Lab no. 9

INVERTER MODE OPERATION OF THE SINGLE-PHASE RECTIFIER

1. Introduction

A common phase-controlled rectifier with natural current commutation (M2 B2, M3, B6 and so on) *can operates only in two quadrants* of the electrical plan $V_d - I_d$ (output DC voltage – output DC current), respectively in the quadrants 1 and 4, as shown in Fig. 9.1.

In the fourth quadrant these converters operate as an inverter, they have the polarity of the output DC voltage reversed, but the output DC current flow is maintained in the positive direction, the one direction possible allowed by the thyristors included in the rectifier topology. ***The reversed V_d voltage is provided by an active load connected at the rectifier output***. *The rectifier imposes only the magnitude of the converter voltage drop through the delay (firing) angle value* $\alpha_{inv} > 90^o$. In this way, the I_d current is adjusted and thus, the power value transferred by the converter from the DC side to the AC side is adjusted. For the active DC load situated at the position of a power source the converter behaves as a power receiver because the output P_d power becomes negative: $P_d = U_d \cdot I_d < 0$.
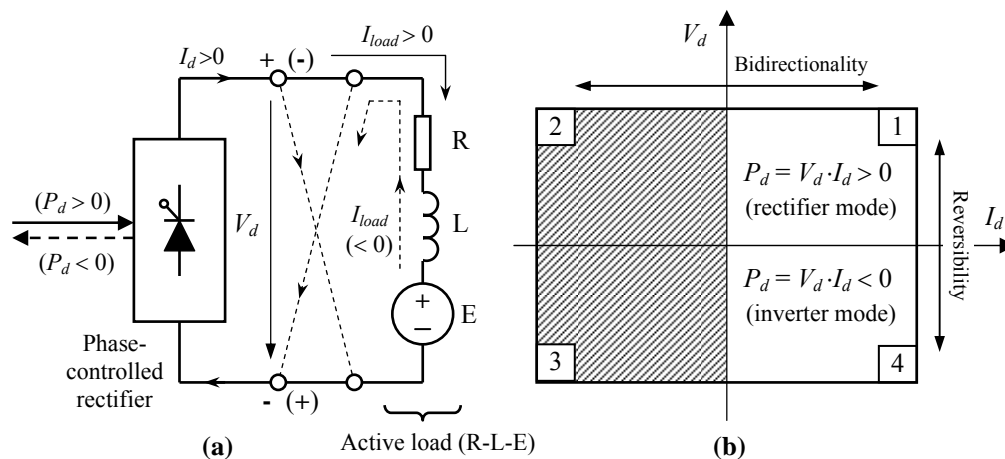

Fig.9.1 (a) Phase-controlled rectifier transition into inverter mode (from the 1 into 4 quadrant); (b) Electric plan: $V_d - I_d$.

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The feature of a power electronic converter to reverse the polarity of its output DC voltage is called *reversiblity* and it can occur by a transition from the quadrant 1 to the quadrant 4 and vice versa, as suggest the arrows shown in Fig.9.1(b). Although, another reversibilty process can take place by a transition between 2 and 3 quadrants, but this movement is not possible because the converter operation in these quadrants is impossible.

2. Inverted mode operation of the single-phase bridge rectifier

For a phase-controlled rectifier to operate in inverter mode (in quadrant 4 of the electric plan $I_d - U_d$) is not enough to change the firing angle value corresponding to an inverter angle α_{inv}, included in the range of $(90^o \div \alpha_{inv(max)}]$. Besides this condition, it is required that the active load to be connected in such a manner at the output terminals of the rectifier so that its internal voltage (E) to become the source that maintains the I_d current flow in a positive direction, as shown in Fig.9.3. Thus, the electronic converter moves in the position of the power receiver from its load and the output voltage given by the firing angle α_{inv}:

