Lab no. 2

OVERVIEW OF POWER SEMICONDUCTOR DEVICES AND POWER MODULES

1. Introduction

The power structure of the static converters contains as basic elements various power semiconductor devices which act as an electronic switch (static breaker). During the on steady state these power devices never operate in their linear (active) region, where they act as a variable resistance, because unacceptable power losses would occur. For this reason, in power electronics the semiconductor devices operate only in two stable modes: the full conduction mode (on-state) when the electric current is fully permitted to flow through the device, ideally without a voltage drop across it, and the blocking mode (off-state) when the current flow is completely disrupted. The transitions between the two steady states can be induced by the power circuit or by a control circuit and must be fast in order to minimize the switching power losses. For this reason and in order to reduce the size of the power electronic equipments by increasing the switching frequency, the transitions speed of the power semiconductor devices wants to be great. Also, because the power semiconductor devices operate, usually, with high voltages and/or large currents the semiconductor structure of these devices is different than the structure of low-power devices.

2. Power semiconductor devices classification

Depending on the control modality (controllability criteria), these power semiconductor devices can be divided into three categories:

1) **Uncontrollable power devices** – a category constituted by power diodes that have only two power terminals, without control terminal. The conduction or blocking state is dictated by the way these diodes are polarized (biased) inside the power circuit.

2) **Controlled turn-on power devices** – a category that includes the thyristors and the triacs. Historically speaking, the thyristor was the first power semiconductor device with three terminals, two power terminals (anode, cathode) and a control terminal known as the gate. In order to induce the on-state, a thyristor must be forward biased and must be injected a short current pulse between the grid and the cathode terminals. Once the on-state is obtained, the gate current can be interrupted because the device remains latched in this state until the blocking conditions are met; more

precisely, a reverse voltage is applied on the device (reverse biased). The off-state cannot be induced through the gate and for this reason one can say that the thyristor is a half-controlled device. The research efforts to obtain a semiconductor structure closer to the thyristor with controlled turn-off feature have lead to achieve the **G**ate **T**urn-**O**ff Thyristor (GTO). This is a device from the full controlled devices class. The triac may be equated with a structure consisting of two thyristors connected in parallel.

3) **Controllable power devices** – there are switch elements which can be brought into an on-state and an off-state through the control signals. With a few exceptions (e.g. GTO, ***MOS C**ontrolled **T**hyristor*-MCT) the opening signal must be continuously applied on the control terminal in order to maintain their on-state as long as the device is forward biased. The off-state happens automatically when the signal is removed or falls below a certain threshold. Yet, in many applications there is a preference to obtain the turn-off transition and to maintain the off-state with a reverse control signal in order to be sure that they won't open accidentally. In this last situation can appear short-circuits in the power electronic circuits.

Depending on the nature of the control signals, the controllable power devices can be further divided into two distinct groups:

a. **Current-controlled devices** :

- ***Bipolar Junction Transistors (BJT)*** – there are relatively a low-speed devices (high switching power losses), but they have the advantages of a low on-state voltage drop (small on-state power losses).
- ***Gate-Turn-Off Thyristors*** **(GTO)** – used in high power applications. A positive current pulse with low amplitude is needed to opening these devices (same as for the thyristor) and a negative current pulse with high amplitude is needed to blocking them.

b. **Voltage-controlled devices** – they are also called power semiconductor devices with MOS (**M**etal-**O**xide-**S**emiconductor) gate or isolated gate. Taking into account their undisputed qualities (low control power, high switching frequency etc.), the research concerning power semiconductors and the technological efforts involved in manufacturing have been focused on developing these particular devices. Today, the market offers a plethora of these devices. The following MOS gate examples are those that are the most used or have played a central role in power electronics' evolution:

- ***MOSFET power transistors (MOS F**ield **E**ffect **T**ransistors)* – are fast devices (with small switching power losses) and for this reason they are used in converters with high switching frequencies (tens or hundreds of kHz). Their limitation involves a rapid increase in the on-state resistance ($r_{DS(on)}$ – catalogue parameter) along with the rise of the maximum blocking voltage rating. These increases will lead to important power losses during conduction. For this reason, they are not used in high power applications.

- ***Insulated Gate Bipolar Transistor – IGBT*** is a hybrid transistor, a mixture between the bipolar junction transistor whose main quality is the low on-state power losses and the MOSFET transistor from which it borrowed the high switching speed (low switching power losses). The result was a transistor that can be used in switch-mode converters with high switched frequencies (kHz ÷ tens of kHz) and until powers of megawatts. Today the IGBT transistor is the engine of power electronics, the most widely used semiconductor device from this technical field.

