state resistance of the device is high. In this region, the I_C value is fixed by the I_B value:

$$I_C = \beta \cdot I_B \tag{4.1}$$

If the external load circuit limits the collector current to a certain value I_C and the base current keep the condition:

$$I_B > \frac{I_C}{\beta} \tag{4.2}$$

the operating point A (see Fig.4.3.a) is placed in the saturation region on the *i-v* characteristics where the on-state resistance becomes very small. In this steady state, the collector current is not controlled by the transistor, it is imposed exclusively by the load. The on-state voltage becomes very small $V_{CE(sat)}$= (1÷2)V which lead to the small power conduction losses. This quality makes the BJT a performer at this chapter,

along with the thyristor. In catalogues we find the maximum collector current I_C that can flow continuously through the saturated transistor and the maximum pulse collector current I_{CM}.

In Fig.4.3(a) the entire saturation region of the *i-v* characteristics (hard and quasi-saturation regions) was approximated with a line labeled *saturation line*. If the saturation condition is respected, the operating point is situated in the saturation area where a negligible voltage drop occurs across the transistor. Thus, the saturated line can be approximated with the idealized conduction characteristic from Fig.4.3(b). This static characteristic and the forward blocking characteristic suggest that the power BJT has the behavior of an ideal unidirectional switch.

The voltage breakdown process of the BJTs is called *primary breakdown*. There are also so-called the *secondary breakdown*, when the semiconductor structure is thermally destroyed. This occurs when the power losses are high and the heat can not be successfully evacuated from the silicon chip. This phenomenon evolves in avalanche due to the positive temperature coefficient of the bipolar junction transistors. In Fig.4.3(a) we can see the border where the temperature reaches the melting value.

In Fig.4.3(b) the area bounded by the blocking and conduction static characteristics is the ***S****afe* ***O****perating* ***A****ria* (SOA). This is a very important parameter that must be taken into account at the design stage, when the transistor is chosen according to the voltage, current and the switching frequency. In Fig.4.3 (b) is shown, hatched, the SOA corresponding to a continuous on-state of the transistor.

Because in power electronics the transistors operate in two stable states, the on-state and the off-state, the operating point crosses the first quadrant formed by the two axes in Fig.4,3(b), during the turn-on (ON) and turn-off (OFF) transient states. When the power transistor operates in switching-mode with a certain duty ratio value the SOA can be extended with the increasing of the switching frequency in the direction of the arrow shown in the figure.

4. Base current drive circuits for power BJTs

Usually, the power bipolar junction transistors are used in structures consisting of elementary switching cells. Such cell, a step-down voltage converter is shown in Fig.4.4 (a). This allows a DC/DC conversion, modifying the DC voltage based on the ***P****ulse* ***W****idth* ***M****odulation* (PWM) technique. The converter output voltage was labeled $v_{o(ut)}$ and the load is of resistive-inductive type (*R-L*). Also, the structure includes a recovery diode *D* that takes the discharge current of the *L* inductance that suddenly appears after the transistor is turned off. To operate, the power transistor *T* needs a ***base current drive circuit*** (***driver***) that receives the control PWM signal and sends it to the transistor control terminal as a base current i_B.

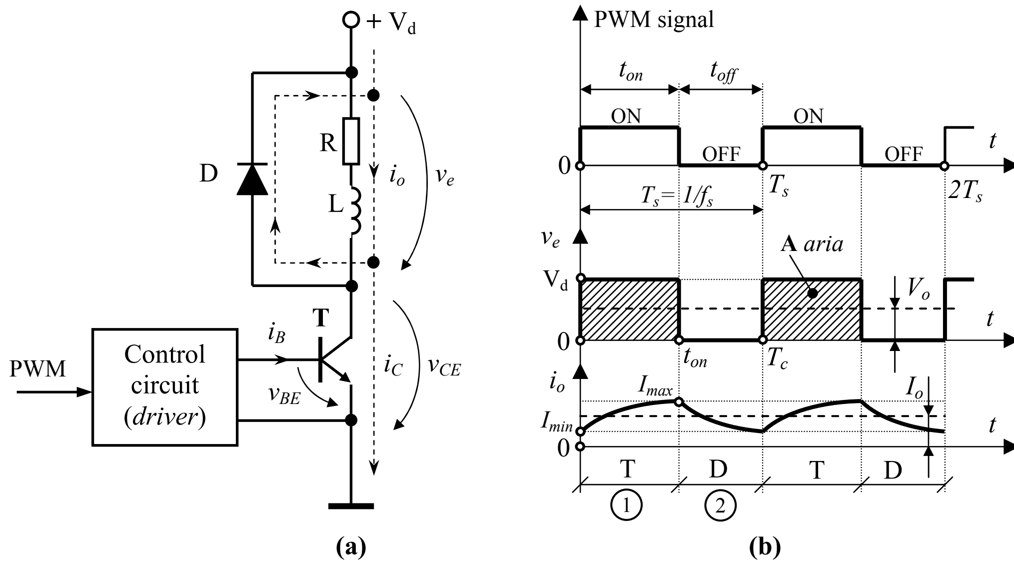

Fig. 4.4 (a) A step-down one-quadrant DC/DC converter (chopper) with BJT; (b) PWM control technique applied to the DC/DC conversion.