$$V_{d\alpha(inv)} = V_{d0} \cdot \cos \alpha_{inv} < 0 \qquad (9.1)$$

sets the value of the voltage drop across the converter. Based on this voltage drop the DC current I_d can be adjusted. Also, through the transition of the converter in the receiver position it is posible to explain the *negative polarity of the output DC voltage* which is provided by the active load not by the converter as in the case of the rectifier mode operation.
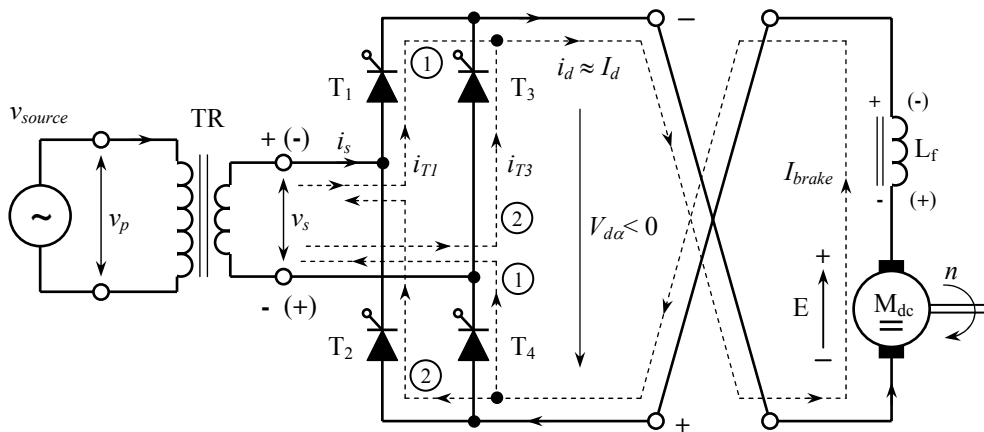

Fig. 9.2 The active load reverse connection at the phase-controlled rectifier output to operate in inverter mode.

In Fig.9.2 was chosen as an active load a DC motor. It is the most suggestive and widespread application in which the rectifier transition in the inverter mode operation is justified. If the DC motor is first supplied from the phase-controlled rectifier in a motor mode, as shown in Fig.8.1(b) (see Lab no.8), then a generator (recovery braking) mode is desired by bringing the converter in the 4 quadrant, the following successive operations must be carried out:

1. Stoping the gate trigger pulses or the firing angle is increased towards 90° to allow the cancellation of the I_d current through the motor;

2. Disconnection of the active load ($M_{dc} + L_f$) and its inverse reconnection at the rectifier output (***reverse connection***), as shown in Fig.9.3, to obtain the reverse polarity of the output voltage V_d;

3. Converter control with a firing angle $\alpha_{inv} \subset (90^o \div \alpha_{inv(max)}]$. The inverter firing angle must be well chosen at the first moment ($\alpha_{inv} = 180^o - \alpha_{rectifier}$) to avoid the thyristors damage due to the increasing of the I_d current over a maximum acceptable value.

In the invertor mode the DC current I_d is given by the equation:

$$I_d = \frac{E - \left|V_{d\alpha(inv)}\right|}{\sum R} = I_{brake} \qquad (9.2)$$

where:

– E is the electromotive force (emf) proportional with the motors speed n;

– $\sum R = R_a + R_{Lf} + R_{secTR}$ is a sum consisting of the DC motor armature resistance (R_a), the filters inductor resistance (R_{Lf}) and the resistance of the transformer secondary winding (R_{secTR}).

The I_d current given by (9.2) equation flows also in the positive direction through the converter, but in reverse direction through the DC motor (the direction imposed by the emf voltage E) being actually a braking current ($I_{brake} < 0$).

All resistances of the sum $\sum R$ belong to windings (coils) and have low values (tenths of $\Omega \div \Omega$). Therefore, care should be taken in the first moments after the inverter mode appears that the numerator of the equation (9.2) to be not too large in order to limit the thyristors average current $I_{Th(averrage)} = I_d /2$ up to maximum catalog value. If the motor speed or the emf voltage E aren't known is indicated that the transition of the rectifier in inverter mode to be made at a maximum inverter delay angle $\alpha_{inv(max)}$, then α_{inv} is decreased progressively ($|U_{d\alpha(inv)}|$ decreases) until the I_d current value is kept within acceptable limits.

If the electrical motor operates in a braking mode for stopping, its speed decreases over time causing a progressive decrease of the emf voltage E. To obtain the shortest braking time the current $I_{brake} = I_d$ must be maintained all the time at its

acceptable maximum value because the electromagnetic (braking) torque of the motor is proportional to the armature current. For this purpose, the converter control circuit must be completed with a current regulator (closed current loop) that reduces progressively the firing angle α_{inv} as the motor speed decreases.

There is also the possibility of the motor braking at cvasi constant speed when its mechanical load is of potential type (eg. a regenerative braking of an electric vehicle that descends a slope). In such a situation the electric motor generates a braking torque in reverse direction, against the potential torque which causes the motion, to prevent the speed increase over a certain value due to the weight.

