Lab no.18

ONE AND TWO QUADRANT CHOPPERS

1. Introduction

DC/DC converters allow a DC/DC static conversion of the electrical power through which only the magnitude of the DC voltage is modified. For this reason these converters can be also named *DC voltage regulators* or *DC voltage variators*. Most of the DC/DC converters operate in switch-mode using the PWM technique described in Lab no.4. Since this technique of conversion is based on the DC voltage chopping with a certain frequency (*switching frequency*), some of the DC/DC converters are referred in literature as ***choppers***. There are also DC/DC converters which operate on the principle of resonant converters.

The switch-mode DC/DC converters form one of the most diverse class of power electronic converters which are used in many applications within the power range from several watts to hundreds kW. Most applications are found in the category of ***S****witch-****M****ode* ***P****ower* ***S****upplies* (SMPS), at the interconnection of power sources, including the renewable sources and in the electrical drives. A brief classification of the switch-mode DC/DC converters can be done as follows:

- *Step-down DC/DC converters* **–** the output voltage is lower than the input voltage;
- *Step-up DC/DC converters* **–** the output voltage is higher than the input voltage;

Each one of them can be:

- *Non-isolated DC/DC converters* - they don't electrically isolate the input from the converter's output. These converters can operate in ***one, two or four quadrants***. Most of the non-isolated DC/DC converters provide an adjusted output DC voltage from an input DC voltage considered constant. Therefore, the majority of applications are found in the adjustable electric drives with DC motors and in high power DC supplies.

- *Isolated DC/DC converters* – they electrically isolate the input from the output. The isolation barrier is achieved using high-frequency transformers to reduce the weight and size of the converters. These transformers are supplied with a variable high frequency voltage provided by an inverter structure. Thus, the isolated DC/DC converter is, in fact, an ensemble of two converters (a power electronic system): an inverter and a rectifier. The direction of the power flow through this converter is, usually, unidirectional. The majority of the applications can be found in the category of *switching DC power sources* (SMPSs – ***S****witch-****M****ode* ***P****ower* ***S****upplie****s***) used to supply the electronic equipments (audio-video, PC, digital systems, measurement systems, etc.). The output DC voltage must be regulated (kept constant with a certain tolerance) when the input voltage or the converter load may change.

DC/DC converters can operate either with ***current filters*** connected to the output (often the current filter is even the inductance of the converter load) or with ***voltage filters*** included in their structure (e.g. structures *buck, boost*, etc.) or connected to the output (e.g. switching power supplies).

Generally, the basic structures of the DC/DC converters with voltage filters can operate in a single quadrant of the electrical plane: output voltage – output current (V_o–I_o). If we want to obtain a converter that can operate in more quadrants we must use combinations of such one-quadrant converters. On the other hand, when we speak about DC/DC converters which can operate in two or four quadrants we refer to the *converters with current filters called also* ***choppers***. Based on this observation, in what follows it will be analyzed the one and two-quadrant choppers with an active load of *R-L-E* type (DC motor).

2. One-quadrant chopper

The structure of some converter is shown in Fig.18.1(a). The topology includes a controllable switch labeled with *T* (usually a power transistor – in figure an IGBT) and a recovery (freewheeling, flyback, etc.) diode labeled with *D* that conducts the current maintained by the load inductance L_a after the transistor *T* is turned off.

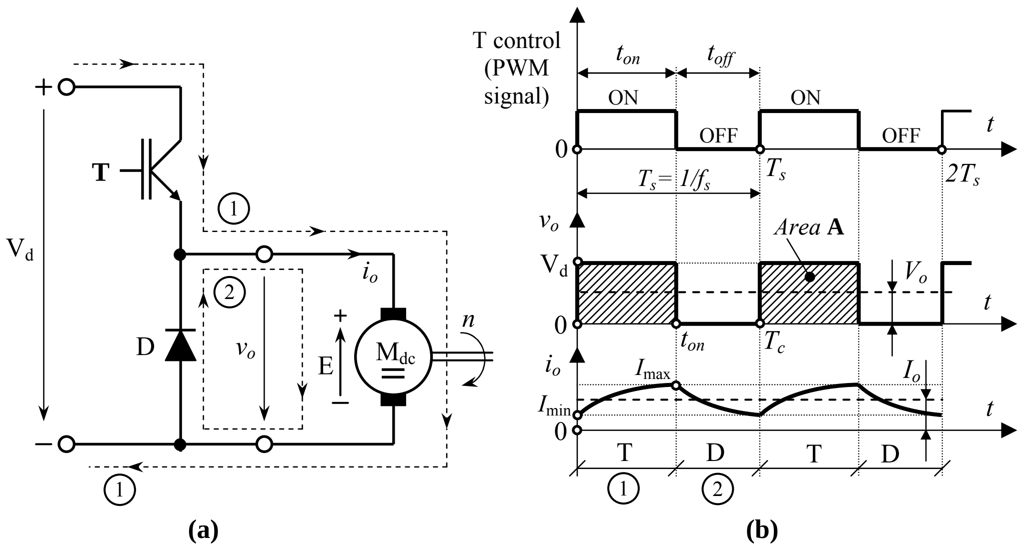

Fig. 18.1 (a) One-quadrant chopper achieved with an IGBT type transistor; (b) Waveforms in case of continuous current conduction mode.

The load connected to the converter's output is a DC motor (M_{dc}) whose equivalent scheme is a series circuit with the armature resistance R_a, the armature inductance L_a and the electromotive force (emf) *E,* proportional with the motor speed. The instantaneous value of the converter output voltage is noted with v_o and that of the output current with i_o.