Taking into consideration the diversity of the controllable power devices and their common capacity to be brought in on-state or in off-state through the control signals, it results the need to represent these devices by a unique, a generic symbol in the power schemes. In Fig. 2.1 there are two versions of the same symbol used in the literature.

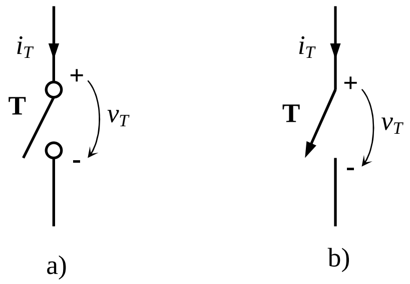


Fig. 2.1 - Symbols used for controllable semiconductor devices.

The first version (Fig. 2.1.a) is similar to the symbol used for an electric contact of a contactor or a relay. The second version (Fig. 2.1.b) is more stylized and highlights the unidirectional current conduction feature of these devices (the arrow of the contact) [Mohan et al.]. The variables i_T and v_T represent the current that flow through the device T and the voltage drop across it, respectively. In the following laboratory works, version (b) will be preferred to version (a), because the latter is more adequate for the bidirectional electronic switch used in matrix converters.

A second classification criterion of power semiconductor devices could be the number of steady state volt-ampere (*i*-*v*) characteristics obtained by each device. All of these, ideally defined, are presented in Fig. 2.2 on the $i_T - v_T$ axes system. The following characteristics and their corresponding states of the power semiconductor devices can be thus emphasized:

- ✓ *Forward blocking characteristic* – is obtained when the device blocks forward (positive) voltages. No current flows through the device in this off-state.

- ✓ *Forward conduction characteristic* – is obtained when the device is in full conduction with a positive current determined by the forward voltage. The voltage drops on an ideal device in the on-state is considered to be zero.
- ✓ *Reverse blocking characteristic* – is obtained when the device blocks reverse (negative) voltages. No current flows through the device in this off-state.
- ✓ *Reverse conduction characteristic* – is obtained when the device allows flowing reverse (negative) currents. This characteristic is specific to the bidirectional devices.

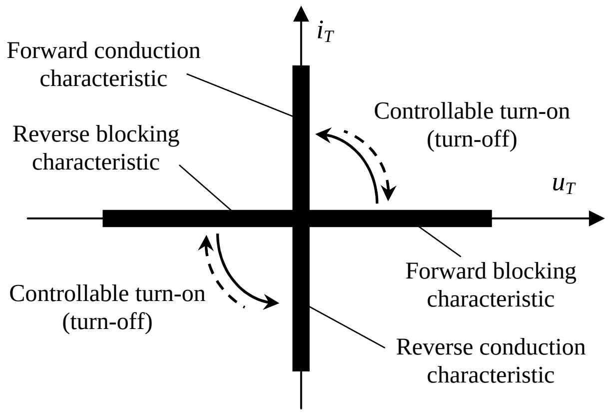
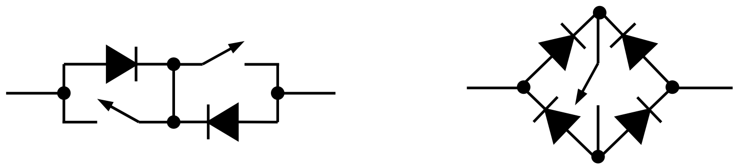


Fig. 2.2 All the ideal steady state current-voltage (*i-v*) characteristics which can be obtained by a power switch.

The majority of the semiconductor devices used in power electronics cannot obtain all the characteristics above mentioned. Thus, the diodes can operate only on two characteristics from Fig.2.2, the forward conduction and the reverse blocking characteristics, the transition between the two is made uncontrollably, depending on the external bias voltage. The controllable devices can accomplish two or three characteristics, such as: the forward and reverse blocking characteristics, as well as the forward conduction characteristic, noting that the passing between the two forward characteristics is made if the control signal is used.

As mentioned before, the elementary (discrete) power semiconductor devices are, in general, unidirectional valves for the current that flows through them. In some modern power electronics structures certain power devices are necessary which are able to materialize all the four steady state *i-v* characteristics presented above, known as a bidirectional devices or bidirectional switch cells. In order to obtain a fully controllable and bidirectional switch, two power transistors can be anti-parallel connected. If the used transistors have a small reverse blocking capacity, fast diodes are added and connected as shown in Fig.2.3.