Fig.9.3 shows the waveforms coresponding to a single-phase phase-controlled rectifier that operates in inverter mode at a firing angle $\alpha_{inv} = 120^o$. Looking at the $v_d(t)$ voltage waveform we can see that it contains larger portions of the negative half-waves than the portions of the positive half-waves. Thus, the average output voltage of the rectifier is negative because the negative B area has their modulus greater than the positive A area:

$$V_{d\alpha(inv)} = \frac{1}{\pi} \int_{\alpha}^{\pi+\alpha} v_d(\omega t) \cdot d(\omega t) = \frac{1}{\pi} \cdot \left(Area\ A + Area\ B\right) = V_{d0} \cdot \cos\alpha_{inv} < 0 \qquad (9.3)$$

The presence of the $i_d(t) > 0$ during the v_s negative half waves is caused by the active load voltage (E). During these time intervals the instantaneous power in the converter DC side is negative, which corresponds to the power flow from the DC side to the AC side (instantaneous inverter mode). Because the time intervals corresponding to the instantaneous inverter mode are greater than the time intervals corresponding to the instantaneous rectifier mode (intervals where $v_d(t) > 0$), the average power in the DC side is negative and the converter operates in (global) inverter mode:

$$P_d = V_{d\alpha(inv)} \cdot I_d < 0 \qquad (9.4)$$

This power is provided by the active load and transferred to the AC source through the converter, being found in the AC side of the converter as an active power.

It can be demonstrated that, in the AC side, the active power corresponding to a non-linear load, as the phase-controlled rectifier, is given by:

$$P = V_s I_{s1} \cdot \cos\varphi_1 \qquad (9.5)$$

where: I_{s1} is the rms value of the $i_s(t)$ current fundamental harmonic and φ_1 is the phase displacement between the fundamental harmonic $i_{s1}(t)$ and the AC voltage $v_s(t)$ at the rectifier input, considered sinusoidal.

Looking at the $i_{s1}(t)$ waveform in Fig.9.3 we can see that the fundamental harmonic of the AC side current $i_s(t)$ is shifted from the AC supply voltage with the phase displacement: $\varphi_1 = \alpha_{inv} > 90^o$

Consequently, the active power in the AC side becomes:

$$P = U_s I_{s1} \cdot \cos \varphi_1 = U_s I_{s1} \cdot \cos \alpha_{inv} < 0 \qquad (9.6)$$
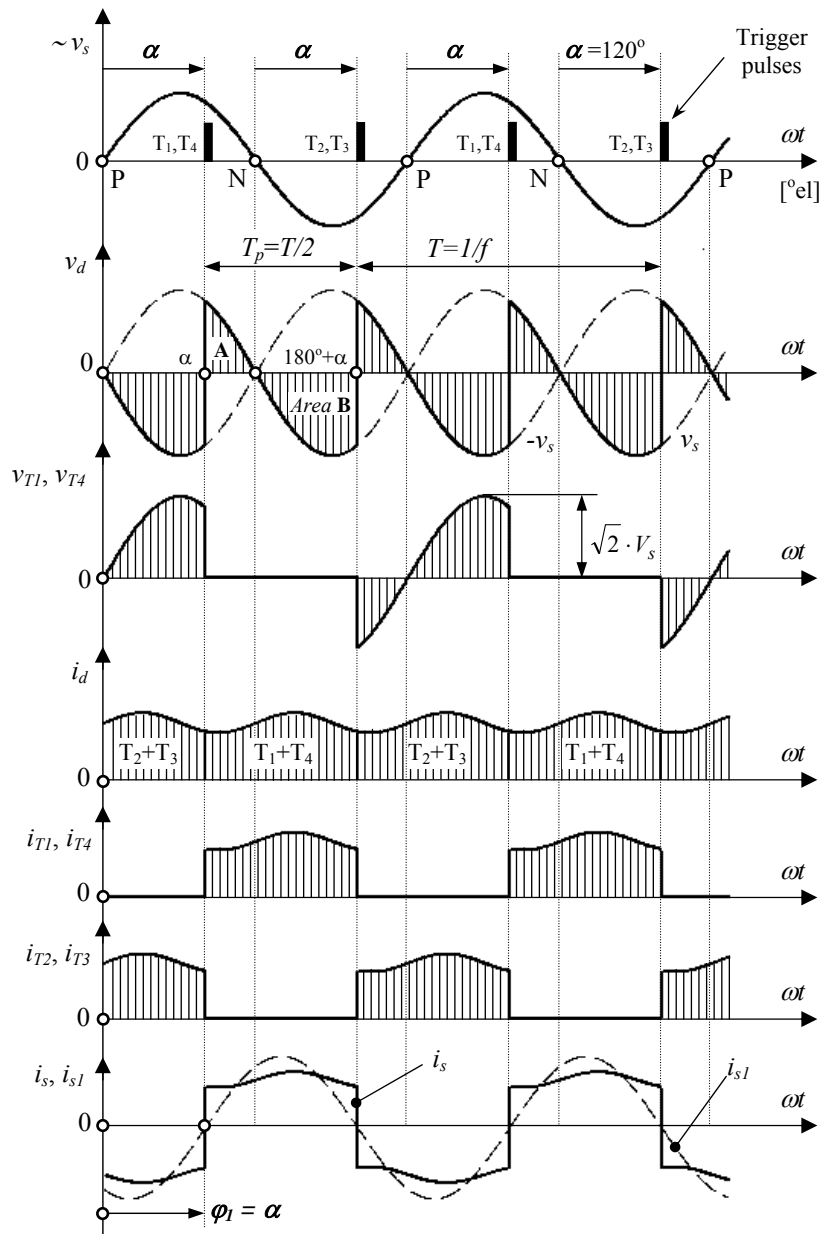
Fig. 9.3 The waveforms corresponding to a single-phase phase-controlled bridge rectifier operating in inverter mode (α_{inv}=120°).