The converter operation has been described in detail in Lab no.4, more exactly in the paragraph devoted to the PWM technique analysis. Further, it will resume shortly this analysis taking into account the presence of the *E* emf voltage in the equivalent circuits corresponding to the transistor states – see Fig.18.2. It will highlight also the flow direction of the energy (power) through the converter and the motor operating aspects.

The switch *T* is cyclically controlled as shown in Fig.18.1(b). During the switching time period T_s the transistor is on a time interval t_{on} and off a time interval t_{off} , so that: $T_s = t_{on} + t_{off}$. Thus, the switching frequency of the transistor and implicitly of the converter is:

$$f_s = 1/T_s \tag{18.1}$$

During the t_{on} time interval the supply voltage V_d is connected through the transistor directly to the DC motor. The equivalent circuit of the converter together with the *R-L-E* load is shown in Fig.18.2(a). Considering *T* as an ideal switch (without voltage drop in on-state) we can write:

$$v_o(t) = V_d, \quad 0 \le t \le t_{on} \tag{18.2}$$

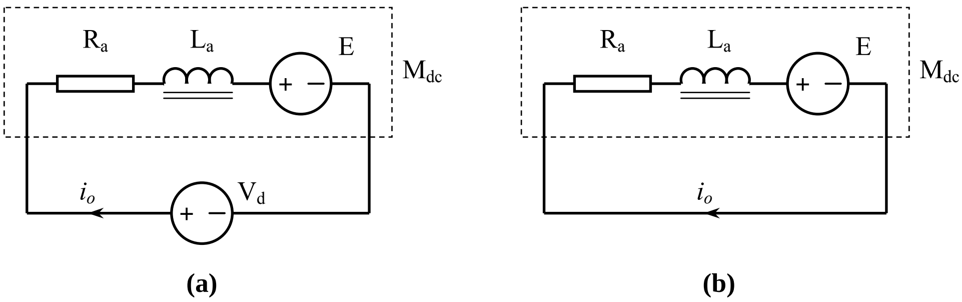

Fig.18.2 Equivalent circuit of the structure shown in Fig.18.1(a) in case of: (a) *T* in on-state; (b) *T* in off-state and *D* in conduction.

When the transistor *T* is turned on the current i_o begins to flow through the path (1) from Fig.18.1(a). Its time evolution can be determined by writing the voltage equation in the loop shown in Fig.18.2(a):

$$V_d - E = R_a \cdot i_o + L_a \cdot \frac{di_o}{dt}, \quad 0 \le t \le t_{on} \tag{18.3}$$

The E voltage can be considered constant during a switching time period (hundreds or tens of µsec) since the motor speed can't have large variations within these short time intervals due to the inertia of the masses under rotation movement.

Solving the differential equation (18.3) by taking into account the initial condition we obtain the following expression for the output current during t_{on} time interval:

$$i_o(t) = I_{\min} \cdot e^{-\frac{t}{\tau}} + \frac{V_d - E}{R_a} \cdot \left(1 - e^{-\frac{t}{\tau}}\right), \qquad 0 \le t \le t_{on} \tag{18.4}$$

where: $\tau = L_a / R_a$ is the time constant of the loop from Fig.18.2(a) and $I_{\min}$ is the value of the i_o output current at the beginning of the t_{on} time interval (initial condition).

As shown in Fig.18.1(b) and the expression (18.4) suggests, during the t_{on} time interval the current through the DC motor increases exponentially. At the end of t_{on} interval the i_o current reaches the I_{max} value.

After T is turned off, **during the t_{off} time interval**, the i_o current will continue to flow through the recovery diode D, along the path (2) from Fig.18.1(a), maintained by the energy stored in the electromagnetically field of the L_a inductance. The equivalent circuit during this time interval is shown in Fig.18.2(b) and the loop voltage equation is:

$$-E = R_a \cdot i_o + L_a \cdot \frac{di_o}{dt}, \quad t_{on} < t < T_c \tag{18.5}$$

Taking into account that, at beginning of the t_{off} interval, $i_o = I_{\max}$, the solution of the differential equation (18.5) is:

$$i_o(t) = I_{\max} \cdot e^{-\frac{t}{\tau}} - \frac{E}{R_a} \cdot \left(1 - e^{-\frac{t}{\tau}}\right), \quad t_{on} < t < T_c \tag{18.6}$$

The i_o current waveform during the t_{off} time interval is a decreasing exponential (see Fig.18.1.b). At the end of the t_{off} interval the output current reaches again 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 is zero (D diode bypasses the load circuit):

$$v_o(t) = 0, \quad t_{on} < t \le T_c \tag{18.7}$$

Based on the equations (18.2), (18.7) and on the Fig.18.1(b) we see that the waveform of the v_o output voltage appears as a sequence (train) of rectangular pulses with V_d amplitude and t_{on} width. The DC voltage V_o of this periodic waveform can be calculated using the average value formula:

$$V_o \overset{not}{=} \text{average value of } v_o(t) = \frac{1}{T_s}\int_0^{T_s} v_o(t) \cdot dt = \frac{1}{T_s}\int_0^{t_{on}} V_d \cdot dt + \frac{1}{T_s}\int_{t_{on}}^{T_s} 0 \cdot dt =$$

$$= \frac{Area\ \mathbf{A}}{T_s} = \frac{1}{T_s} \cdot V_d \cdot [t]_0^{t_{on}} = V_d \cdot \frac{t_{on}}{T_s} = V_d \cdot d \qquad (18.8)$$