(a) (b)

Fig.2.3 Bidirectional and controllable switch cells obtained with diodes and discrete controllable devices having a low reverse blocking capacity.

3. Capsule, semiconductor structure, symbols and operating parameters of the power semiconductor devices

All the solid state power devices contain an active part built from a semiconductor chip, hermetically sealed in a ***capsule***. The chip is divided into layers or regions different doped with impurities. Thus, a ***semiconductor structure*** is formed (e.g. a silicon wafer) on which depend the operating parameters of the device. The surfaces of the semiconductor chip in contact with the terminals are metallized and the semiconductor superficial layer under the metallized area is heavily doped in order to avoid a high contact resistance. The surfaces that remain are passivated and protected with dielectric materials added or formed directly from the semiconductor material such as, the silicon dioxide (SiO_2).

The ***capsule*** of the device has different shapes and sizes depending on its type, on the producer, on the rating voltages, on the maximum current, of the cooling method, etc. There is a tendency of the companies to align themselves to the same standard whether it is the size of the capsule or that of the modules. The capsule has a multiple role: it gives mechanical resistance to the devices, it assures the protection of the semiconductor structure against any environment factors such as humidity, sustains the connection terminals, and last, but not least, assures the heat transfer, sometimes with galvanic isolation, between the semiconductor chip and the exterior.

The ***symbol*** of a semiconductor device is a graphical representation which defines the device type and highlights all of its power and control terminals. Through the use of the graphic symbol, the exact position of a semiconductor in a scheme can be marked and pinpointed, as well as its connexions with other circuit elements or with other functional blocks.

In order to define the operating performances of a semiconductor device and having the criteria by which one can compare it with other types of devices, one must first define its ***characteristics***. These one can be grouped into two categories:

- **static (steady state) characteristics:** through which the rated voltages are highlighted, the forward or reverse breakdown voltages, the rating, maximum and leakage currents, the on-state voltage, the on-state power losses, the saturation and the active regions, the safe operating aria (SOA) etc. All these parameters are defined for a steady state operation, conduction and blocking state. Some of these parameters are presented in the device’s catalogue and other depends on the control signal value. In general, the static parameters are given through the volt-ampere (*i*-*v*) characteristics drawn in the electric plan presented in Fig. 2.2.

- **dynamic (transient) characteristics:** through which the dynamic performances of the devices are evaluated, more precisely the transition parameters from the off-state to the on-state and vice versa. These parameters are: the switching times, the maximum switching frequencies, the switching power losses, the increase and decrease slopes of the current or voltage waveforms, the rates of recombination of the charges that contributed to the conduction, the switching overvoltages, etc.

4. Power losses in the semiconductor devices

A very important aspect tied to the operation of the power semiconductor devices is represented by their losses. ***The power losses are a fraction of the electrical power that flows through the device which is retained by it and converted into heat.*** Taking into account the low size of the semiconductor devices (low thermal constant), the temperature device can rapidly rise which can leading to the thermal destruction.

It must be outlined that, during forward or reverse blocking state, the real devices act like an ideal switch, because the leakage currents are negligible, being a few microamperes (μA), consequently no losses occur in this state. Instead, once the on-state is activated the current i_T appear in the presence of a nonzero voltage drop u_T. This will determine the absorption of an instantaneous electric power by the device, formulated by the following equation:

$$p_T(t) = v_T(t) \cdot i_T(t) \quad (2.1)$$

Two situations can be highlighted in which power semiconductor devices do indeed switch. In the first situation, in ***switch mode*** or ***hard switching***, during the switching intervals (*crossover time intervals* - t_c), an important voltage drop across the device occur simultaneously with an increasing current (during turn-on transition → $t_{c(on)}$) or with a decreasing current (during turn-off transition → $t_{c(off)}$). For this reason, the instantaneous power at the device level is important, resulting in the so called ***switching power losses*** (P_s).

Soft-switching without losses can be obtained in the case of semiconductor devices included in ***resonant converters***. In the following lines the discussion will focus on the switch mode, because it is widely used and the it is most relevant when talking about losses.