From the point of wiev of the AC source a negative active power signifies a received power. This is exactly the power transferred through the converter from the DC side. It follows that the rectifier makes a DC/AC power conversion, so this converter operates in *inverter mode*.

In conclusion, a phase-controlled rectifier can operate in two modes in terms of the power flow direction, the rectifier mode and the inverter mode if certain conditions are met. First, the choice between one of two modes is done through the delay angle value. Secondly, in order to obtain the inverter mode the DC load must be active and connected at the converter output terminals so as to facilitate the current flow in the positive direction, the same direction as in the rectifier mode.

The successive operations performed to switch the phase-regulated converters from the rectifier mode into inverter mode and vice versa introduce an important delay time that negatively affects many applications. For this reason, in practice four-quadrant rectifiers (bidirectional line-commutated rectifiers) are used. These consist of two classical phase-regulated rectifiers in antiparallel connection.

3. Four-quadrant operating of the DC load

In most applications which include phase-controlled rectifiers as DC motor drives, DC voltage sources for the inverters and choppers supply, power electronic systems dedicated to the renewable energy sources interconnection etc., particularly interest in the ability of the rectifier to pass from quadrant 1 to quadrant 2 or otherwise its ability to retrieve a current in the opposite direction, to be *bidirectional*. In fact, the mechanical reverse connection of the active load in order to switch the rectifier operation in inverter mode, from quadrant 1 into quadrant 4, allows a load passage from quadrant 1 to quadrant 2 because the current through it changes the direction flow and the voltage polarity across it remains the same (Fig.9.1→ I_{brake}<0). On the other hand, the rectifier keeps its current direction (I_d>0), but the DC voltage polarity is changed across it ($V_d < 0$). Based on this mechanical reverse connection maneuver an adaptation is made between the possibility of the active load to provide power by changing the current direction flow and the rectifier possibility to retrieve this power by changing the polarity of the output DC voltage.

If the active DC load has a limited amount of power, the rectifier in inverter mode of operation can transfer this entire power to the AC side. A good example of such a situation is the electric braking process of a DC motor until it stops. At the end of this process the converter may return gradually in the rectifier mode *without modifying the reversed connection* of the load. In this case, from the point of view of the rectifier we have a return from quadrant 4 to quadrant 1 of the electric plane, but from the point of view of the DC motor we have a transition from quadrant 2 to quadrant 3 of the mechanical plane $n - M_e$ (rotational speed– electromagntic torque) because the shaft rotations direction changes (n<0) due to the polarity change of the supply DC voltage ($V_d < 0$). Further, the electrical motor can brake from the reverse