a) PWM control technique

To explain the PWM control technique we assume that the power transistor T is cyclically controlled (switched) as shown in Fig.4.4(b). During the ***switching period*** T_s the device is in on-state (ON) a t_{on} time interval and in off-state (OFF) a t_{off} time interval, so that: $T_c = t_{on} + t_{off}$. The frequency corresponding to the T_s period is:

$$f_s = 1/T_s \tag{4.3}$$

called the ***switching frequency*** or the *converter working frequency*. In practice, this frequency can be of kilohertz (kHz) order for the power BJTs.

During the time interval in which the T transistor, from Fig.4.4(a), is in on-state, the supply voltage V_d is connected to the R-L load. Thus, the instantaneous output voltage $v_o(t)$ is:

$$v_o(t) = V_d, \quad 0 \le t \le t_{on} \tag{4.4}$$

With the entry into conduction of T transistor the current through the load circuit begins to increase exponentially as a result of applying a voltage step to the R-L load circuit.

$$i_o(t) = I_{\min} \cdot e^{-\frac{t}{\tau}} + \frac{V_d}{R}\left(1 - e^{-\frac{t}{\tau}}\right), \qquad 0 \le t \le t_{on} \tag{4.5}$$

where $\tau = L/R$ is the time constant of the *R-L* circuit and $I_{\min}$ is the value of output current $i_o(t)$ at the beginning of t_{on} time interval (initial condition). At the end of t_{on} interval the current through the *T* switch and R-L load reaches the I_{max} value.

After *T* is turned off the $i_o(t)$ current will continue to flow through the recovery diode *D,* maintained by the energy stored in the electromagnetically field of the *L* inductance. The current waveform during the t_{off} time interval is a decreasing exponential:

$$i_e(t) = I_{\max} \cdot e^{-\frac{t}{\tau}}, \qquad t_{on} < t < T_c \tag{4.6}$$

At the end of t_{off} interval the output current reaches the I_{min} value.

Considering the diode as an ideal switch, without any voltage drop in on-state, during t_{off} time interval the instantaneous output voltage $v_o(t)$ is zero (*D* diode bypasses the load circuit):

$$u_o(t) = 0, \qquad t_{on} < t \le T_c \tag{4.7}$$

Based on the equations (4.4), (4.7) and from the Fig.4.4(b) result that the v_o waveform appears as a sequence (train) of rectangular pulses with V_d amplitude and t_{on} width. The average value of this periodic signal is the DC voltage obtained at converter output that can be calculated using the formula of average value:

$$\begin{aligned} V_o \overset{not}{=} \text{average value of } v_o(t) &= \frac{1}{T_s}\int_0^{T_s} v_o(t)\cdot dt = \frac{1}{T_s}\int_0^{t_{on}} V_d \cdot dt + \frac{1}{T_s}\int_{t_{on}}^{T_s} 0 \cdot dt = \\ &= \frac{\textbf{A}\text{ aria}}{T_s} = \frac{1}{T_s} V_d \cdot [t]_0^{t_{on}} = V_d \cdot \frac{t_{on}}{T_s} = V_d \cdot d \end{aligned} \tag{4.8}$$

where $\frac{t_{on}}{T_s} \overset{not}{=} d$ is the ***duty ratio*** of the transistor *T*. Because $0 \le t_{on} \le T_s$ then $0 \le d \le 1$.

Taking into consideration the (4.8) equation results:

$$0 \le d \le 1 \Rightarrow 0 \le V_o \le V_d \tag{4.9}$$

The (4.9) and (4.8) equations highlight that at the converter output it is obtained a train of voltage pulses whose average value (the DC component) is dependent on the pulses width (t_{on}). This method for the DC voltage adjust is known as ***Pulse Width Modulation*** (***PWM) technique***.