It must be outlined that during the switches, the voltage and the current waveforms evolve in different directions, either simultaneously or separately (e.g. the switching cells with recovery diodes). In the case of a separate evolution, the current transitions through the power semiconductor device appear all the time when the voltage drop is quite high. Thus, during a turn-on transition, first there will increase the current from zero to the I_d value, after which the voltage will drop to its on-state voltage V_{on} (saturation value); during the turn-off transition, the voltage will first rise from the V_{on} value to the source value V_d, after which the current drops to zero. In order to generally evaluate the losses, only the last case will be taken into account, because it covers every situation. From a quantitative point of view, the power losses can be equated to the energy retained by the static switch in a second time interval, value which, in fact, corresponds to the average power converted into heat. With these specifications and knowing that f_s opening-blocking transitions pairs occur per second, it can be obtained the *switching power losses equation* [see Mohan et al.]:

$$P_s = \frac{1}{2} \cdot U_d \cdot I_d \cdot f_s \cdot \left(t_{c(on)} + t_{c(off)} \right) \tag{2.2}$$

where: $t_{c(on)}$ and $t_{c(off)}$ are mentioned above, $f_s = 1/T_s$ is the switching frequency of the device, $T_s = t_{on} + t_{off}$ is the switching time period, t_{on} is the on-state time interval and t_{off} is the off-state time interval.

From the (2.2) equation one can conclude that *the switching power losses increase proportionally with the switching frequency and with the rise of the switching times*. Thus, in order to obtain a high switching frequency for a power electronic equipment, so as to diminish its mass and size, fast and ultra fast devices must be chosen with very short switching times (e.g. MOSFET type power transistors).

The instantaneous power p_T, which determines the losses in the device, appears not only during the device's transition, but also during the on-state. The losses afferent to the conduction state, called ***on-state power losses*** (P_{on}), can be calculated using the average power taken by the device in the t_{on} time intervals [see Mohan et al.]:

$$P_{on} = f_s \cdot V_{on} \cdot I_d \cdot t_{on} = V_{on} \cdot I_d \cdot \frac{t_{on}}{T_s} = V_{on} \cdot I_d \cdot D \tag{2.3}$$

where: $D = t_{on} / T_c$ is the duty ratio (duty cycle) of the device.

It can be observed that on-state power losses are proportional with the on-state voltage V_{on}, with the I_d value of the steady state current that flows through the device and with the on-state time interval t_{on}. In order to increase the I_d current without exceeding the on-state power losses, a device with low on-state voltage V_{on} must be chosen (e.g. BJT or IGBT type power transistors).

The ***total power losses*** during the device operation are given by the sum of the switching and on-state power losses:

$$P_{tot} = P_s + P_{on} \tag{2.4}$$

These losses are limited by the heat transfer capacity of the device – radiator assembly and by the maximum temperature at which the device can operate without thermal destruction.

5. Power modules

In the beginning of power electronics, only ***discrete*** semiconductor devices were used in order to obtain the power topologies. These ones were mounted on the radiators placed in a certain order. The connections between terminals were manually manufactured with wires whose section was calculated depending on the currents values. This kind of architecture had to be designed with care in order to avoid parasitical inductances, to minimize the losses in the wires and to decrease the electromagnetic disturbances induced by the switching currents. In the case of a structure with more identical sections, e.g. the three-phase structures, a symmetrization is needed. It is also necessary to design the entire system compact with the lowest possible size, maintaining at the same time a maximum heat transfer capacity of the radiators. Using these old manufacturing solutions, the above demands were difficult to transpose into the practice.

The constructive solution that won over time resulted from the observation that mostly of the modern power electronic structures use well-known repetitive combinations: transistors associated with discharge diodes, half bridge structures with diodes, thyristors or power transistors, etc. Consequently, the idea of “packaging” has arisen in order to gather all these standard structures in a single capsule as ***power modules***. Over time, the concept was adopted and developed by the majority of the important companies, a certain level of standardization being obtained. This standardization is reflected today in the topologies incorporated in the modules, in the capsule shapes, in the arrangement and the numbering of the terminals, in the manufacturing technology, in the rating voltages and currents etc.

By using the modules in power electronics, the following advantages are obtained:

- ✓ size decrease and compactness of the power electronic system;
- ✓ increased immunity to the disturbances;
- ✓ decrease of the parasitical inductances and electromagnetic emissions;
- ✓ power losses decrease during operations;
- ✓ radiator isolation from the under voltage parts;
- ✓ easy assembly and cost reduction for the whole system;

The first manufactured modules were restricted to the integration in a monolithic form of the most widely used power electronic structures. These ones are the most simple and form the so called category of ***P****ower* ***I****ntegrated* ***M****odules* (PIMs). They still retain the widest market share due to their diversity, of their quality, robustness, low price and last, but not least, due to their high power, voltages and currents for which their were made. As the manufacturing technologies were perfected, the complexity of these modules has increased. Today, one module may contain several converter structures such as: converter-inverter-brake circuit → CIB).