rotation if it goes from quadrant 3 in quadrant 4 of the mechanical plane (see Fig.9.2). For this, the rectifier will pass once more from quadrant 1 to quadrant 4 of the electrical plane making sure that before this operation was carried out, the reverse connection of the DC motor (it returns to the original connection when the load was operating in quadrant 1) and considering all the restrictions corresponding to the firing angle bringing in the inverter range. After stopping the motor from the reverse shaft rotation, the converter can move back again to quadrant 1, bringing with him the active load that ends a full cycle in which it passed through all the four quadrants of the mechanical plane in *counterclockwise* direction, the normal operation of a *reversible drive*: the rotation of the electrical motor in a positive direction ($n>0$) $\rightarrow$ braking and stopping the motor from the positive rotation $\rightarrow$ rotating the motor in the negative direction ($n<0$) $\rightarrow$ braking and stopping the motor from the negative rotation $\rightarrow$ accelerating again in the positive rotation direction.

From the above mentioned, we can observe that having only a ***single two-quadrant rectifier***, by means of mechanical reverse connections and delay angle changes, the active load can pass through all four quadrants of the mechanic plane. Due to this reverse connection maneuvers in such an operating cycle, a single line-commutated rectifier twice passes its specific operating cycle (round trip between the quadrant 1 and 4).

The reverse connection of the DC motor (M_{dc}) to the output of the rectifier can be obtained in practice by means of contacts included in the mechanical switching devices named *direction contactors (relays)* (K_1, K_2), as shown in Fig.9.4 for a reversible electric drive (four-quadrant drive). The electrical machine operates as a motor in quadrant 1 if the K_1 contacts are closed and the converter A operates in rectifier mode ($V_d > 0$). Here the voltage across of the DC load (of the motor) is positive ($U_{load.}>0$) and corresponds to a positive rotation speed ($n>0$). For the quadrant 1 the load current flows on the path 1 ($I_{load.}= I_{motor}>0$) and it generates a positive electromagnetic torque M_e, in the same direction as the rotation speed.

To bring the electrical machine into braking (generator) mode, in quadrant 2 where the electromagnetic torque become negative (opposes to the motion), it necessary to perform the successive operatios described in previous section. First the delay angle value is increased, from the rectifier value the first quadrant ($\alpha_{rectifier}$) to the value of 90° and further to inverter values (α_{inv}) to allow the cancellation of the current that flows throught the motor ($I_{load.}=0$). In this way, the reverse connection, achieved by releasing the contactor K_1 and closing the contactor K_2, will be made without a load current and thus the contacts will be protected from the emergence of a powerful electric arch. First a large inverter delay angle is chosen ($\alpha_{inv} = 180^o- \alpha_{rectifier}$) to avoid a dangerous current through the converter. The next step is to decrease the inverter delay angle to the value of 90° simultaneously with the decreasing of the speed, so the braking current (I_{brake} – path 2 in Fig.9.4) does not exceed the maximum value accepted by the converter and the motor (I_{max}):

