POWER ELECTRONICS LAB

EE 536

EXPERIMENTS MANUAL

SAFETY INFORMATION

- Laboratory work always entails a higher risk of accidents.
- The device may only be operated by persons who are in a position to recognize shock hazards and to implement the proper safety measures.
- If measurements are to be made where there is a shock hazard, IT IS NOT PERMITTED TO WORK ALONE: a second person must be informed.
- In accordance with the IEC regulations, metal parts not carrying a voltage in normal operation (e.g. housings) are to be connected to the PE ground conductor. The ground conductor is provided solely for this purpose and may not be connected with the neutral conductor, N, of the circuit!
- Always use safety connecting leads.
- Do not switch on the power mains until the circuitry has been carefully checked
- The mains voltage must be disconnected before intervening in the experiment set-up and making any changes or additions to circuitry.

EXPERIMENT ONE

UNCONTROLLED RECTIFIERS

INTRODUCTION

Static rectifiers with diodes perform the basic function of dc rectification: the output voltage of a rectifier is a pulsating unipolar voltage with an average value. The common type of an ac/dc converter is composed by a transformer and a diode rectifier circuit, as shown in Fig.1.

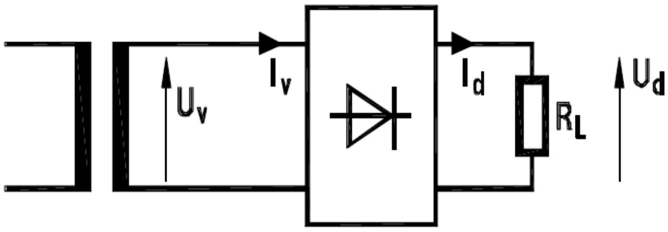


Fig. 1 AC/DC uncontrolled rectifier

In considering rectifier circuits it is important to know the relationships between the input (rms values) and output (average values) parameters, which are:
U_v = alternating line voltage (r.m.s.)
I_v = alternating line current (r.m.s.)
U_d = output dc voltage
I_d = output dc current

SINGLE PULSE RECTIFIER

The single pulse rectifier, or half wave rectifier of Fig.2, represents the simplest form of a static ac/dc converter.

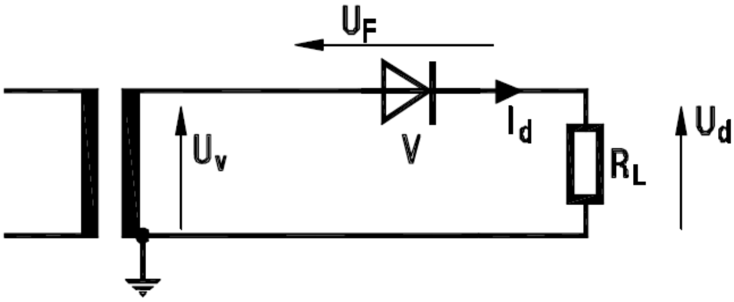


Fig. 2 Half wave uncontrolled rectifier, ohmic load

When an ohmic load R is applied, the diode switches the positive half of the ac voltage U_v to the load and blocks the negative half-wave. As a result, the dc voltage U_d is made up of intermittent (discontinuous) sinusoidal half-waves: the direct current I_d follows the same sinusoidal time profile as the dc voltage and is in phase with the latter, as illustrated in the following Fig.3.

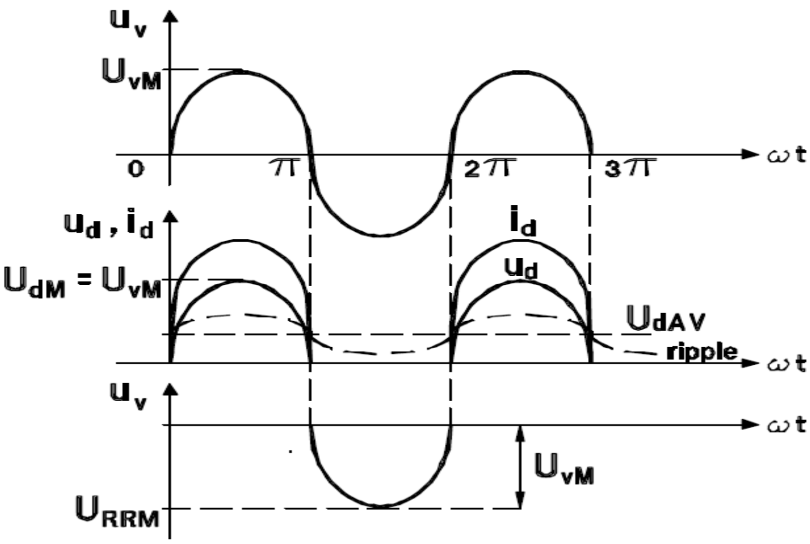


Fig. 3 Voltage and current waveforms, half-wave uncontrolled rectifier, ohmic load

All the following formulae apply to resistive load, neglecting losses in the rectifier.

Average value of output voltage $U_{dAV} = 0.45U_V$

Rms value of output voltage $U_{dRMS} = 0.707U_V$

Form factor of output voltage $f = U_{dRMS}/U_{dAV} = 1.57$

Ripple factor $w = 100(f^2-1)^{0.5} = 121\%$

Repetitive peak reverse voltage value of the diode $U_{RRM} = U_{VM} = 1.414U_V$

Inductive and ohmic-inductive loads

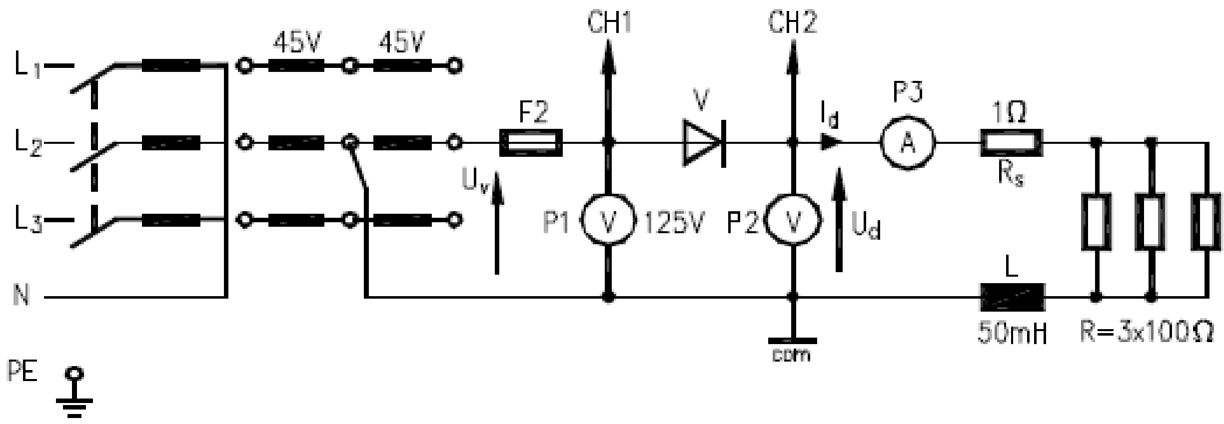
If we examine the theoretical load case of a purely inductive load, the diode conducts at the positive zero transition of the ac voltage U_v and the current I_d increases continuously: the choke stores magnetic energy. At the next zero transition with negative ac voltage, the direct current continues to flow at a decreasing rate until the choke has been discharged: since there are no resistive losses, the discharge time equals the charging time and the current conduction time equals the cycle duration T of the ac voltage.