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

Taking into consideration the (18.8) equation, it results:

$$0 \le d \le 1 \Rightarrow 0 \le V_o \le V_d \qquad (18.9)$$

The (18.8) and (18.9) equations highlight that at the converter's output are obtained voltage pulses whose average value (the DC component) can be regulated through the duty ratio of the transistor *T*. This ***DC voltage is always positive*** as suggests the equation (18.9). Also, by analyzing the structure shown in Fig.18.1(a) and the waveforms of Fig.18.1 (b) it is noted that the flow direction of the output current i_o cannot be changed since neither the transistor *T*, nor the diode *D* cannot conduct a current in the opposite direction. Consequently, both the instantaneous and the ***average value of the output current are always positive values***:

$$i_o(t) \ge 0 \quad \Rightarrow \quad I_o \ge 0 \qquad (18.10)$$

Based on the above observations, it is clear that the chopper topology shown in Fig.18.1 can operate only in the first quadrant of the electrical plane $V_o - I_o$, as shown in Fig.18.3.

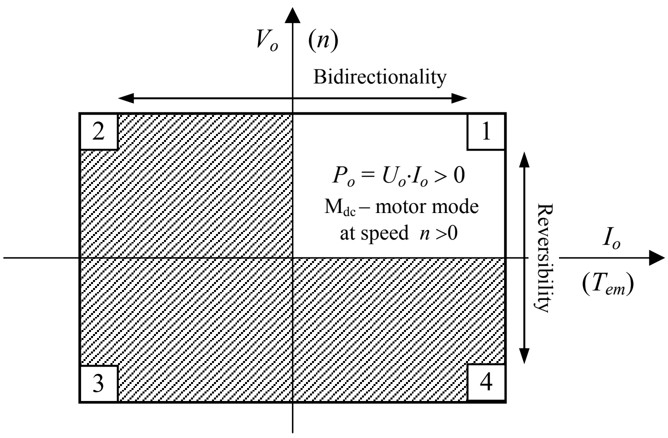

Fig.18.3 First quadrant of the electrical and mechanical plane in which operates the converter-motor system.

In the first quadrant of the electrical plane the output power is always positive ($P_o = U_o \cdot I_o > 0$) which means that the flow direction of the power through the converter is from the input to the output, from the V_d source to the DC motor.

It is known that the rotational speed n of a DC motor is proportional to the supply DC voltage and the electromagnetic torque T_{em} is proportional to the motor current if the excitation magnetic flux Φ_{ex} is constant. Thus, if we associate to the electrical variables V_o, I_o, the mechanical variables n, respectively T_{em}, we can say that the DC machine operates only in the first quadrant of the mechanical plane n - T_{em}. From the load's point of view this means that the DC machine M_{dc} takes the power transferred through the chopper and converts this electrical energy into mechanical energy. Therefore, the machine operates in ***motor mode*** at a positive speed (n >0). There is not the possibility for the DC machine of operating in the ***braking mode***, in the second quadrant of the mechanical plane, since the DC/DC converter cannot operate in the second quadrant of the electrical plane.

If we increase the average voltage from the chopper output, the DC motor accelerates, entering in an ***electromechanical transitory state*** towards a new ***electromechanical steady state,*** at a higher rotational speed. The new steady-state speed value is fixed by the new value of the V_o voltage and by the mechanical load on the motor shaft:

$$V_o = E + R_a \cdot I_o = k_e \cdot \Phi_{ex} \cdot n + R_a \cdot I_o \quad \Rightarrow$$
$$\Rightarrow \quad n = \frac{V_o}{k_e \cdot \Phi_{ex}} - \frac{R_a \cdot I_o}{k_e \cdot \Phi_{ex}} \quad \text{(in steady state)} \tag{18.11}$$

Knowing that the current value absorbed by the motor is proportional to the mechanical load (load torque - T_{load}) in steady state: $T_{load} = T_{em} = k_m \cdot \Phi_{ex} \cdot I_o$ we obtain:

$$n = \frac{V_o}{k_e \cdot \Phi_{ex}} - \frac{R_a \cdot T_{load}}{k_e \cdot k_m \cdot \Phi_{ex}^2} \tag{18.12}$$

where: k_e is the emf constant, k_m is the torque constant, Φ_{ex} is the excitation magnetic flux, maintained constant.

If we decrease the chopper output DC voltage until $V_o < E$, the average current I_o becomes zero, but cannot reverse, as mentioned above. Consequently, the electromagnetic torque becomes zero and the DC machine is ***braking freely*** due to the load torque if it exists or only due to friction torque if the motor is unloaded.

Analyzing the waveform of the i_o output current shown in Fig.18.1(b) we can see that it is filtered to a certain degree by the inductance of the load circuit. The limits between which the current varies are $I_{\min}$ and $I_{\max}$. These are closer to each other as the load inductance or the switching frequency increase. The latter parameter is chosen depending on the power transistor type, so that do not increase beyond a certain limit the switching power losses. Therefore, for a given switching frequency and for a given load inductance, if the average value of the output current decreases under a critical value I_o^*, the lower limit $I_{\min}$ reaches the zero value. We say that we are on the *boundary between continuous and discontinuous current conduction mode*. Further if the motor mechanical load (T_{load}) decreases more ($I_o < I_o^*$) the one-quadrant DC/DC converter will operate in the discontinuous current conduction mode.

Discontinuous conduction mode

In the discontinuous conduction mode the voltage and the current waveforms from the output of the one-quadrant chopper with an active load are changed as shown in Fig.18.4.