There are DC loads which do not accept to be supplied with voltages that have a pulse waveform, even these voltages containing a DC component. In such situations, depending on the nature of the load, current filters or voltage filters are used. In the power structure of Fig.4.4(a) the load inductance *L* acts as a filter that smoothes the current waveform as shown in Fig.4.4 (b). If, for example, the load is a DC motor, the current must be filtered because it is responsible for the electromagnetic torque generation. In this case an inductive filter (an inductance) must be used in series with the motor. If the converter switching frequency is high, a good current filtration can be achieved only with the motor’s own inductance.

b) Functions of the base current drive circuits

The power BJTs and the MDs are current-controlled devices (modules). This control variable must be maintained at an adequate value during the entire time interval in which the transistor needs to maintain its on-state. For this purpose we use base current drive circuits named ***drivers***. This term applies to all control circuits of the power transistors.

The functions which a transistor driver must fulfill are partially similar with those of a thyristor gate trigger circuit:

- The isolated and the communication function - through which multiple communication lines, with or without isolation, are maintained between the driver and its digital control structure as a hierarchical superior stage. The main line is dedicated to the logic control signal reception that contains the information about the transistor on-state or off-state at a time. Usually this signal is applied to a trigger input type which could repair the signal if it was affected by the disturbances. There are also communication lines for other input signals, such as RESET, START/STOP etc. and for feed-back signals, through which the different states of the electronic power system are transmitted back to the digital control structure.
- The adaptation function of the control signal to the power transistors` requirements. Through this function the driver makes a conversion of the logic control signal in a current or a voltage signal with the necessary parameters to obtain the transistor on-state or off-state. If the power transistor is a bipolar junction one, a current with a certain value and waveform must be injected into the base terminal to induce the on-state. On the other hand, to obtain an accelerated turn-off process a reverse voltage must applied on the B-E junction. If the power transistor is a MOS gate one (MOSFET, IGBT), for example with an *n* channel, then the logic control signal is converted into a positive voltage for the on-state and into a zero or a negative voltage for the off-state.

- Protection function – that ensures the protection of the power transistor against the faulty situations like: over currents through the device, the voltage supply decrease, lack of the negative blocking voltage, rise of the device temperature over an accepted limit etc. In case one or several disturbances of these occur the power transistor is turned-off and an isolated ***fault signal*** is transmitted back to the control structure.

c) Structures of the base current drive circuits

As has been presented above, the power BJTs and even the MDs require a relatively high control power due to their small current gain. This control power must flow through the base current drive circuits, reason for which these drivers can't be included in the integrated circuits. The final stage of the base current drive circuits must be capable of handling Amps or even tens of Amps. In Fig.4.5 there are shown two types of such stages at which the low or the medium power transistors have been represented by the switches K_{on} and K_{off}.

In Fig.4.5(a) it is shown a simple final stage that does not use a negative voltage for the B-E junction. The turn-off acceleration of the transistor is obtained with the $R_{B(off)}$ resistance, connected between the base and emitter terminal (ground). This resistance allows to flow the recombination current $i_{B(off)}$ determined by the electrical charges from base layer which participated to the transistor conduction. The $R_{B(off)}$ value is the result of a compromise. A smaller resistance means a shorter turn-off time. On the other hand, a smaller resistance means that a greater part of the I_{B+} current (supplied by the V_{B+} source) is directed to the ground when the transistor is in on-state. So, to obtain enough base current we have to increase the $I_{B(on}$ current very much, which in turn, increases the control power:

$$P_{control} = V_{B+} \cdot I_{B+} \tag{4.10}$$

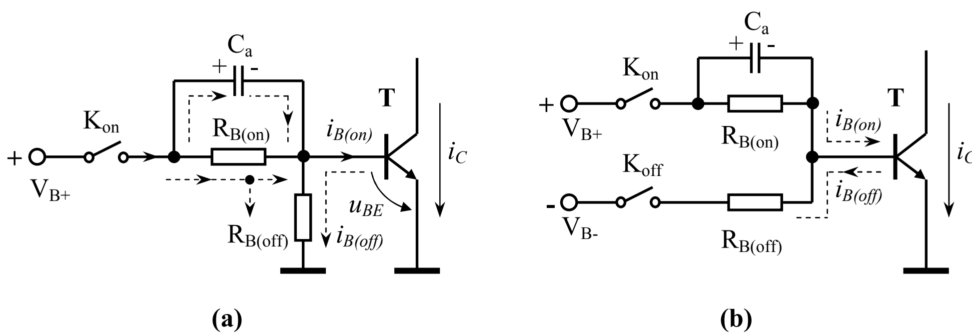

Fig. 4.5 Final stage structures for the base current drive circuits: a) without negative blocking voltage; (b) with negative blocking voltage.