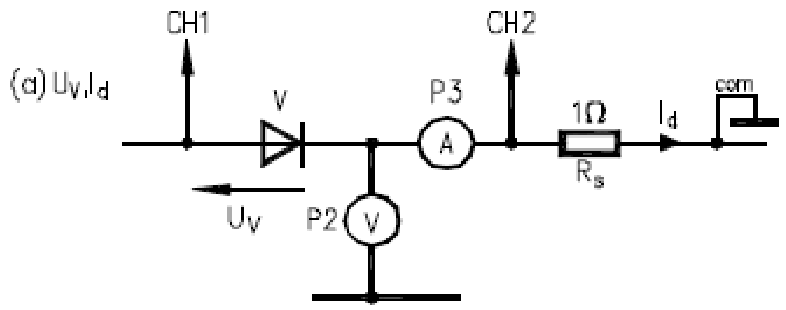
If we now consider the real case of an ohmic-inductive R-L series load, the current conduction time varies between T/2 and T, depending on the magnitude of R and L. More details can be found in the theoretical part of the next Experiment when controlled rectifiers are discussed.

SINGLE-PULSE UNCONTROLLED RECTIFIER, OHMIC-INDUCTIVE LOAD

Objectives:
- Recording voltage and current time profiles
- Voltage and current measurements
- Determination of various characteristic data

Circuit diagram





Experiment procedure
Assemble the circuit according with the foregoing topographic diagram, disregarding detail (a) at first.

1) Voltage and current measurements
Supply the circuit and measure:
1.1) the rms value U_v of the supply voltage by the voltmeter P1;
1.2) the average value U_{dAV} and the rms value U_{dRMS} of the output voltage by the voltmeter P2;
1.3) the average value I_{dAV} and the rms value I_{dRMS} of the output current by the ammeter P3.
Enter the measured value in the following table.

U_v (V)	U_{dAV} (V)	U_{dRMS} (V)	I_{dAV} (A)	I_{dRMS} (A)

Evaluate the following characteristic data of the rectifier

Form factor =

Ripple factor =

2) Recording on the oscilloscope

Note
Since the basic instrument set does not normally allow simultaneous measurements, the measures may have to be carried out successively.

2.1) Recording the supply U_v and direct U_d voltages.
Oscilloscope setting
DC coupling; Yt mode. Trigger: AC Line.
Channel 1 (voltage U_v)
Channel 2 (voltage U_d)

2.2) Recording the voltage U_v and the output current I_d.
Oscilloscope setting
Assemble the measuring circuit according with detail (a).
Channel 1 (U_v voltage)
Channel 2 (current I_d proportional to voltage at shunt R_s =1 Ω): 0.5 V/div

3) Repeat steps (1) and (2) above for L = 100 mH and L = 125 mH

4) Compare measurements with the expected theoretical values.

EXPERIMENT TWO

SINGLE-PULSE THYRISTOR-CONTROLLED CONVERTER

INTRODUCTION

The single-pulse converter is the simplest form of controlled rectifier circuits, as shown in Fig. 1.

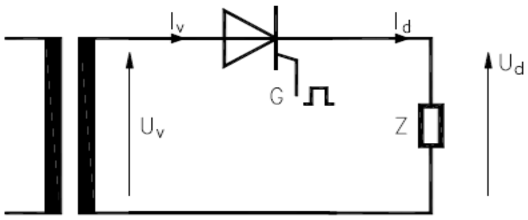


Fig.1 Single-pulse converter

In practical power electronics this power converter is of little importance on account of the high ripple of the dc voltage. Nevertheless, this converter will be investigated since the resultant knowledge is of fundamental importance in understanding converters with higher pulse numbers.

Single-pulse converter with ohmic load

Ohmic load represents the simplest and most easily described load variant for a rectifier since the characteristic curves for a voltage and current at the ohmic load are identical in time and phase.

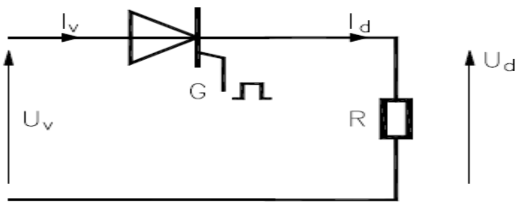


Fig.2 Converter with ohmic load

With no trigger pulses the silicon controlled rectifier (SCR), or thyristor, is in off state and the current cannot flow. When the anode voltage is positive the SCR is triggered after a delay controlled by the gate angle α: the current flows in the load until the current again drops to zero when the feed voltage crosses zero and the SCR blocks. The gate angle α can be controlled from 0° to 180° and the conducting angle is (Θ = 180°-α).The voltage and current time profiles are illustrated in Fig.3. Note that α = 0° corresponds to diode case (uncontrolled rectifier).

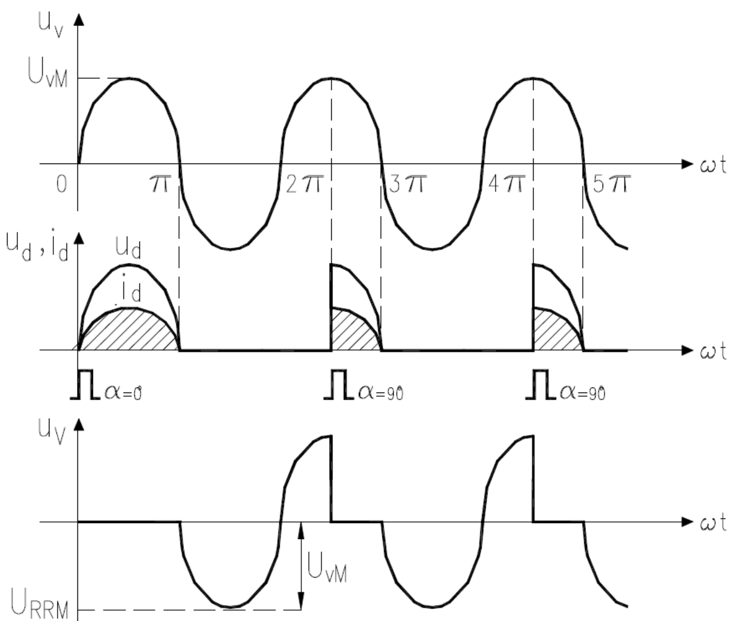


Fig.3 Voltage and current time profiles of the single pulse converter with ohmic load

All the following formulae apply to resistive load, neglecting losses in the converter.
Assuming that $U_{dAVo} = U_{vM}/\pi$ and $U_{dRMSo} = U_{vM}/2$ are the average and rms values for the gate angle $\alpha = 0°$.
Average value of output voltage $U_{dAV} = 0.5(1+\cos\alpha)U_{dAVo}$

Rms value of output voltage $U_{dRMS} = U_{dRMSo}[1-(\alpha/\pi)+[\sin(2\alpha)/(2\pi)]]^{0.5}$

Form factor of output voltage $f = U_{dRMS}/U_{dAV}$

Ripple factor $w = 100(f^2-1)^{0.5}$

Single-pulse converter with inductive load
The purely inductive load represents an ideal load; in practice the choke coil has an ohmic dissipative resistance which cannot be disregarded.