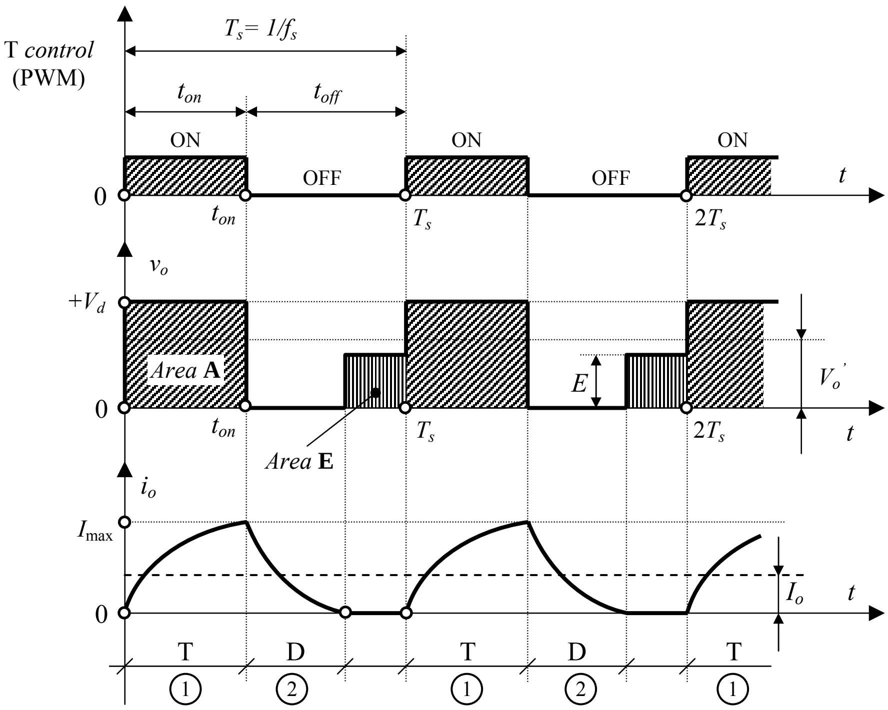

Fig.18.4 Waveforms corresponding to a one-quadrant chopper in discontinuous current conduction mode.

Fig.18.4 shows that, during the time interval in which the output current i_o is discontinuous (zero), the waveform of the v_o output voltage contains portions of the emf E voltage. Thus, the DC voltage, noted with $V_o^{'}$ in discontinuous conduction mode, increases by a certain value because in the formula of the average voltage, at the positive area **A** is added the area **E**, also positive:

$$V_o^{'} = \frac{1}{T_s}\int_0^{T_s} v_o(t)\cdot dt = \frac{1}{T_s}\cdot\left(Area\,\mathbf{A} + Area\,\mathbf{E}\right) > V_o = \frac{1}{T_s}\cdot Area\,\mathbf{A} \qquad (18.13)$$

The **E** area value depends on the average value of the I_o load current, supplied by the chopper. As the average current decreases, the time intervals in which the instantaneous current i_o is zero, increase. Thus, in the average value formula the **E** area increases. Consequently, the output DC voltage can't be adjusted exclusively through the control parameter (d – duty ratio), being dependant also on the load current (random variable):

$$V_o = f(d, I_o) \tag{18.14}$$

We can say that, in the discontinuous conduction mode, *the converter becomes uncontrollable*. Also, as in the case of the discontinuous conduction mode for the rectifiers, negative effects occur at the load level if this is a DC electrical machine:

- *noisy functioning* due to the cancellation of the electromagnetic torque during the time intervals where the current i_o is zero;
- *increasing of the power losses in the machine* (the iron losses and the Joule losses on the motor resistance) since of the overlapping of an important alternative (AC) component over the DC component of the current (high form factor). Due to the growth of the losses, the DC machine may overheat.

In addition, if the converter-motor system is a part of a control loop (speed, position etc.) and the discontinuous conduction mode occurs at a time, this may cause the system instability since the regulators were tunned considering the normal operation mode of the converter (continuous conduction mode).

Unlike the rectifiers for the choppers there is a cheap and safe solution to avoid the possibility of discontinuous conduction mode. This consists in choosing a two or four quadrants chopper with a much simpler structure than a rectifier that can operate in four quadrants.

3. Two-quadrant choppers

The two-quadrant chopper topology includes two controllable semiconductor devices (transistors) with antiparallel recovery (freewheeling) diodes, forming the well known bridge leg structure named *half bridge*. The way in which the half bridge structure used for a two-quadrant chopper is connected to the supply DC voltage V_d and to the load (DC motor) is presented in Fig.18.5.

A comparison between one and two-quadrant choppers highlights a minimum additional investment for the latter: one power transistor more with its recovery diode. However, the operational advantages compensate the additional investment. Other argument in this regard is the possibility of using a power integrated module PIM that implements exactly the half bridge structure. Such power modules are offered by many companies, are cheap and easy to use because all the connections between devices are made inside the capsule.