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$$I_{brake} = I_d = \frac{E - \left|V_{d\alpha(inv)}\right|}{\sum R} \leq I_{max} \tag{9.8}$$
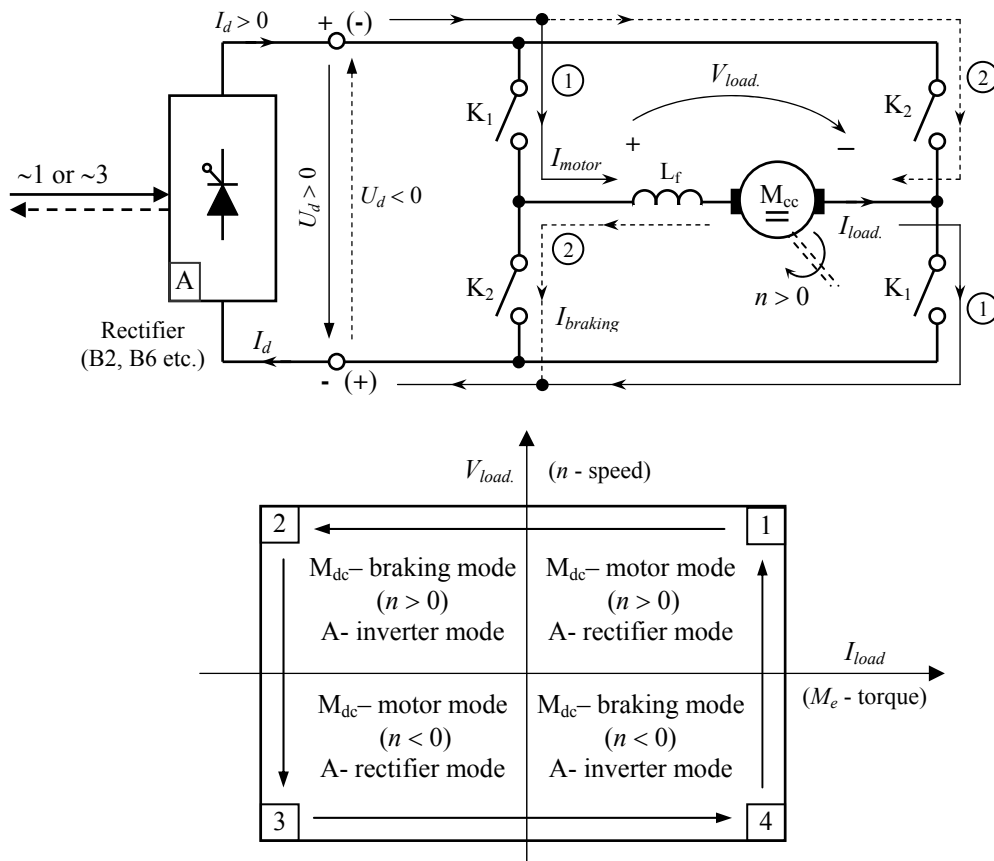

Fig. 9.4 A four-quadrant electrical drive achieved with a DC motor (M_{dc}) and with a two-quadrant rectifier reverse connected using contactors (relays).

As a result of the motor braking operation in the quadrant 2, the delay angle of the converter reaches the value of 90° when the motor stops. If, further, the delay angle is decreased below this value, the converter goes back in rectifier mode and the electrical machine will operate as a motor in quadrant 3. The combination of K_2 closed and K_1 released is beeing kept. It is necessary that, in the acceleration mode of the motor in reverse rotation direction, the decreasing of the control angle to be moderate to avoid the exceeding of the I_{motor} maximum limit (path 2 for the quadrant 3):

$$I_{motor} = I_d = \frac{V_{d\alpha(rectifier)} - E}{\sum R} \leq I_{max} \tag{9.9}$$

The motor braking in reverse rotation direction, in quadrant 4, is obtained if all the operations required for the reverse connection (K_2 released and K_1 closed) are performed and the converter is bringing in the inverter mode. Further, the passing of the DC load from quadrant 4 into quadrant 1 is done with the same combination of K_1 closed and K_2 relesed and with the converter returned in rectifier mode fulfilling the equation (9.9).

From the foregoing it results that, in order to achieve the DC load operation in all four quadrants using a single phase-controlled rectifier, they are necessary reverse connection operations, changes of the delay angle value and a control of the load current.

4. Laboratory application

In order to experimentally study of the inverter mode operation of a single-phase bridge rectifier the laboratory set-up whose block diagram is shown in Fig.9.5 and whose image is shown in Fig.9.6 will be performed. The set-up includes approximately the same circuit elements as in the laboratory application dedicated to the operation of the single-phase full-bridge structure in rectifier mode (see Lab no.8). To obtain the active load able to continuously generate power to the inverter a laboratory stand with the two identical DC electric machines, mechanically coupled, is used. The active load is emulated by one of the two DC machines, which operates as a generator (G), when it provides power. The generator is mechanical driven by the second machine that operates as a motor (M). In addition, the machine stand also includes an encoder (EN) and a tachogenerator (TG), both mechanically coupled with each one of the two machine shafts (see Fig.9.6). Using the tahogenerator we can easy monitor the rotation speed (n) using a voltmeter because this transducer generates a DC voltage proportional to the rotation speed. For safety reasons the supply circuits for both DC machines use line-frequency transformers ($TR1, TR2$) in interface with the utility grid which provides in the secondary windings low voltages of $24V_{ac}$. The first transformer supplies the thyristor full-bridge converter studied in inverter mode and the second transformer supplies through an autotransfrormer (ATR) and a diode single-phase rectifier the DC motor M. The bridge with the thyristors $T_1 \div T_4$ is integrated in a power module mounted on a heat sink with the connection terminals (banana socket). The gate trigger circuit of the thyristors achieved with the UAA145 integrated circuit is one of those described in Lab no.3. The power of the two DC electric machines is 120W and does not require separate excitation because they are made with permanent magnets. The L_f inductance is specifically designed to use in the laboratory, has a fixed value, being provided with banana socket connection terminals.