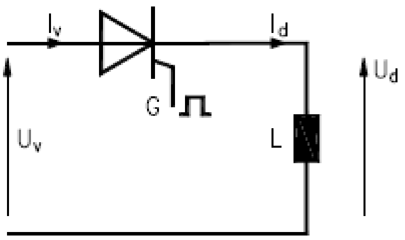


Fig.4 Converter with inductive load

As in circuit with ohmic load, the SCR can be triggered when the anode voltage is positive.
According to law of induction, the load current varies continuously and not abruptly as in the case of an ohmic load. During the positive voltage half-cycle, magnetic energy is stored in the inductance; when the feed voltage crosses zero the load current continues to flow until the inductance has been discharged. The gate angle α can be controlled from 0° to 180° while the conducting angle is $\Theta = 2(180° - \alpha)$. The voltage and current time profiles are illustrated in Fig.5. Note that $\alpha = 0°$ corresponds to diode case (uncontrolled rectifier).

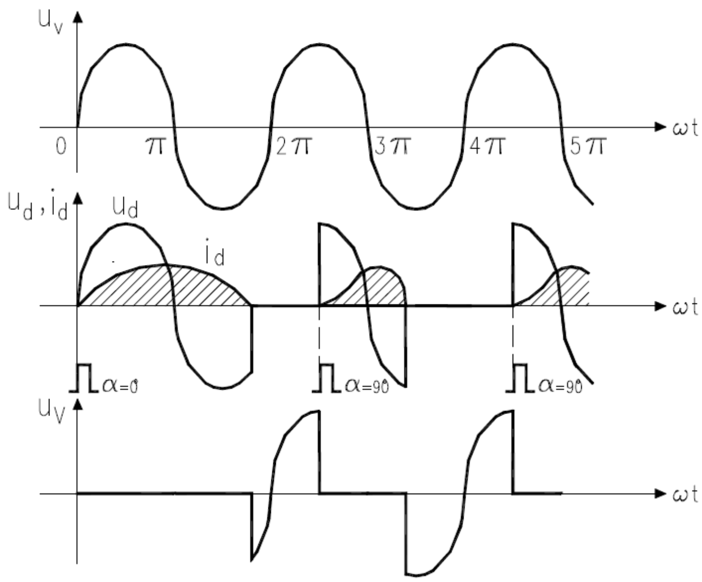


Fig.5 Voltage and current time profiles with inductive load

Single-pulse converter with series ohmic-inductive load

Circuits containing R and L in series are a load type frequently found in practice.

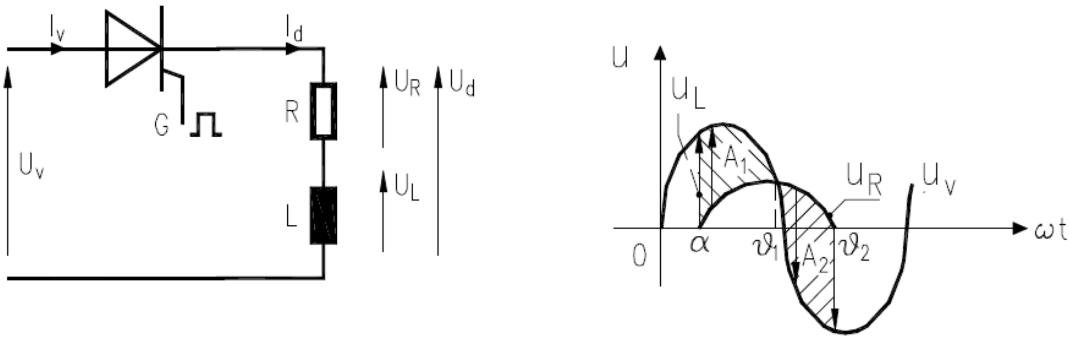


Fig.6 Converter with series comic-inductive load

Once again the inductance prevents any abrupt load current changes. When the SCR is fired on at α control angle during the positive half-cycle of voltage u_v, the current begins to flow.

During α to ϑ, the voltage $u_L = u_v - u_R$ is positive and the current increases; beyond ϑ_1, u_L becomes negative and the current begins to decline and becomes zero at $\omega t = \vartheta_2$ corresponding to area A_1 = area A_2. The direct current time profile is made up of a sinusoidal current which lags behind the u_v voltage by the load phase angle $\varphi = \arctan(\omega L/R)$ and the equalizing current decaying with time constant $\tau = L/R$: at firing point the value of equalizing current is opposite and equal to sinusoidal current value. Since the direct current continues to flow as a result of the storage capacity of the inductance when the feed voltage crosses zero, the direct voltage time profile is made up of positive and negative areas: the negative area reduces the mean value.

The gate angle α cam be controlled from 0° to 180° while the conducting angle Θ lies between (180°- α) and 2(180°- α).The direct current decreases constantly as the gate angle α increases and when α = 180° the I_{dAV} and I_{dRMS} values are zero. The voltage and current time profiles are illustrated in Fig. 7

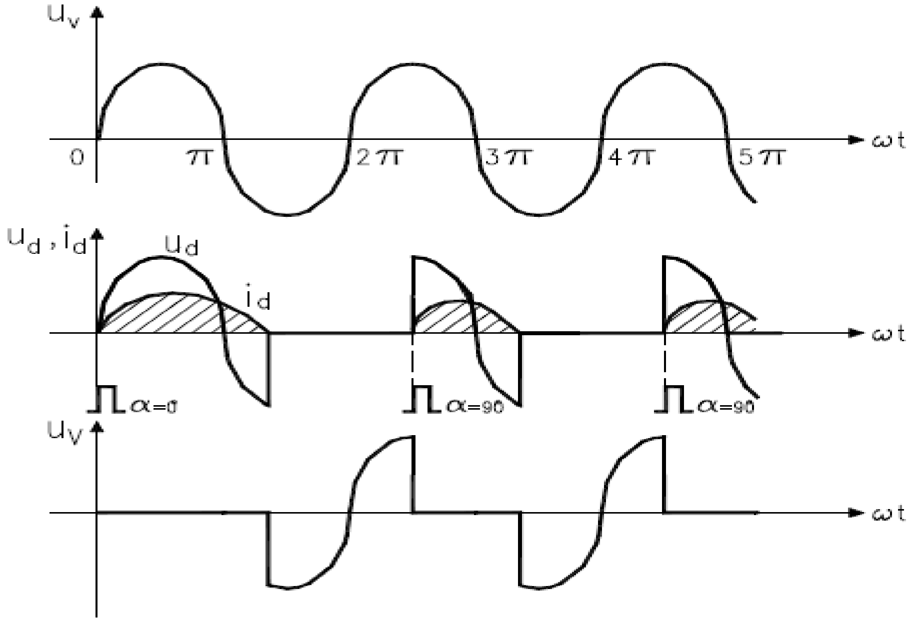


Fig. 7 Voltage and current time profiles with series R-L load

Assuming no energy is initially stored in the inductor, the load current can be expressed as

$$i_d = (U_{vM}/Z)[\sin(\omega t-\phi+\alpha)+\sin(\phi-\alpha)e^{(-t/\tau)}]$$

Where $Z = [R^2 + (\omega L)^2]^{0.5}$

To find the average value of output voltage, conduction angle,θ should be first determined, then use

$$U_{dAV} = (0.5U_{vM}/\pi)[\cos\alpha - \cos(\alpha+\theta)]$$

Single-pulse converter with free-wheeling diode and ohmic-inductive load

To avoid that with ohmic-inductive load the voltage negative areas reduce the mean value of the load voltage a free-wheeling diode V_F is connected in parallel to the load and its polarity is such that it turns off when the voltage U_d is positive.