The I_{B+} current supplied by the source depends on the $I_{B(on)}$ base current value necessary to saturate the transistor and on the $R_{B(off)}$'s off-state resistance value:

$$I_{B+} = I_{B(on)} + \frac{V_{BE(on)}}{R_{B(off)}}, \quad I_{B(on)} \geq \frac{I_C}{\beta} \tag{4.11}$$

The value of the $V_{BE(on)}$ voltage can be obtained with the help of the B-E junction *i-v* static characteristic, $V_{BE(on)} = f(I_{B(on)})$, from the transistor catalog. Analyzing the (4.10) equation we find that, by having a given I_{B+} current, there is an alternative to decrease the control power during the transistors' on-state, decreasing as much as possible the V_{B+} voltage. In practice the values for this voltage are between 7 and 10V.

The $R_{B(on)}$ base resistance has the role of limiting the I_{B+} current at a value given by the (4.11) equation. After we have chosen the U_{B+} voltage the $R_{B(on)}$ resistance can be calculated using the equation:

$$R_{B(on)} = \frac{V_{B+} - V_{BE(on)}}{I_{B+}} \tag{4.12}$$

Because the B-E junction voltage is small ($V_{BE(on)} < 1V$), the powers dissipated in this junction and on the $R_{B(off)}$ resistance are also small. Therefore, a significant part of the control power (sometimes tens of watts) is dissipated by the $R_{B(on)}$ resistance.

The C_a capacitor connected in parallel with the $R_{B(on)}$ resistance is called an ***acceleration capacitor*** and has the role of speeding up the transistors' transition into on-state by injecting a peak current into the base. The peak current appears immediately after the K_{on} switch is closed, when the C_a capacity is charged. Thus, the i_{B+} current bypasses the $R_{B(on)}$ resistance, only being limited by the internal resistance of the source and by the dynamic resistance of the B-E junction. The capacitor starts charging until its' voltage equals the drop-voltage on the $R_{B(on)}$ resistance. From this moment the entire I_{B+} current will flow through the $R_{B(on)}$ resistance.

In Fig.4.5(b) is shown the final stage of a BJT driver that uses a negative blocking voltage V_{B-}. As soon as the $I_{B(on)}$ current is cut off by K_{on}, the B-E junction is reverse biased by V_{B-} through the K_{off} switch. Thus, the recombination current $I_{B(off)}$ appears, which is greater than the same current presented in Fig.4.5(a). This increased value leads to a faster turn-off transition of the BJT. It can be said that the final stage presented in Fig.4.5(b) is an improved version of the one presented in Fig.4.5(a). In applications, the $R_{B(off)}$ resistance from Fig.4.5(b) can be removed if we don't want to control the turn-off speed and we don't wish to limit the switching overvoltages. Because the B-E junction has a low reverse breakdown voltage, it is recommended that the blocking voltage V_{B-} does not exceed – (7÷10)V.

As it has been highlighted in paragraph (3), an increased base current, over a certain value, pushes the transistor into a deep saturation state. It is not a desired state because they is an excess of carriers (electrical charges) accumulated in the drift region which prolongs the turn-off transition. Because of this, the drivers must be capable of maintaining a light BJT saturation state. If the value of the collector current I_C is always the same in steady state, an optimal saturation of the transistor can be obtained by choosing the right value for the $I_{B(on)}$ base current. However, the I_C current depends on the converters load current which is considered a random variable. To have a full control in any situation, we can choose the base current $I_{B(on)}$ dependent on the maximum collector current I_{CM} or on the maximum load current. However, there is a problem with this method: at low loads the transistor goes into a deep saturation state. In order to obtain an adaptive control, depending on the collector current, we can use antisaturation diodes (D_{as}) in the final stage of the driver - see Fig.4.6.

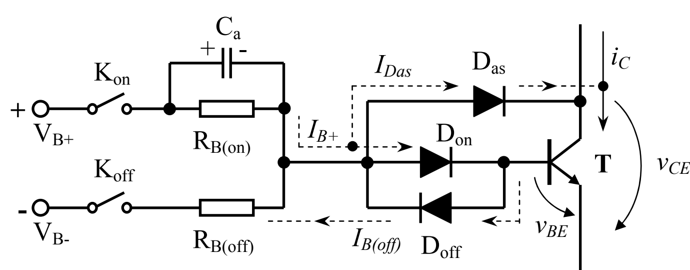

Fig. 4.6 The final stage of a power BJT driver with antisaturation diode (D_{as}).

The antisaturation diode deflects a part of the base current $I_{B(on)}$ when the power transistor tend to go in the deep saturation state. In some situations, to implement this it must introduce multiple D_{as} diodes connected in series, so that, in light saturation state the voltage drop on the bases' branch has a value slightly lower than that on the antisaturation diodes' branch: $V_{D_{on}} + V_{BE(on)} < V_{D_{as}} + V_{CE(sat)}$ and the D_{as} diode is in off-state.