For the lab application it will be choosen a steady state inverter mode when the G machine operates as a barke for the M machine (motor), at a constant speed. With the help of the ATR autotransformer it can be adjusted the voltage that supplies

the motor, its speed n and implicitly the emf voltage E of the generator G. Thus, we can adapt the level of this voltage to the maximum inverter voltage:

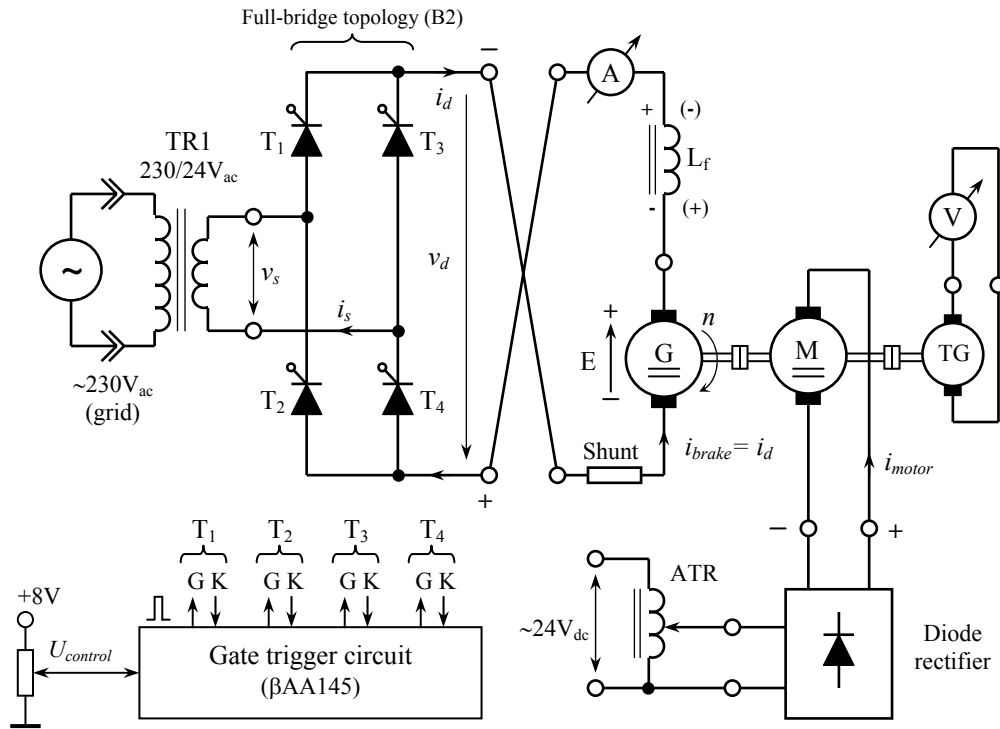$$U_{d\alpha(inv)\max} = U_{d0} \cdot \cos\alpha_{inv(\max)} \approx E \qquad (9.10)$$

Fig. 9.5 Laboratory setup block-diagram to study the inverter mode operation of a single-phase full-bridge rectifier (B2).

All the mentioned circuit elements can be interconnected by means of wires provided at their ends with banana plugs, as shown in Fig.9.6. It will be used two voltmeters to measure the average voltage V_d and the TG voltage, an amperemeter to measure the avarage value I_d and an oscilloscope with two spots.

As indicated in the section 2 to bring the converter in inverter mode operation they are necessary precautions and certain operations. Therefore, for this laboratory application it must be performed the following successive operations:

➢ Connecting the gate trigger circuit to the thyristor full-bridge B2 and verifying the operation of this structure in rectifier mode supplying the G machine (machine M is not powered);
➢ V_{d0} voltage measurement with a voltmeter connected to the output of the B2 structure when it operates in rectifier mode with a delay angle $\alpha = 0^\circ$.

➢ Stopping the rectifier operation and $U_{d\alpha(inv)\max}$ voltage calculation using the (9.10) equation for $\alpha_{inv(max)} = 150^o$.