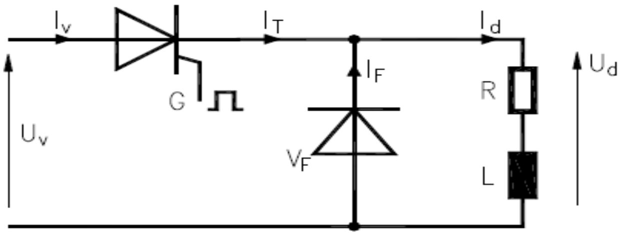


Fig.8 Converter with free-wheeling diode

When the feed voltage crosses the zero, the free-wheeling diode V_F continuously conducts the inductive current without return of energy into ac supply and fixes the load negative voltage at about 1V until the magnetic energy stored in the inductance has been discharged with time constant $\tau = L/R$. Since there are no negative components the mean value of direct voltage is the same as that in the case of an ohmic load. As a result, free-wheeling diode prevents negative voltage areas and thus the return of energy from the load to the ac supply while if the inductance is sufficiently large a non-intermittent (continuous) load current flows. The voltage and current time profiles with intermittent (discontinuous) conduction are illustrated below.

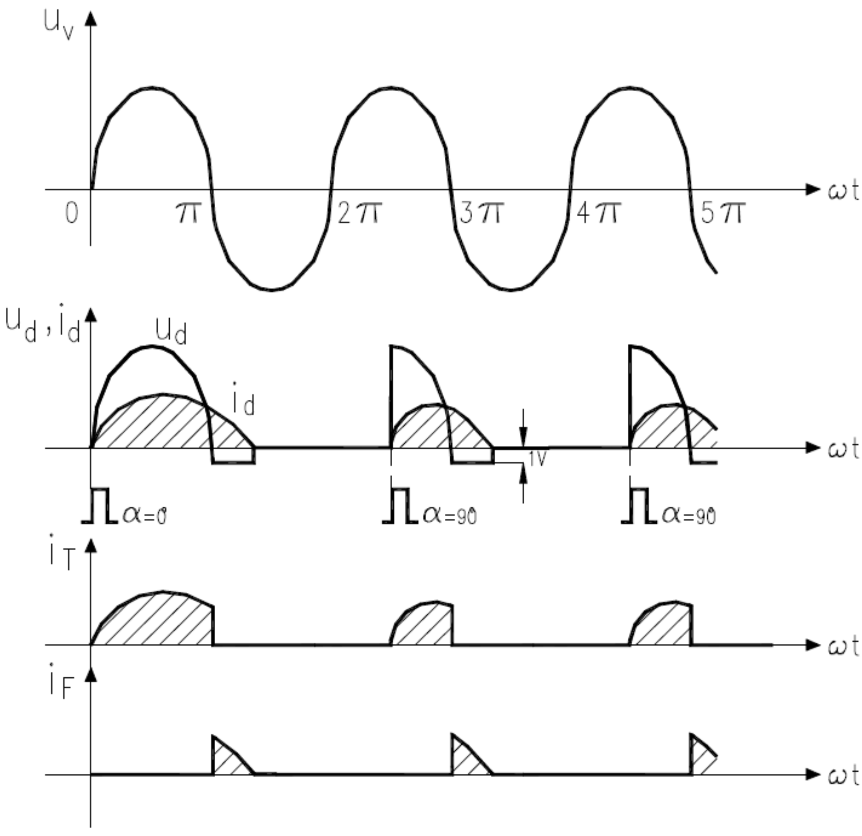


Fig.9 Voltage and current time profiles, Ohmic-inductive load and free-wheeling diode, intermittent (discontinuous) conduction

For both ohmic and ohmic-inductive loads the average value of output voltage, assuming lossless circuit can be expressed as

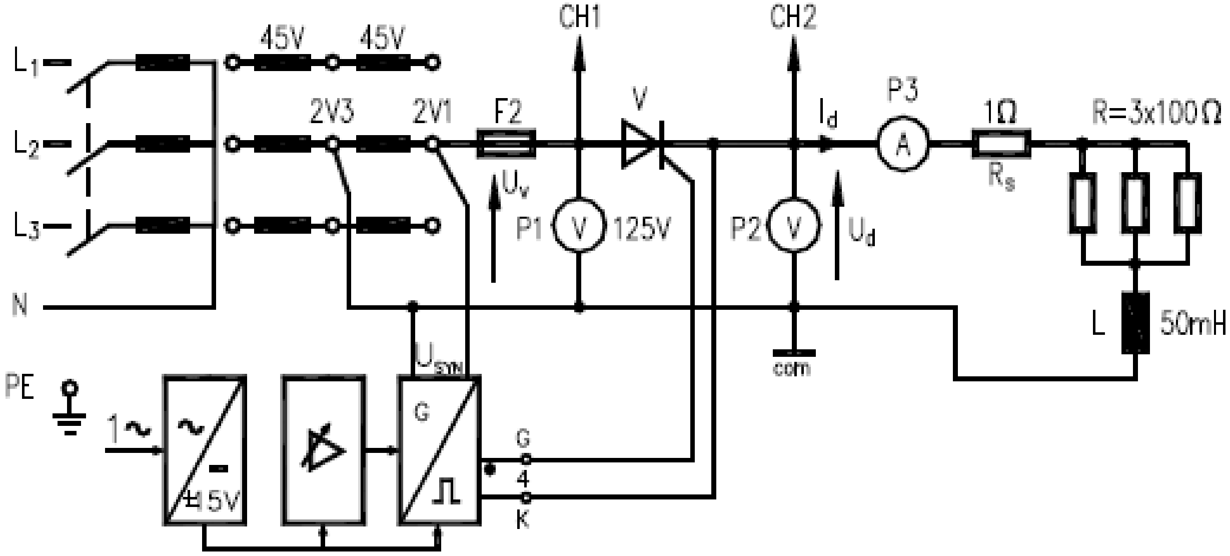
$$U_{dAV} = (0.5U_{vM}/\pi)(1+\cos\alpha)$$

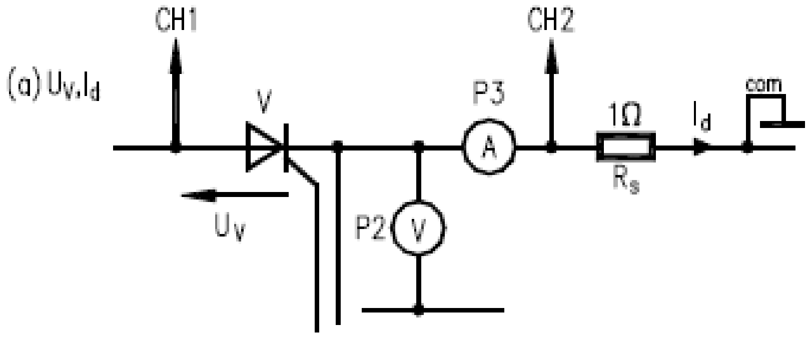
SINGLE-PULSE CONTROLLED CONVERTER, OHMIC-INDUCTIVE LOAD

Objectives:

- Recording voltage and current time profiles
- Voltage and current measurements
- Determination of various characteristic data

Circuit diagram





Experiment procedure
Assemble the circuit according with the foregoing topographic diagram, disregarding detail (a) at first.
1) Connections
Connect the voltage reference generator DL2614 and control unit DL2616 to the power supply +15V/0/-15V.
Connect the output U_o of voltage generator to input U_c of the control unit.
Connect the terminals L/N (U_{SYN}) of the control unit respectively to terminals 2V1/2V3 of the transformer.
Connect the pulse transformer 4 to gate/cathode circuit of the SCR: socket marked with a dot to the gate.

2) Basic settings
2.1) Voltage reference generator DL2614
EXT/INT switch on INT position
(0/+10V)/(0/±10V) switch on (0/+10V) position.
Set point potentiometer to 10 V.
2.2) Control unit DL2616
Control angle α_o switch on 0° position.
"Pulse shape" switch on pulse train position.
Inhibit voltage UINH = 15 V (open).