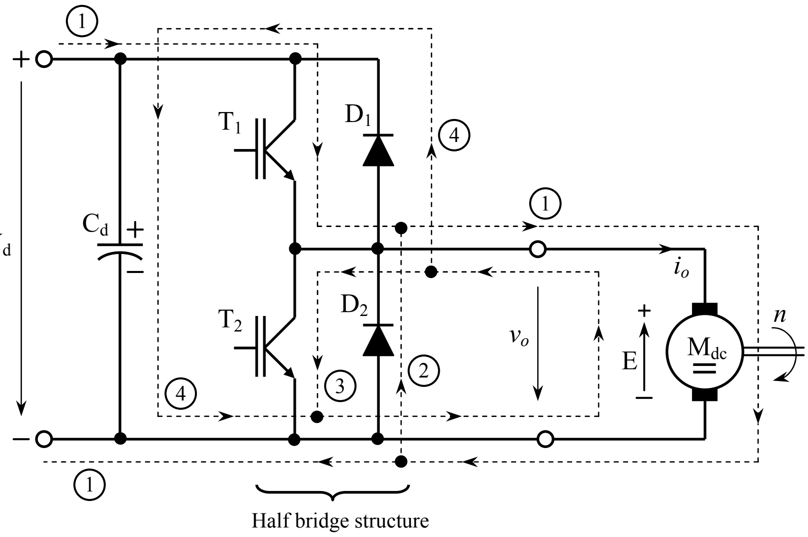

Fig.18.5 Two-quadrant DC/DC converter (chopper) topology.

A problem that must be taken into consideration is the control technique of the two transistors included in the half bridge structure. The solution for this problem and the modalities to implement the transistor drivers have been analyzed in Lab no.6, dedicated to the integrated drivers for the MOS gate transistors. Here we mention only that, the control signals for the two power transistors are of a PWM type and complementary. For an easier understanding, the analysis of the converter's operation will be made under ideal conditions, considering that the power transistors switch instantly. Therefore, the PWM signals can be complementary, without dead time (blanking time), as shown in Fig.18.6. With this approximation, we obtain the following relationship between the two transistors duty ratios:

$$(t_{on(T1)} + t_{on(T2)}) = T_c \quad \Leftrightarrow \quad \frac{t_{on(T1)}}{T_c} + \frac{t_{on(T2)}}{T_c} = 1 \quad \Rightarrow$$

$$d_{(T1)} + d_{(T2)} = 1 \tag{18.15}$$

In reality the power semiconductor devices doesn't switch instantly. To avoid an overlapping conduction of the controllable devices from the half bridge structure (which is equivalent to a short circuit for the V_d source), in practice are used complementary PWM signals with dead time to control the T_1, T_2 transistors. The analysis of the dead time influence on the output DC voltage value can be done later for accurate applications such as servo drives where the control precision is essential.

The waveforms of the v_o output voltage and of the i_o output current for a two-quadrant chopper are shown in Fig.18.6.

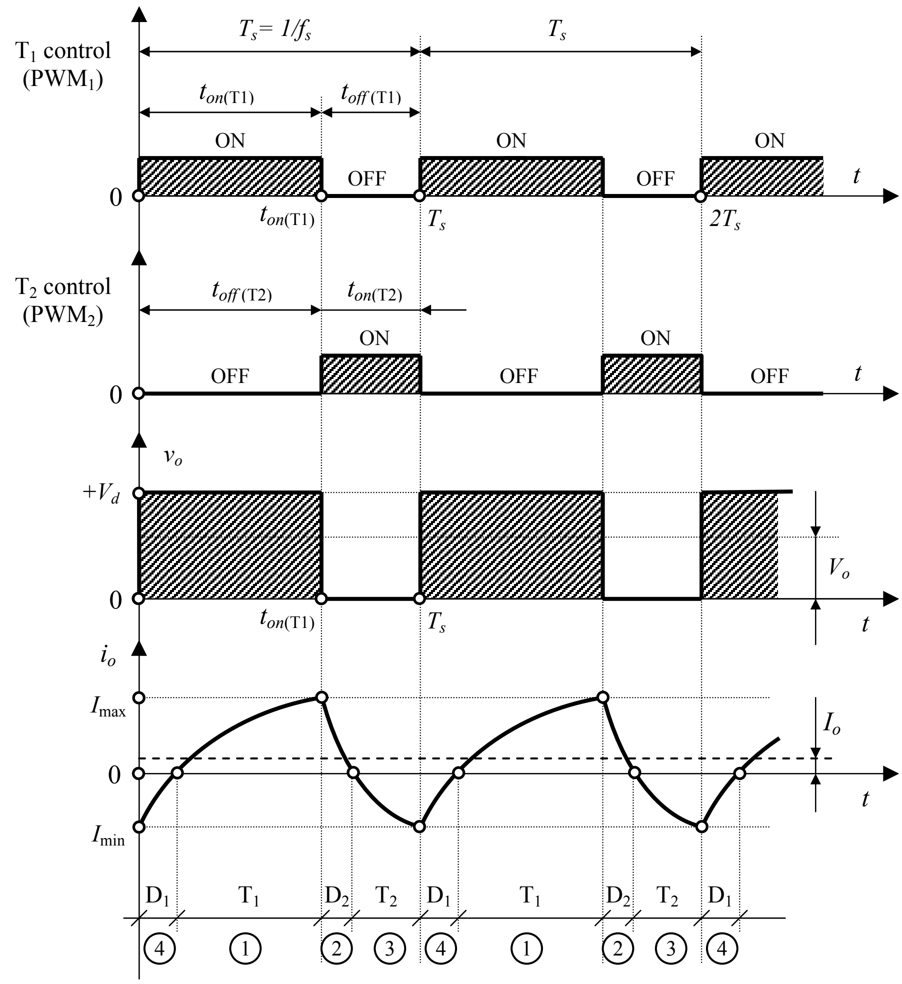

Fig. 18.6 Waveforms for a two-quadrant chopper.