There is a correspondence between $V_{CE(sat)}$ voltages' value and the power bipolar junction transistor's degree of saturation. When the transistor goes from the light saturation state to the deep saturation state, the $V_{CE(sat)}$ voltage decreases, the D_{as} diode turns-on and the base current's excess (which determined the transistor's deep saturation state) bypasses the base terminal through the following route: D_{as} – collector – emitter – ground. The antisaturation diode must be fast and able to sustain high reverse voltages when the transistor is in off-state.

5. Laboratory application

The block diagram of the laboratory setup for the BJT drivers study is presented in Fig.4.7 and the image of the laboratory application is presented in Fig.4.8. As a main block, the laboratory installation includes the driver, the object of our study, achieved with discrete components such as transistors, diodes, resistances, capacitors etc. The driver controls an equivalent power BJT, labeled with *T,* which is actually a triple monolithic Darlington embedded in a power module, SK50120D, manufactured by *Semikron*. In fact, the power module contains two such equivalent transistors together with recovery diodes connected in antiparallel, forming a so-called half bridge structure. From this structure, widely used in power electronics, we used only the higher transistor and the lower recovery diode. In this way we obtain the topology of a DC/DC converter (chopper) if the power transistor is periodically controlled with a PWM signal.

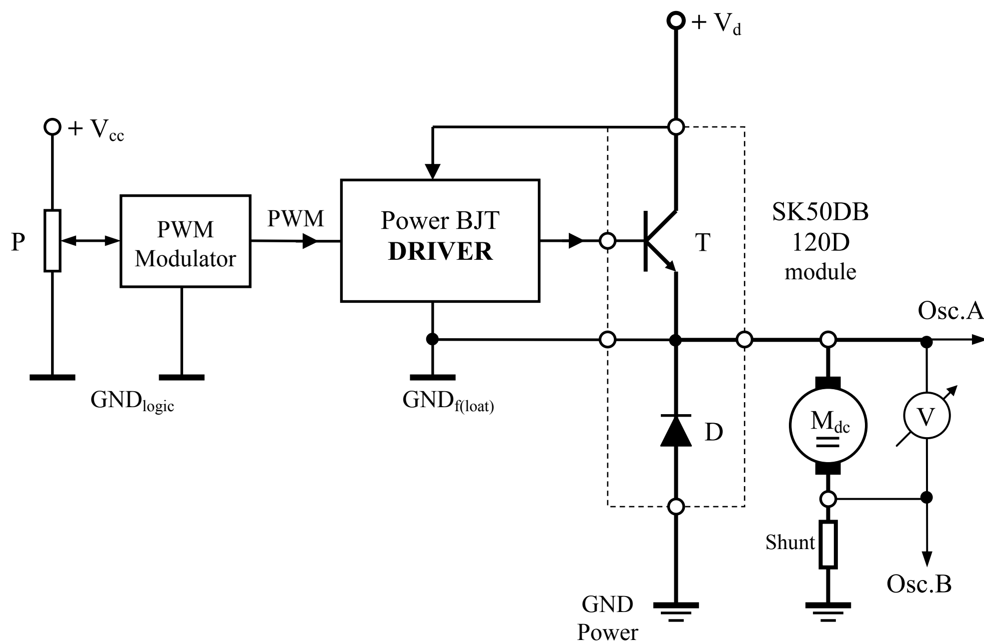

Fig. 4.7 Block diagram of the laboratory application.

The logic control signal applied at the input of the driver is generated by a PWM modulator with a TTL level (5V). The connection between the modulator and the driver is done with a shielded cable having connectors at each end. Using the *P* potentiometer from the PWM modulator we can modify the duty ratio of the logic PWM signal.

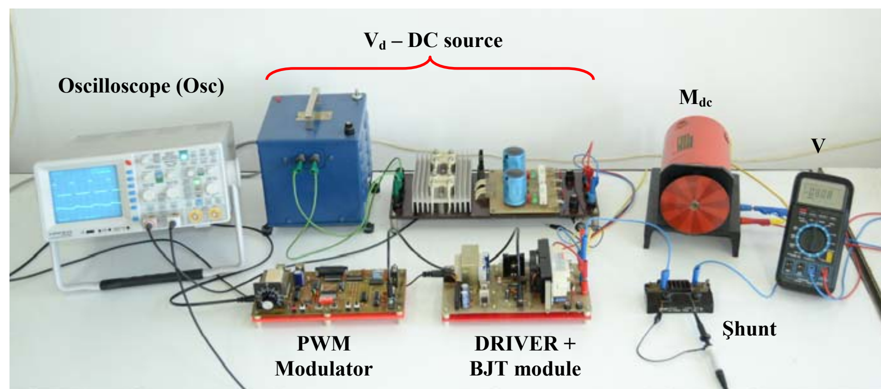

Fig.4.8 Image of the laboratory application.