3) Voltage and current measurements
Supply the circuit and measure:
3.1) the rms value U_v of the supply voltage by the voltmeter P1;
3.2) the average value U_{dAV} and the rms value U_{dRMS} of the load voltage by the voltmeter P2;
3.3) the average value I_{dAV} and the rms value I_{dRMS} of the load current by the ammeter P3.
Enter the measured value as a function of the gate angle α in the table below.

HINT
In order to set the gate angle, set only a half-wave of the direct voltage with the width of 9 (or 6) grid divisions on the oscilloscope: each division then corresponds to an angle of 20° (or 30°).

Another system is the use of phase shift a_0 in the control unit:
1) Set α_0 = 0° and U_c = 10 V to obtain the firing angle α = 0° and carry out the measurements.
2) Set now α_0 = 30° to obtain the firing angle α = 30° and, for example, note down the I_{dRMS30} value.
3) Set again α_0 = 0° and adjust U_c in order to obtain I_{dRMS30} and now set again α_0 = 30° in order to obtain the firing angle α=60°: note down I_{dRMS60}.
4) Set again α_0 = 0° and adjust U_c in order to obtain I_{dRMS60} and now set again α_0 = 30° in order to obtain the firing angle α = 90° and so on.

U_v =

α (°)	**0**	**α_1**	**α_2**	**α_3**	**α_4**	**α_5**	**α_6**	**α_7**
U_{dAV} (V)								
U_{dRMS} (V)								
I_{dAV} (A)								
I_{dRMS} (A)								

α (°)	**0**	**α_1**	**α_2**	**α_3**	**α_4**	**α_5**	**α_6**	**α_7**
U_{dAV}/U_{dAV0}								
I_{dAV}/I_{dAV0}								
Form factor								
Ripple factor								

Draw the transfer characteristic $U_{dAV}/U_{dAV0} = f(\alpha)$.

Compare the measurements with the expected theoretical values.

4) Recording on the oscilloscope **(Use α = 90°)**

Note
Since the basic instrument set does not normally allow simultaneous measurements, the measures may have to be carried out successively.

4.1) Recording the supply U_v and load U_d voltages.
Oscilloscope setting
DC coupling; Yt mode. Trigger: AC Line.
Channel 1 (voltage U_v)
Channel 2 (voltage U_d)

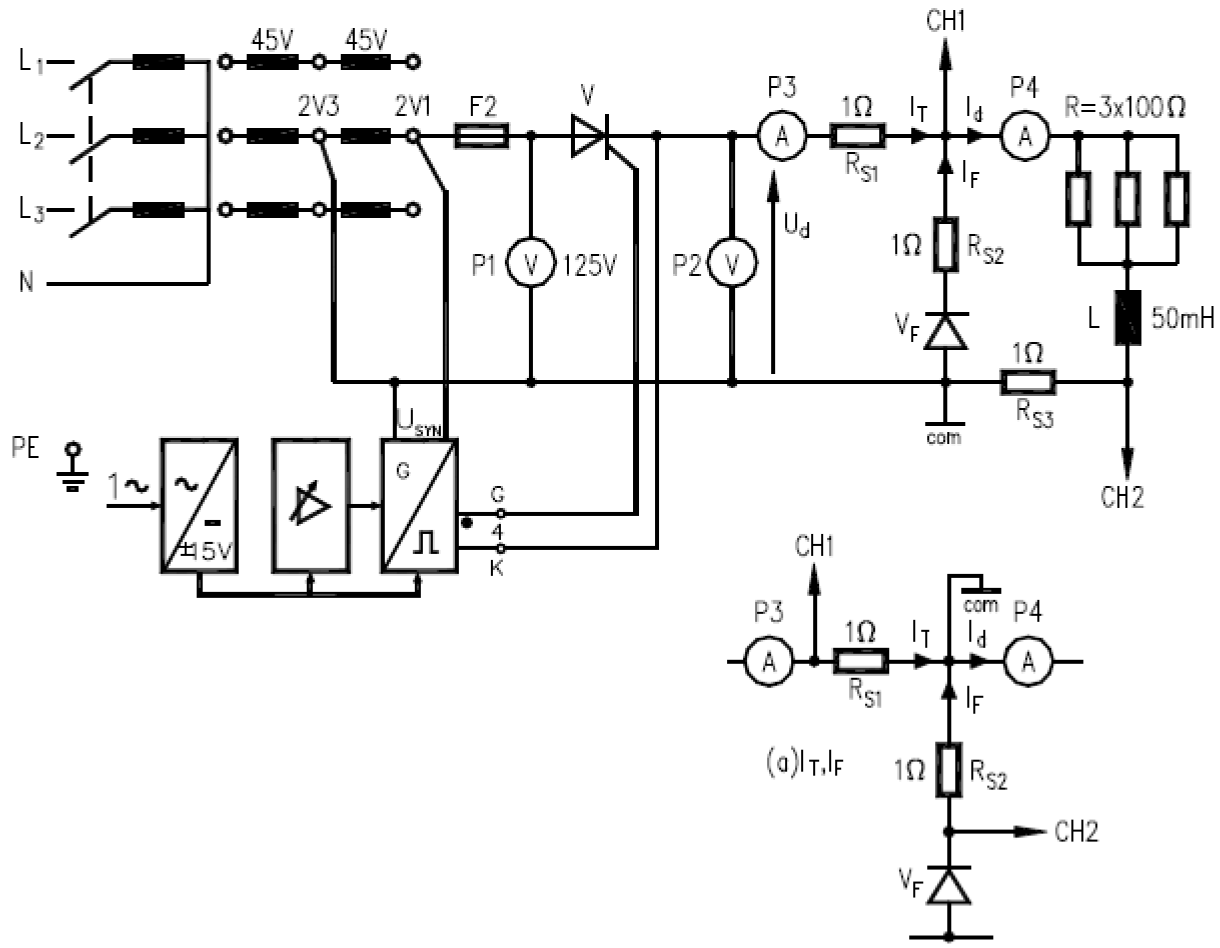
4.2) Recording the voltage U_v and the load current I_d.
Oscilloscope setting
Assemble the measuring circuit according with detail (a).
Channel 1 (U_v voltage)
Channel 2 (current I_d, proportional to voltage across shunt resistor $R_S = 1\ \Omega$):1 V/div.

SINGLE-PULSE CONVERTER OHMIC-INDUCTIVE LOAD AND FREEWHEELING DIODE

Objectives:

- Recording voltage and current time profiles
- Voltage and current measurements
- Determination of various characteristic data

Circuit diagram



Experiment procedure
Assemble the circuit according with the foregoing topographic diagram, disregarding detail (a) at first.
1) Connections
Connect the voltage reference generator DL2614 and control unit DL2616 to the power supply +15V/0/-15V.
Connect the output U_o of voltage generator to input U_c of the control unit.
Connect the terminals L/N (U_{SYN}) of the control unit respectively to terminals 2V1/2V3 of the transformer.
Connect the pulse transformer 4 to gate/cathode circuit of the SCR: socket marked with a dot to the gate.

2) Basic settings
2.1) Voltage reference generator DL2614
EXT/INT switch on INT position
(0/+10V)/(0/±10V) switch on (0/+10V) position.
Set point potentiometer to 10 V.
2.2) Control unit DL2616
Control angle α_o switch on 0° position.
"Pulse shape" switch on pulse train position.
Inhibit voltage UINH = 15 V (open).