➢ Starting the *M* machine in the opposite direction with respect to the previously rotating direction of the *G* machine and adjust the speed until the condition given by the (9.10) equation is met (emf voltage *E* can be measured directly at the *G* terminals);

➢ Ensure that the emf voltage *E* inversely biased the output of the B2 structure, as shown in Fig.8.12;

➢ Starting the B2 bridge operation in inverter mode with the maximum delay angle $\alpha_{inv(max)}$ afterwards this firing angle is gradually reduced until the generator is loaded → a speed decrease is detected and an increase of the I_d ($\approx$ 4A).
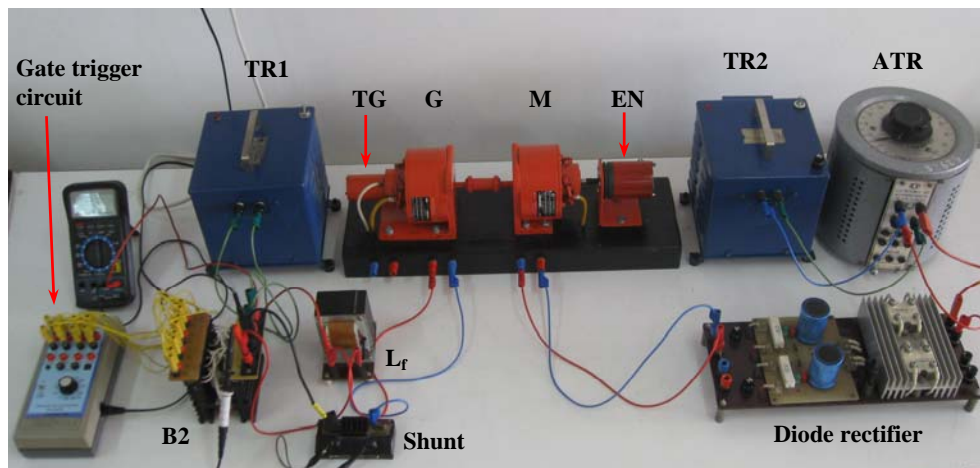

Fig. 9.6 The image of the laboratory setup.

5. Objectives and procedures

1. It will be analyzed the possibilities of energy exchange between an active DC load and an AC source through a phase-controlled rectifier and the correlation between the quadrants of the $I_d - U_d$ electric plan and the power flow directions;

2. It will be studied the theoretical aspects reffering to the inverter mode operation of a phase-controlled rectifier and the maneuvers which need to be carried out in order to switch the converter operation from the rectifier mode to the inverter mode;

3. It will be analyzed how, by changing the connection between the DC machine and the converter outputs (reverse connection), a phase-controlled rectifier operates in quadrant 4 of the electric plan and the electrical machine operates in quadrant 2 of the mechanical plan;

4. It will be analyzed how we can obtain a four-quadrant DC motor electrical drive with the help of a single phase-controlled rectifier;

5. It will be performed the laboratory setup with the block diagram shown in Fig.9.7 and the two parts of it will be tested separately, first starting the B2 structure in rectifier mode operation, then the phase-controlled rectifier will be stoped and the *M* machine will be supplied with a variable DC voltage by means of a the diode rectifier and the *ATR* autotransformer;

6. It will be started the B2 thyristor converter in inverter mode operation following all the successive steps, as mentioned in the previous section;

7. It will be displayed, with the help of a two spots oscilloscope, the u_d and i_d waveforms in inverter mode and it will be compared these waveforms with the theoretical ones presented in Fig.9.4;

8. It will be highlighted the load increase of the inverter, generator G and hence of the motor M with the decreasing inverter delay angle. This can be quantified following:

  − the i_d current waveform on the oscilloscope (the DC component will increases);
  − the A ampermeter which measures the average value of the i_d current;
  − the taho-generator voltage that will decrease because, by the motors load increasing, the speed decreases at the same supply voltage value (the evolution of the operating point on the motor mechanical characteristic);

9. It will be noted that, as the delay angle value tends to 90°, the converter in inverter mode behaves like a element that effectively short circuits the generator armature and current I_d greatly increases;

10. It will be stopped the *M* supply and it will be noted how through the decrease under 90° of the delay angle the electrical machine group will rotate in the opposite direction with respect to the previous situation;

11. Further, if the delay angle value is returned again over 90° it will be notice that the phase-controlled rectifier cannot operates in inverter mode because the motor *M* does not drives the generator *G* in reverse rotation direction (operation synonymous with the reverse connection).

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