The power structure, which contains the equivalent transistor *T* and the recovery diode *D,* supplies with voltage pulses (width modulated) the DC motor (M_{dc}). By adjusting the duty cycle of the PWM signal the average voltage (DC component) that supplies the electrical machine is adjusting and therefore the motor speed is regulated. The average voltage can be measured using the voltmeter (V). The laboratory circuits allow an easy view, with the help of a two spots oscilloscope, the waveforms of the logic PWM signal, base current and of the converter's output voltage v_o and current i_o (the shunt voltage) - see Fig.4.8.

The driver scheme used in the laboratory to control a power bipolar junction transistor is presented in Fig.4.9 and the image in Fig.4.10. The base current drive circuit was achieved with discrete components. This driver includes the isolation function, the overcurrent protection and the antisaturation diodes as in Fig.4.6. The two switches (K_{on} and K_{off}) were implemented with the help of the T_{on} and T_{off} transistors. Because the $I_{B(on)}$ base current is in the order of Amps (1.5A), a Darlington structure was used for the T_{on} (T_{on1} - D44H10 and T_{on2} - 2N2222). The T_{on2} transistor is controlled by a LM339 comparator, an integrated circuit with an *''open collector''* output. The LM339 assures the control of the final stage and the power BJT with bipolar voltage (positive for on-state and negative for off-state).

The comparator integrated circuit has also the role to reshape the PWM control signal received from the HCPL2212 optocoupler, which ensures the electrical isolation between the PWM modulator and the power structure. The turn-off transistor T_{off} does not have a Darlington configuration because it is less loaded in current (it takes only current pulses during the turn-off switching). For the laboratory driver, T_{off} is the complementary of the final transistor from the T_{on} configuration (D45H10).

The activation of the HCPL2212 optocoupler is equivalent with the power BJT turn-on. By activating the led-phototransistor ensemble at the HCPL2212 output (pin 6) the voltage decreases progressively, including at the inverting input of the LM339 comparator. When this voltage reaches the value set by the resistance divider

R_2-R_3, the comparator switches their state and turns off its final transistor. Therefore, the voltage at the LM339 output, fixed through the R_4 resistance, increases steeply causing the C_1 charging with the polarization shown in Fig.4.9. The current pulse through C_1 capacitor turns-on the T_{on} Darlington configuration which, in turn, ensures the base $I_{B(on)}$ current for the power bipolar junction transistor T. Consequently, the power transistor T is turned on and its collector voltage decreases toward the $V_{CE(sat)}$ saturation value. Thus, the Zener diode Dz is turned on and the $I_{B(T1)}$ base current begins to flow. By switching the T_1 transistor into on-state, the base current for the T_{on} configuration is provided, after C_1 charging.

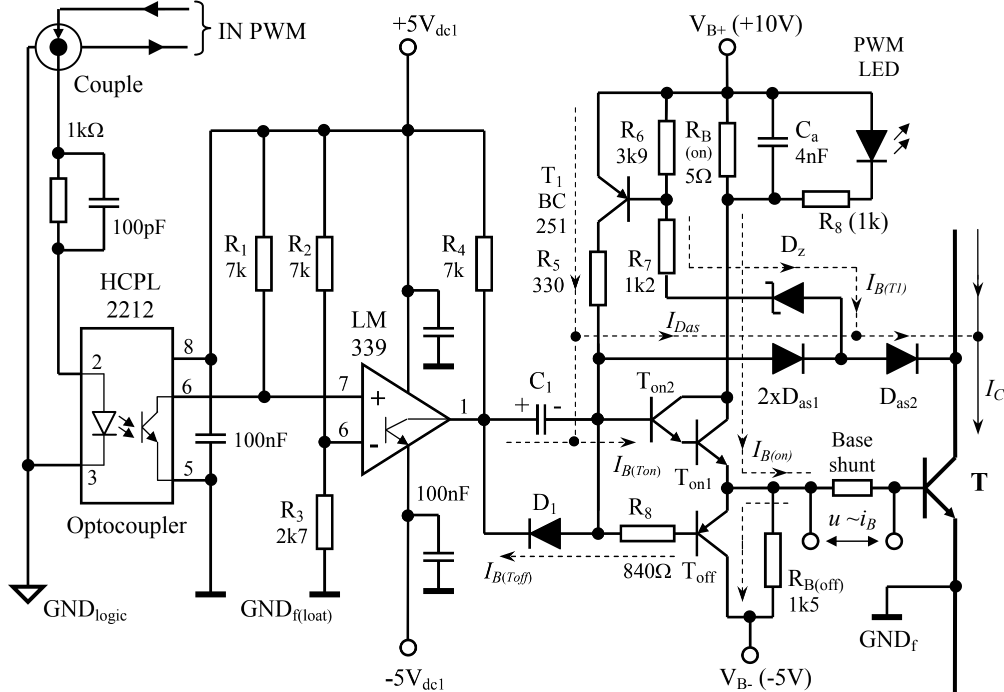

Fig.4.9 Scheme of the laboratory BJT driver.