We start the analysis of the converter when the T_1 transistor is on and begins to conducts the i_o current that flows through the path labeled with (1) in Fig.18.5. This is a positive current that produces a positive electromagnetic torque at the DC motor level ($T_{em} > 0$), torque that helps the movement of the rotor, has the same direction with the n speed. During this on-time interval of the T_1 transistor the supply voltage V_d is applied to the load (DC motor):

$$v_o(t) = V_d \rightarrow \text{ during the time interval (1) in Fig.18.6} \qquad (18.16)$$

The output current evolves in time following an increasing exponential according to the expression (18.4) obtained for the one-quadrant chopper. When the T_1 transistor is turned off, the i_o current can't further flow through the path (1). Therefore, it searches an alternative path, denoted with (2) in Fig.18.5, to discharge the inductive energy accumulated in the electromagnetic field of the L_a inductance. Consequently, the D_2 diode is turned on and, thus, the output terminals of the converter are connected together (motor terminals are shorted) and the output voltage is zero during the subcycle (2):

$$v_o(t) = 0 \rightarrow \text{ during the time interval (2) in Fig.18.6} \qquad (18.17)$$

The inductive energy is consumed by the motor, being converted into mechanical energy since in subcycle (2) the electromagnetic torque remains positive (i_o >0). A small part of this energy is converted also into heat by the R_a resistance. When there is no energy left in the inductance field, the current i_o reaches zero value at the end of the time interval (2). After this interval can finally enter into conduction, the transistor T_2 which has been turned on since the $t_{on(T1)}$ moment. Thus, the output current becomes negative due to the E voltage and flows in the loop formed by the DC motor and the T_2 transistor, path labeled with (3) in Fig.18.5. In subcycle (3) the i_o current evolves in time following further the decreasing exponential from subcycle (2), whose expression is given by equation (18.6). With the entry in conduction of the T_2 transistor the connection between the output terminals of the converter is maintained. Therefore, the output voltage remains zero during the subcycle (3):

$$v_o(t) = 0 \rightarrow \text{ during the time interval (3) in Fig.18.6} \qquad (18.18)$$

The i_o current evolution to the steady-state value of the decreasing exponential is stopped at a time when the T_2 is turned off, after the switching period T_s. At the end of subcycle (3) the L_a inductance has a certain inductive energy in the electromagnetic field, corresponding to the negative current I_{min}. This energy maintains the i_o current flow through the path denoted with (4) in Fig.18.5, through the recovery diode D_1. Practically, the energy from the inductance field is transferred to the C_d input capacity in subcycle (4), reason for that, during this time interval, the negative amplitude of the output current decreases until reaches the zero value when whole the energy is discharged. After this moment the transistor T_1 can conduct a positive current, conduction determined by the supply voltage V_d. Thus, restarts again the subcycle (1). The evolution of the i_o current during the subcycle (4) and (1) follows the increasing exponential (see equation 18.4).

After the T_2 turn-off and D_1 turn-on the upper output terminal of the converter is connected at the positive potential of the supply voltage V_d. Consequently, the output voltage is equal with the V_d voltage during the time interval (4):

$$v_o(t) = V_d \rightarrow \text{ during the time interval (4) in Fig.18.6} \qquad (18.19)$$

Taking into consideration the equations (18.16)÷(18.19) it can be obtained the waveform for the output voltage v_o, which is the same as in the case of the one-quadrant chopper – see Fig.18.6. Therefore, the average value of the output voltage for a two-quadrant chopper can be calculated with the help of the same equation (18.8):

$$V_o = V_d \cdot d \geq 0$$

The average value of the output current (DC current) I_o is located approximately at halfway between I_{max} and I_{min} on the diagram shown in Fig.18.6 and can be calculated with the approximate equation:

$$I_e \approx \frac{I_{\max} + I_{\min}}{2} \qquad (18.20)$$

Depending on how are located the two extremes I_{max} and I_{min} ***the average output current can be positive or negative.***

a) If $I_o > 0$ the electrical machine operates in ***motor mode*** producing a positive electromagnetic torque (T_{em}>0) in the same direction as the rotation speed (n>0). Both the converter and the electric machine operate in the first quadrant (see Fig.18.7), as was shown for the one-quadrant chopper.

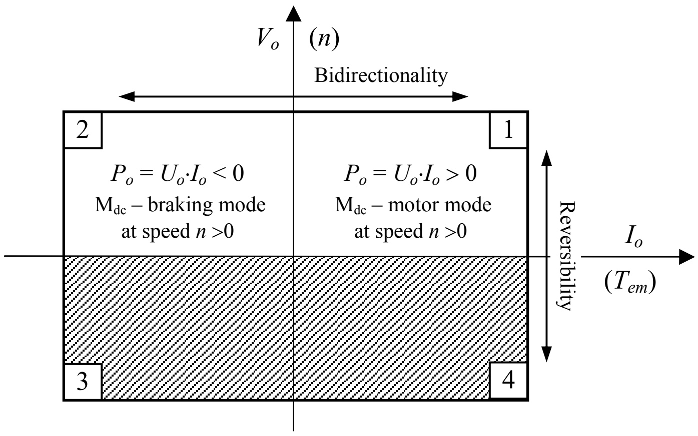

Fig. 18.7 First and the second quadrant of the electrical and mechanical plane in which operates the converter-motor system.