3) Supply the circuit and measure:
3.1) the rms value U_v of the supply voltage by the voltmeter P1;
3.2) the average value U_{dAV} and the rms value U_{dRMS} of the output voltage by the voltmeter P2;
3.3) the average value I_{TAV} and the rms value I_{TRMS} of the SCR current by the ammeter P3.
3.4) the average value I_{dAV} and the rms value I_{dRMS} of the direct current by the ammeter P4.
Enter the measured value as a function of the gate angle α in the table below.

U_v =

α (°)	**0**	**α_1**	**α_2**	**α_3**	**α_4**	**α_5**	**α_6**	**α_7**
U_{dAV} (V)								
U_{dRMS} (V)								
I_{dAV} (A)								
I_{dRMS} (A)								
I_{TAV} (A)								
I_{TRMS} (A)								

α (°)	**0**	**α_1**	**α_2**	**α_3**	**α_4**	**α_5**	**α_6**	**α_7**
U_{dAV}/U_{dAV0}								
I_{dAV}/I_{dAV0}								
Form factor								
Ripple factor								

Draw the transfer characteristic $U_{dAV}/U_{dAV0} = f(\alpha)$.
Compare measurements with the expected theoretical values.

4) Recording on the oscilloscope **(use α = 90°)**
Note: *Since the basic instrument set does not normally allow simultaneous measurements, the measures may have to be carried out successively.*
4.1) Recording the load voltage U_d and the load current I_d.
Oscilloscope setting
DC coupling; Yt mode. Trigger: AC Line.
Channel 1 (voltage U_v)
Channel 2 (current I_d proportional to voltage at shunt $R_{S3} = 1\ \Omega$): 1 V/div.
4.2) Recording the SCR current I_T and the free-wheeling diode current I_F
Oscilloscope setting
Assemble the measuring circuit according with detail (a).
Channel 1 (current I_T proportional to voltage at shunt $R_{S1} = 1\ \Omega$): 500 mV/div.
Channel 2 (current I_F proportional to voltage at shunt $R_{S2} = 1\ \Omega$): 500 mV/div.

EXPERIMENT THREE

TWO-PULSE CONVETERS

(A) TWO-PULSE MIDPOINT CONVERTER (BI-PHASE)

INTRODUCTION

Midpoint converters must include a transformer with centre tapped winding on the secondary side to have two partial and equal ac voltages and two SCRs, as shown in Fig.1.

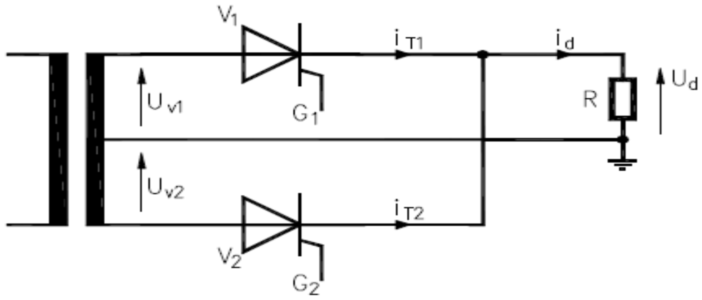


Fig.1 Two-pulse converter, with ohmic load

If we refer the voltages U_{v1} and U_{v2} to the midpoint (neutral) these voltages are in phase opposition and for positive anode voltages the SCRs are alternatively fired and conduct the current of the corresponding line voltage from firing point to the zero cross-over.

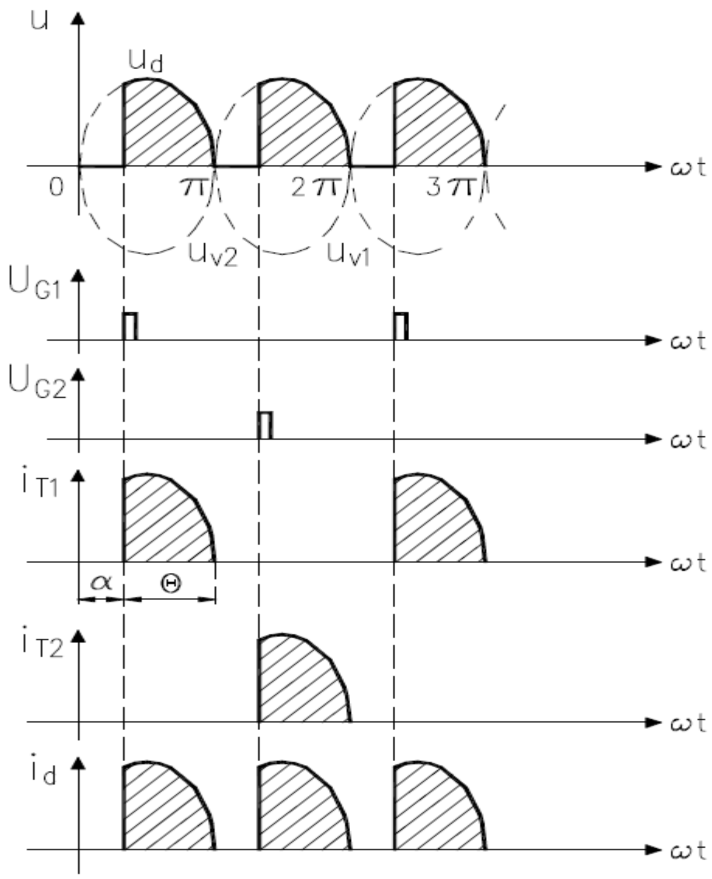


Fig.2 Voltage and current time profiles

The load current i_d is composed of the two SCR currents; it is an intermittent (discontinuous) pulsating current. The average value of output voltage is

$$U_{dAV} = 0.5U_{dAVo}(1+\cos\alpha)$$

Where

$$U_{dAVo} = 0.9\ U_{v1} = 0.9\ U_{v2}$$

is the average value for the gate angle $\alpha = 0°$

Ohmic-inductive load

Circuits containing R and L in series are a load type frequently found in practice.

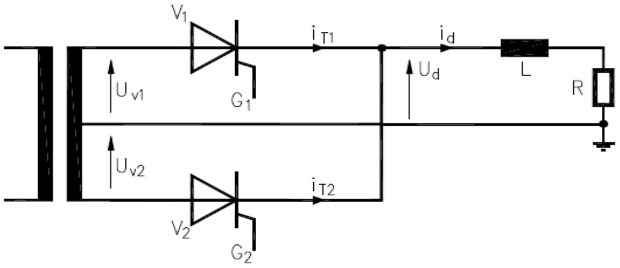


Fig.3 Converter with ohmic-inductive load

The inductance prevents any abrupt load current changes. To understand how the circuit operates, initially assume that the load phase angle $\varphi = \arctan \omega L/R$ is adjusted for a non-intermittent operation (very large smoothing choke L), as shown in Fig.4.

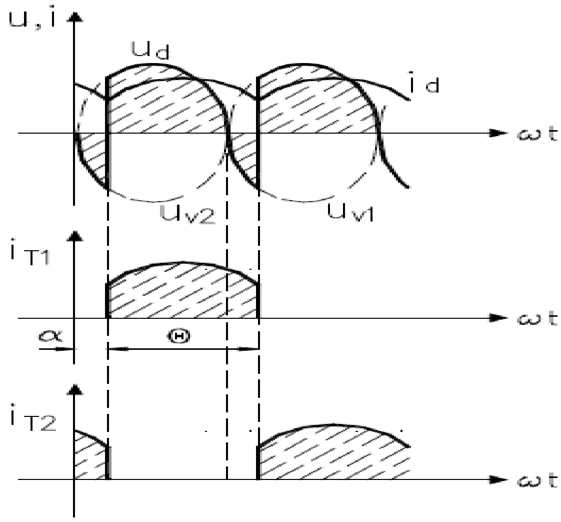


Fig.4 Voltage and current time profiles, RL load, non-intermittent (continuous) operation

At the control angle α the direct current is alternatively conducted through the SCRs V_1 and V_2 that conduct current through the zero crossing of supply voltages until the following SCR is triggered. The conduction angle is $\Theta = 180°$. The dc voltage takes on +ve and -ve values.