Practically, during the on-state time interval, the transistor driver operates like a latching circuit. The HCPL2212 optocoupler only initiates the on-state, it being maintained with the help of the T_1 transistor if the collector (load) current value is below a maximum threshold. If the functioning point of the power transistor leaves the saturation region (line – see Fig.4.6.a), as a consequence of an overcurrent, the collector voltage increases and turns off the diodes on the $I_{B(T1)}$ current path:

$$V_{CE(T)} \geq V_{B+} - (V_{BE(T1)} + V_{Dz} + V_{Das2}) \tag{4.13}$$

Therefore, all the transistors T_1, T_{on}, T are turned off. To avoid dangerous switching overvoltages which can appear due to fast interruptions of high currents (great *di/dt*) it

is preferred a slow power transistor turn-off by an adequate choosing of the $R_{B(off)}$ resistance. This is a variant of implementation the protection function, called DESAT, against the short-circuit currents through the power transistors. The value of the overcurrent at which the protection becomes active is set by the Zener diodes' voltage value.

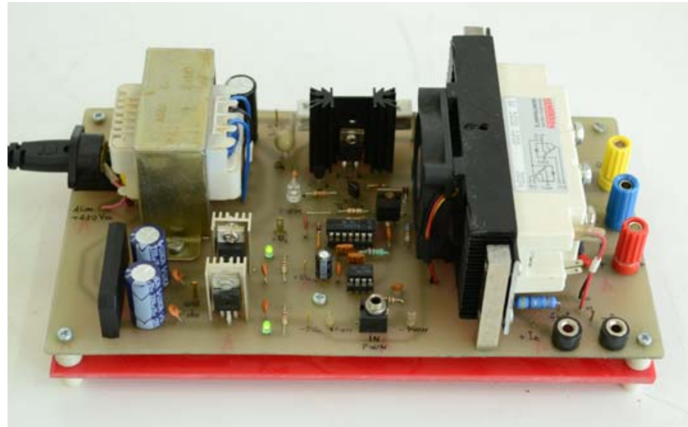

Fig. 4.10 Image of the driver, power module and DC source.

The deliberate power transistor turn-off is obtained if the PWM logic signal from the input of the HCPL2212 become $0L_{(ogic)}$. Thus, at the optocoupler output and implicit at the inverting input of the LM339 comparator the voltage increases. LM339 is switched and turns-on the final transistor from its structure that connects its' collector (the comparator's output) to the negative voltage ($-5V_{cc1}$). Then the $I_{B(Toff)}$ current appears through the base of the T_{off} transistor, first through the path of the C_1 capacitor (until it is depleted and recharged with a reverse voltage) then through the path of the D_1 diode. This is equivalent with the T_{off} on-state that applies the V_{B-} negative voltage on the base of the power transistor to accelerate its' turn-off transition. During the entire time interval in which the power BJT must be in off-state will maintain the B-E junction reverse biased.

The final stage of the BJT driver is connected to the power transistor that operates with high voltages and currents. Because of this there must exist an electrical isolation between the driver and the PWM modulator that can belong to a microcontroller (μC) or to a digital signal processor (DSP). Consequently, a multiple source has been achieved to supply both the logic structure of the driver with a double stabilized voltage ($\pm 5V_{cc1}$) and the final stage with V_{B+}, V_{B-} voltages. Its' schematic is presented in Fig.4.11.

The $\pm 5V_{cc1}$ voltages are obtained with the help of a positive voltage regulator LM7805 and a negative voltage regulator LM7905. The V_{B+} is taken after the rectifier, without passing it through the voltage regulator. The V_{B-} voltage is the same as $-V_{cc1}$

because the V_{B-} is only used for the acceleration of the power transistor's turn-off and for the maintaining of a simple reverse polarization of the B-E junction during the transistor off-state.