b) If, during the DC machine operation with a positive speed (n > 0), the duty ratios of the two transistors are suddenly modified, so that to decrease the DC output voltage under the E voltage, from that instant the average current through the DC machine changes the direction, becoming negative:

$$\left.\begin{array}{r} V_o = E + R_a \cdot I_o \\ V_o < E = k_e \cdot \Phi_{ex} \cdot n \end{array}\right\} \Rightarrow I_o = \frac{U_o - E}{R_a} < 0 \qquad (18.21)$$

A negative current through the DC machine causes a negative electromagnetic torque (T_{em}<0) in opposition to the rotational movement, with the significance of a *braking torque*. Thus, the electric machine operates in ***braking mode*** as a ***DC generator*** in the second quadrant of the mechanical plan n – T_{em} and the DC/DC converter operates in the second quadrant of the electrical plan $V_o - I_o$, as shown in Fig.18.7. In the second quadrant the converter output power is negative ($P_o = V_o \cdot I_o < 0$), which means that it flows through the chopper in reverse direction, from the output to input. Practically, the mechanical (motion) energy (kinetic energy) is converted by the DC machine in electrical energy which is recovered by the chopper and sent back to its input. From here this energy must be taken from other converter or consumed by a braking circuit (e.g. braking resistor). Otherwise, the whole energy is accumulated by the C_d capacity causing a progressively increasing of the V_d until the capacity breakdown.

If the transistors duty ratio are modified to decrease the average output voltage from the V_o value to the other $V_o^{'}$ value ($V_o^{'}<E$), the ensemble motor-mechanical load enters in a *braking transitory state* from a speed corresponding to the V_o toward a lower speed corresponding to the $V_o^{'}$ voltage. It is a forced speed changing made by the braking (electromagnetic) torque. This technique is essential in the controlled electrical drive systems since we obtain short response times for the speed adjustment.

There is the possibility of bringing the converter-motor system in the second quadrant in order to stop the motor. To obtain the shortest stop time it must maintain the brake torque at its maximum value during the whole stop time interval. The maximum electromagnetic torque is given by the maximum current that can be supported by the motor and/or by the converter. Since, during the stopping process, the emf E decreases with the motor speed, the duty ratios of the transistors must be adjusted continuously to maintain the negative current I_o at its maximum value during the whole braking time interval (see equation 18.21). To implement practically such a requirement it must use an automatic system with a current control loop.

Depending on the load inductance value, on the switching frequency and on the average value of the output current I_o is possible to reduce to two the four operating subcycles of the converter, represented in Fig.18.6. For example, in case of the motor acceleration the average value I_o can increase, so that the minimum values I_{min} would become positive. As a result, the four subcycles will be reduced to the subcycles (1) and (2). On the other hand, in a dynamic brake mode the negative magnitude of the I_o can increase, so that the maximum values I_{max} would become negative. In this case remain the subcycles (3) and (4).

4. Laboratory application

The laboratory setup which enables to obtain either the one-quadrant chopper, or the two-quadrant chopper is based on the laboratory stand described in the Lab no.6. As shown in Fig.18.8, it includes a half bridge IGBT power module mounted on an heat sink, a MOS gate driver achieved with the SKHI22H4 module, manufactured by *Semikron,* to control the two transistors of the half bridge structure and a PWM modulator (see Lab no.17) to generate the two complementary PWM signals with dead time. The duty ratio of the transistors can be adjusted via a potentiometer P included in the modulator circuit. The DC motor is connected between the output terminal of the half bridge structure (power terminal labeled with 1) and the ground of the V_d source (*Power* GND). Also, the power module will connect to the supply voltage V_d with the 3 terminal (collector of the upper transistor) to the positive potential and with the 2 terminal (emitter of the bottom transistor) to the negative potential → *Power* GND.

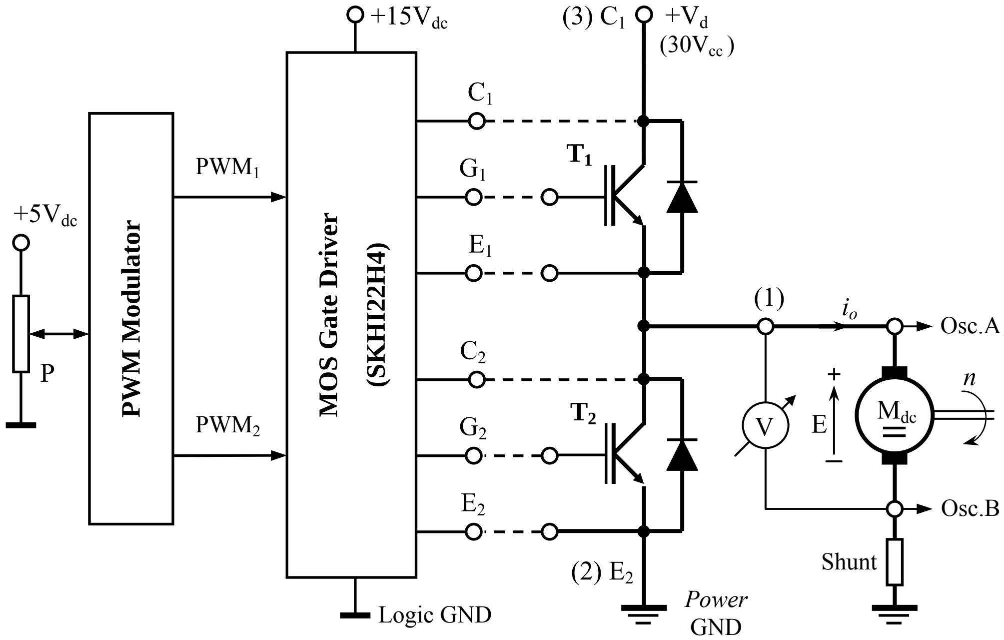

Fig.18.8 Block diagram of the laboratory setup dedicated to study the one and the two-quadrant choppers.