The output voltage average value is positive in control range $0° \leq \alpha < 90°$ (energy is supplied to load from the mains) , it is zero at $\alpha = 90°$ and negative for $\alpha > 90°$ (energy is transferred from the load back into the mains; this type of operation can only continuously be carried out if there is an energy source present in the load).

The average value of output voltage with non-intermittent (continuous) operation is

$$U_{dAV} = (2U_{vM1}/\pi)\cos\alpha = (2U_{vM2}/\pi)\cos\alpha$$

With increasing the control angle α the operation becomes intermittent after a limit control angle has been exceeded, as shown in Fig. 5. To find the average output voltage the conduction angle θ should be determined.

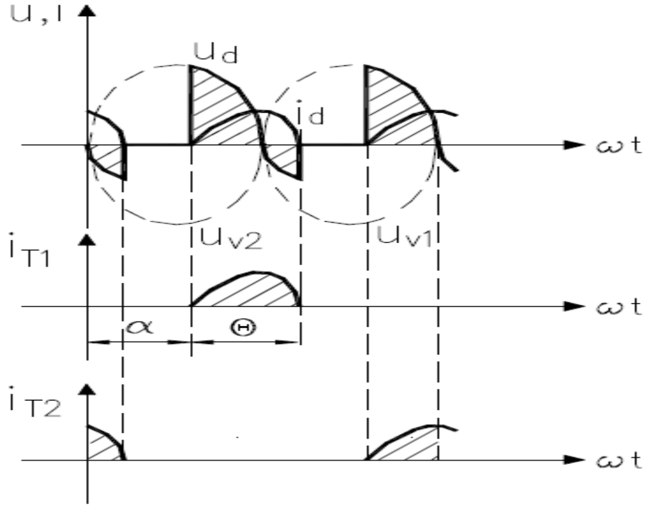
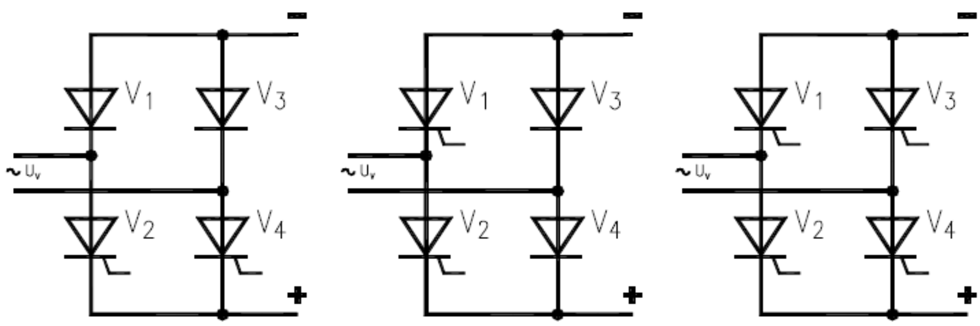


Fig.5 Voltage and current time profiles, RL load, intermittent (discontinuous) operation

(B) SINGLE-PHASE BRIDGE CONVERTERS

These converters can be half-controlled, as shown in Figs. 6 (a) and (b) or fully-controlled as in Fig. 6(c).



(a) **(b)** **(c)**

Fig.6 (a) and (b) are half-controlled bridges while (c) is a fully-controlled bridge

Ohmic load

With ohmic load the operation of the three bridges is similar and the load current voltages are shown in Fig. 7

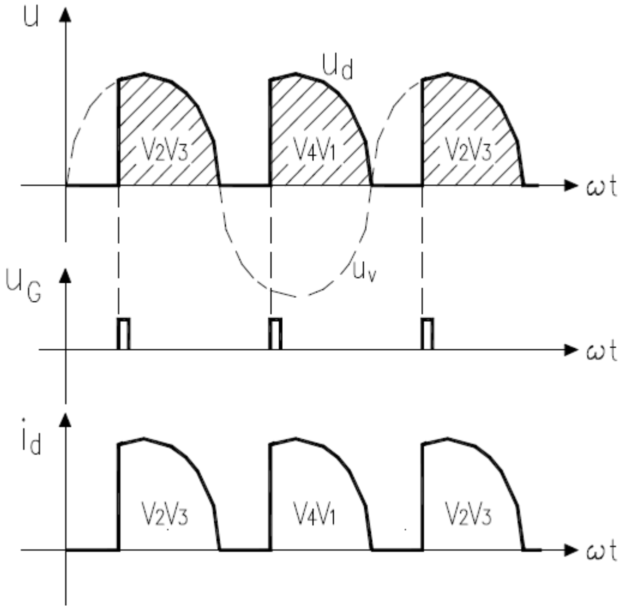


Fig. 7 Time profiles of converters (a), (b) and (c), ohmic load

Current time profile is intermittent (discontinuous) as the extinction angle coincides with the end of the half cycle. At the control angle $\alpha = 0°$ the dc voltage is maximum and the average values is

$$U_{dAVo} = 0.9\ U_v$$

Fully-controlled bridge, ohmic-inductive load

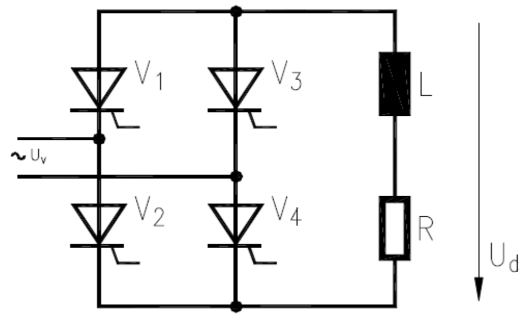


Fig. 8 Fully-controlled bridge converter with ohmic-inductive load

When the trigger pulse is applied to two SCR gates at the same time, each pair of the series connected SCRs in the bridge diagonals (V_2-V_3 or V_4-V_1) conducts alternatively, as shown in the following figure for different control angles.

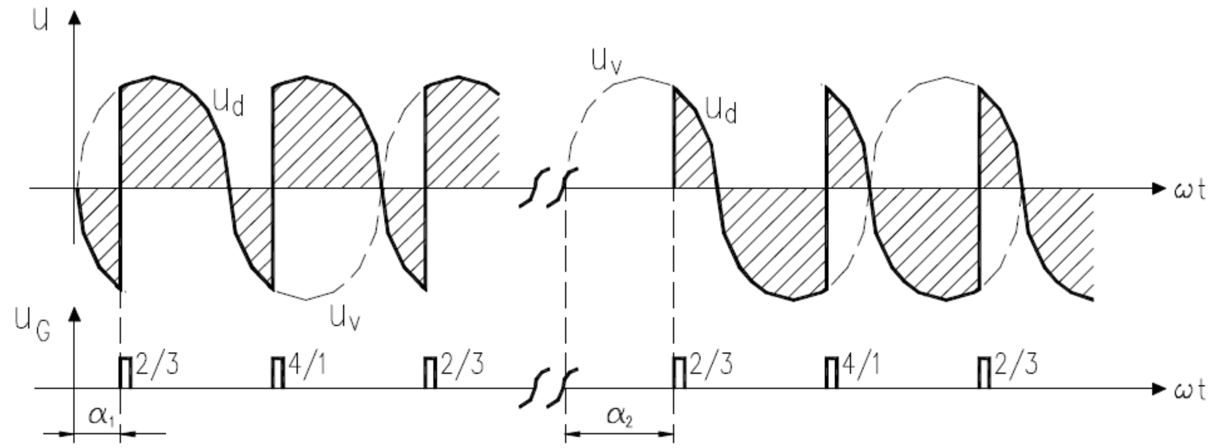


Fig. 9 Voltage time profile, fully-controlled bridge converter with ohmic-inductive load, non-intermittent (continuous) operation