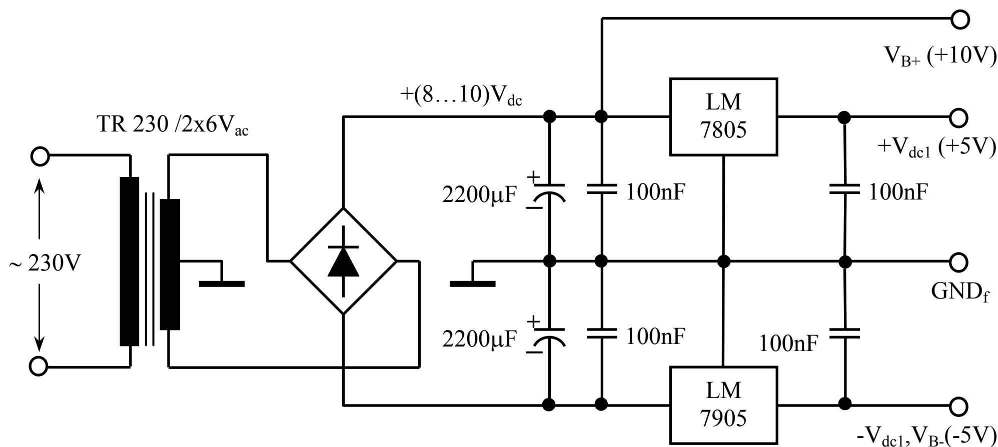

Fig. 4.11 The stabilized DC source that supplies the driver circuit

6. Objectives and procedures

1. It will be studied the theoretical aspects related to the power bipolar junction transistor (BJT) from the first part of the paper: symbols, semiconductor structure, static characteristics etc.
2. It will be analyzed how the power BJT is turned on through the base current and the condition which this control current's value must meet to maintain the transistor in saturation state.
3. It will be analyzed the PWM control technique (the DC/DC conversion principle) and the average voltage relation;
4. It will be reviewed the functions that a power transistor's driver must meet;
5. It will be analyzed the variants of the current base drive circuits for power BJTs (the final stage structures of BJT drivers);
6. It will be analyzed the laboratory circuit for the BJT drivers study, the BJT driver scheme achieved with discrete components and identify these components on the experimental board;
7. It will be realized the experimental circuit as in Fig. 4.7 and Fig.4.8
8. It will be displayed, with the help of an oscilloscope, the waveform of the voltage drop across the R_B base resistance - voltage proportional with the value of the base current (the transistor is controlled with a PWM signal).

9. It will be displayed, with the help of a two-spots oscilloscope, the waveforms of the v_o voltage on the DC motor and the i_o current through it (the converter output voltage and current);

10. It will be highlighted how can be adjusted the average output voltage V_o by adjusting the duty ratio of the PWM signal, using a voltmeter and by noticing how the DC motor's speed modifies.

References:

[1] Mohan N., Undeland T., Robbins W., *Power Electronics: Converters, Applications and Design*, Third Edition, Published by John Willey &Sons Inc., USA, 2003.

[2] Skvarenina T.L. (editor), *The Power Electronics*, Handbook, Industrial Electronics Series, , Purdue University, West Lafayette, Indiana, CRC Press LLC, USA, 2002.

[3] Erickson R., Maksimovic D, *Fundamentals of Power Electronics*, University of Colorado, Boulder, Colorado, Published by Kluwer Academic Publishers, USA, 2001.

[4] Krein P., *Elements of Power Electronics*, Oxford University Press, New York, 1998.

[5] Trzynadlowski A.M., *Introduction to Modern Power Electronics*, John Willey &Sons, New York, 1998.

[6] Hart D., *Introduction to Power Electronics*, Prentice Hall, New York, 1997.

[7] Rashid M., *Power Electronics: Circuits Devices and Applications*, Second edition, Prentice Hall, New York, 1993.

[8] Albu M., *Electronică de putere* - vol I: *Noţiuni introductive, dispozitive, conversia statică alternativ-continuu a energiei electrice*, Casa de Editură "Venus" Iaşi, 2007.

[9] Albu M., Diaconescu M., Bojoi R., *Comanda semiconductoarelor de putere, convertoare statice cu comutaţie naturală*, Casa de Editură "Venus", Iaşi, 2008.

[10] Diaconescu M.P., Graur I.,: *Convertoare statice – baze teoretice, elemente de proiectare, aplicaţii*, Ed. „Gh. Asachi", Iaşi, 1996.

[11] Ionescu Fl., Floricău D., Niţu S., Six J.P, Delarue Ph., Boguş C.: *Electronică de putere - convertoare statice*, Ed. Tehnică, Bucureşti, 1998.

[12] Kelemen A., Imecs M., *Electronică de putere*, Ed. Didactică şi Pedagogică, Bucureşti, 1983.