The DC source that supplies the chopper structures has a low voltage V_d=30V$_{dc}$. This is achieved by means of a single-phase line-frequency transformer TR, a bridge diode rectifier, a filtering capacity which is connected in parallel with a *braking resistor* to consume the power recovered during the braking mode of the DC machine. The DC electrical machine is manufactured with permanent magnets. The image of the laboratory setup is shown in Fig.18.9.

As mentioned above, with the laboratory setup whose block diagram is shown in Fig.18.8 they can be obtained both choppers treated in the present paper. Thus, to achieve the one-quadrant chopper it will be necessary to control only the upper transistor T_1 from the half bridge structure. To avoid an accidentally turn-on of the bottom transistor T_2 their control terminals, the gate and the emitter, must be connected together. Since the T_2 transistor remains in the turn-off state all the times, from the bottom side of the bridge leg will operate only the D_2 device with the role of recovery diode (see Fig.18.1). To achieve the two-quadrant chopper it will be necessary to control both transistors from the half bridge structure (PIM module).

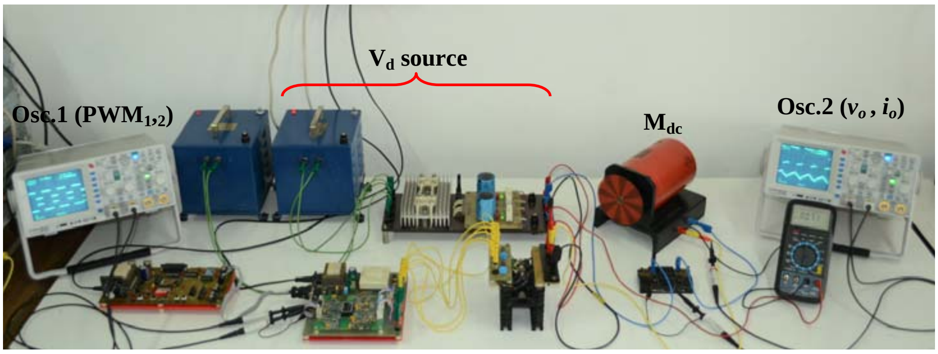

Fig.18.9 Image of the laboratory application.

5. Objectives and procedures

1. It will be studied by comparison the two DC/DC converters, one and two-quadrant choppers, (topology, waveforms, operating modes, voltage and current equations etc.);
2. It will be performed the experimental setup for the one-quadrant chopper with the topology shown in Fig.18.1(a);
3. It will be displayed with the help of a two spots oscilloscope the waveforms of the two complementary PWM signals with dead time generated by the PWM modulator (see Osc.1 in Fig.18.9) – there are measurement points on the modulator board;
4. It will be displayed with the help of a two spots oscilloscope (Osc.2) the waveforms of the v_o output voltage and those of the i_o output current which should result as the diagrams shown in Fig.18.1(b) if the one-quadrant chopper operates in continuous conduction mode;
5. It will be modified suddenly the duty ratio of the T_1 transistor and it will be observed:
   - V_o average value variation measured with the help of a voltmeter once the duty ratio is changed;
   - I_o increasing during the motor acceleration when the duty ratio increases, respectively the I_o decreasing (the converter is unloaded) when the duty ratio is also decreased;

- appearance of the discontinuous conduction mode when the duty ratio is suddenly decreased;
- impossibility to reverse the output current direction at the one-quadrant chopper;

6. It will be performed the experimental setup for the two-quadrant chopper with the topology shown in Fig.18.5;
7. It will be displayed the waveform of the v_o output voltage in correspondence with the waveform of the i_o output current which should result as the waveforms shown in Fig.18.6;
8. It will be modified suddenly the duty ratio of the T_1 and T_2 transistor and it will be observed:

   - V_o average value variation measured with the help of a voltmeter once the duty ratios are changed;
   - I_o increasing during the motor acceleration when the T_1 duty ratio increases;
   - I_o decreasing and reverse direction flow ($I_o < 0$) when the T_1 duty ratio is suddenly decreased;
   - discontinuous conduction mode can't occur at the two-quadrant chopper;

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] Erickson R., Maksimovic D, *Fundamentals of PowerElectronics*, University of Colorado, Boulder, Colorado, Published by Kluwer Academic Publishers, USA, 2001.
[3] Trzynadlowski A.M., *Introduction to Modern Power Electronics*, John Willey &Sons, New York, 1998.
[4] Krein P., *Elements of Power Electronics*, Oxford University Press, New York, 1998.
[5] Albu M., *Electronică de putere* - vol I: *Noțiuni introductive, dispozitive, conversia statică alternativ-continuu a energiei electrice*, Casa de Editură “Venus” Iaşi, 2007.
[6] Diaconescu M.P., Graur I.: *Convertoare statice – baze teoretice, elemente de proiectare, aplicații*, Ed. „Gh. Asachi”, Iaşi, 1996.
[7] Ionescu Fl., Floricău D., Nițu S., Six J.P, Delarue Ph., Boguş C.: *Electronică de putere - convertoare statice*, Ed. Tehnică, Bucureşti, 1998.
[8] Kelemen A., Imecs M., *Electronică de putere*, Ed. Didactică şi Pedagogică, Bucureşti, 1983.