Practical realization of a power structure with controllable devices implies the addition of the control circuits (drivers). In the case of the MOS gate power transistors, the control power is negligible, thus the drivers being made on a small scale like a specialized integrated circuit (IC). These observations offered a foundation for the "packaging" into same capsule of the MOS gate transistors with their drivers. Therefore in the 1990's emerges the concept of ***smart power***. And the products having been made using this procedure are called ***smart power devices***.

The „smart power" concept has entered and developed mostly in the field of the power modules. In a first stage, the module received a complex control circuit capable to manage intelligently the operation of the entire ensemble (control, protection, communication with the outside, etc.). These devices are referred by the majority of the manufacturing companies and by the specialists as ***I****ntelligent* ***P****ower* ***M****odules* (IPMs).

A second stage in developing of the intelligent modules and a third in power modules evolution implies the association to the power structure and to the drivers of a ***D****igital* ***S****ignal* ***P****rocessor* (DSP) with the control function of the entire power electronic system obtained with the power module. Thus, this module can be programmed in order to operate in different applications. Once the control algorithm is loaded, it can function independently. This facility justifies the name of *programmable IPM* or *programmable power module*.

To conclude, three categories of power modules can be outlined:

- *Power Integrated Modules* – PIM;
- *Intelligent Power Modules* – IPM;
- *Programmable power modules*;

There is a power threshold over which the manufacturing of the intelligent and programmable modules becomes too expensive. The integration technology used in the field of microelectronics cannot be applied identically for high power modules, because the manufacturing conditions of semiconductor structures are different: the current densities, the temperatures and the electric fields. For this reason over a certain power thresholds, there is a preference for the silicon devices non-integrated in intelligent modules. Their control and protection is made in a classical way with drivers placed outside of the modules. A future solution to this problem is constituted by the use of more stable semiconductor materials capable to withstand high temperatures in comparison with silicon. This could be *silicon carbide* (SiC) and in a distant future, the *diamond*.

The power semiconductor devices based on ***silicon carbide*** were already obtained. The laboratory testing phases are over and the first devices have been launched on the market. The tests show remarkable advantages, especially at high temperatures (around 200°C) at which its can operate without losing their properties. Consequently, the current densities flowing through the power switches made out of SiC can increase a few times, while the size, for the same current, diminishes in comparison with the silicon devices.

Similar to germanium and silicon, the carbon is a tetravalent element. The crystalline structure of carbon under the form of ***diamond*** resembles with the crystalline structure of the classic semiconductor elements. To be considered an acceptable semiconductor material for manufacturing controllable switches, the structure of the diamond has to be perfect. Not even the purest natural diamonds can be used in these applications. The normal synthetic diamonds obtained through the sedimentation of carbon vapors do not reach the standards necessary for a usable semiconductor material. Only via special conditions can the manufactured diamonds achieve the crystalline structure capable to sustain greater electron mobility than the silicon carbide. The final result is that of a semiconductor material with a higher conductivity than presently used, i.e. lower power losses. Moreover, the diamond has superior advantages due to the stronger electric fields and resistance to higher temperatures. Therefore, it can be obtain static switches with normal sizes that may sustain currents of tens of kilo amperes and voltages of tens of kilovolts without connecting several devices in parallel or in series. It will be the perfect switch.

6. Objectives and procedures

1. It will be studied the classification of the power semiconductor devices according to the controllability criterion and the achieved steady state characteristics. The usually semiconductor devices will be identified in the context of these classifications with its particular characteristics;
2. The definitions for the capsule, for the semiconductor structure, for the symbol and the static and dynamic characteristics of the power semiconductor devices it will be respectively analyzed.
3. It will be identified the power losses that occur at the level of a semiconductor device when it operates in switch mode and the parameters and variables on which these losses depend.
4. It will be analyzed the advantages brought by the integration principle in power electronics and it will be reviewed the types of modules existing today on the market as a result of the integration technology;

5. It will be analyzed the developing perspectives in the field of the semiconductor power devices;
6. It will be study in the laboratory of various samples of the power semiconductor devices and power modules;

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