For all control angles $\alpha > 0°$ the time profile of output voltage has positive and negative instantaneous values and its average value is positive in the control range $0° < \alpha < 90°$ and negative in the range $90° < \alpha < 180°$ (regenerative operation).
Each time an SCR pair is triggered, a commutating process begins: during the commutation duration all four SCRs conduct and in this brief overlap duration a short circuit of the supply transformer results and the direct voltage is zero.
Neglecting overlap and other circuit losses, the average value of output voltage with continuous operation is

$$U_{dAV} = (2U_{vM}/\pi)\cos\alpha$$

With increasing the control angle α the operation becomes intermittent (discontinuous) after a limit control angle has been exceeded. To find the average output voltage the conduction angle θ should be first determined.

<u>Note</u>: Read the theoretical part of experiment 2.

Half-controlled bridge, ohmic-inductive load (Topology 1)

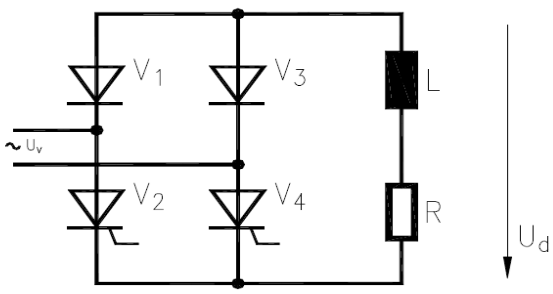


Fig. 10 Half-controlled converter with ohmic-inductive load

After the gate-controlled turn-on time (control angle α), the SCR V_2 and the diode V_3 conduct until the supply ac voltage crosses the zero. Afterwards there is a voltage across the diode V_1 in the forward direction and the diode V_1 conducts and the load current commutates from diode V_3 to diode V_1: the magnetic energy stored in the inductance L maintains the current through the path SCR V_2 and diode V_1 until the coil has been discharged through the resistance R. Fig. 11 shows the non-intermittent (continuous) operation.

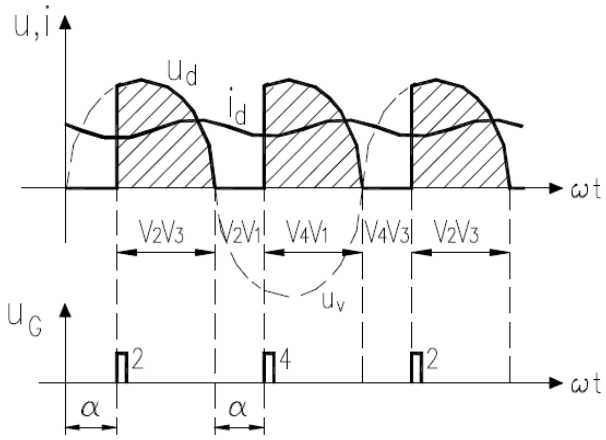


Fig. 11 Voltage and current profiles, half-controlled converter with ohmic-inductive load, non-intermittent (continuous) operation

Until the following SCR V_4 is triggered, the load circuit is short-circuited via the paired arm V_2/V_1 (free-wheeling) until the following SCR V_4 is turned on while the dc voltage is zero and the feedback into ac supply is not possible.

SCRs and diodes conduct over 180° independently of the control angle, while the dc voltage can not be controlled to zero and the upper control limit is approximately 150°.

At large control angles (α > 90°) the free-wheeling current can pass through zero before the following SCR is turned on: in that case the operation is intermittent (discontinuous), as shown in Fig. 12

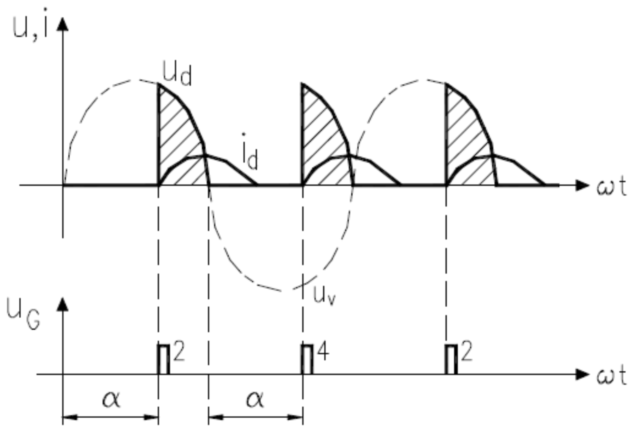


Fig. 12 Voltage and current profiles, half-controlled converter with ohmic-inductive load, intermittent operation

Half-controlled bridge, ohmic-inductive load (Topology 2)

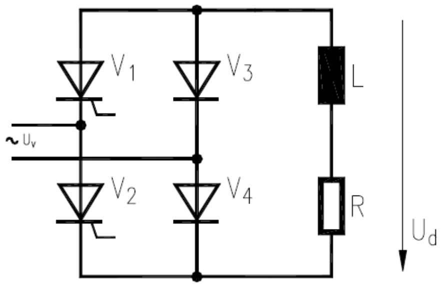


Fig. 13 Half-controlled converter with ohmic-inductive load

After the gate-controlled turn-on time (control angle α), the SCR V_2 and the diode V_3 conduct until the supply ac voltage crosses the zero. Afterwards there is a voltage across the diode V_4 in the forward direction and so the diodes V_4 and V_3 form a direct free-wheeling arm and prevent a delivery of the energy back into the mains. The time profile of direct voltage is identical with the time profile of case (a), as shown

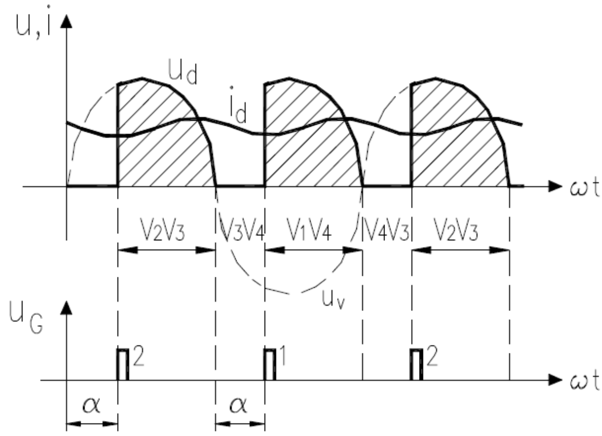


Fig. 14 Voltage and current profiles, half-controlled converter with ohmic-inductive load, non-intermittent operation

When the control angle $\alpha > 0°$ the conduction angle of diodes V_3 and V_4 is higher than that one of the SCRs V_2 and V_1 and so the diodes are loaded more. The control angle can be changed from 0° to 180° and therefore the direct voltage can be controlled down to zero.

Neglecting circuit losses, the average value of the output voltage for the two topologies of half controlled bridge rectifiers can be expressed as

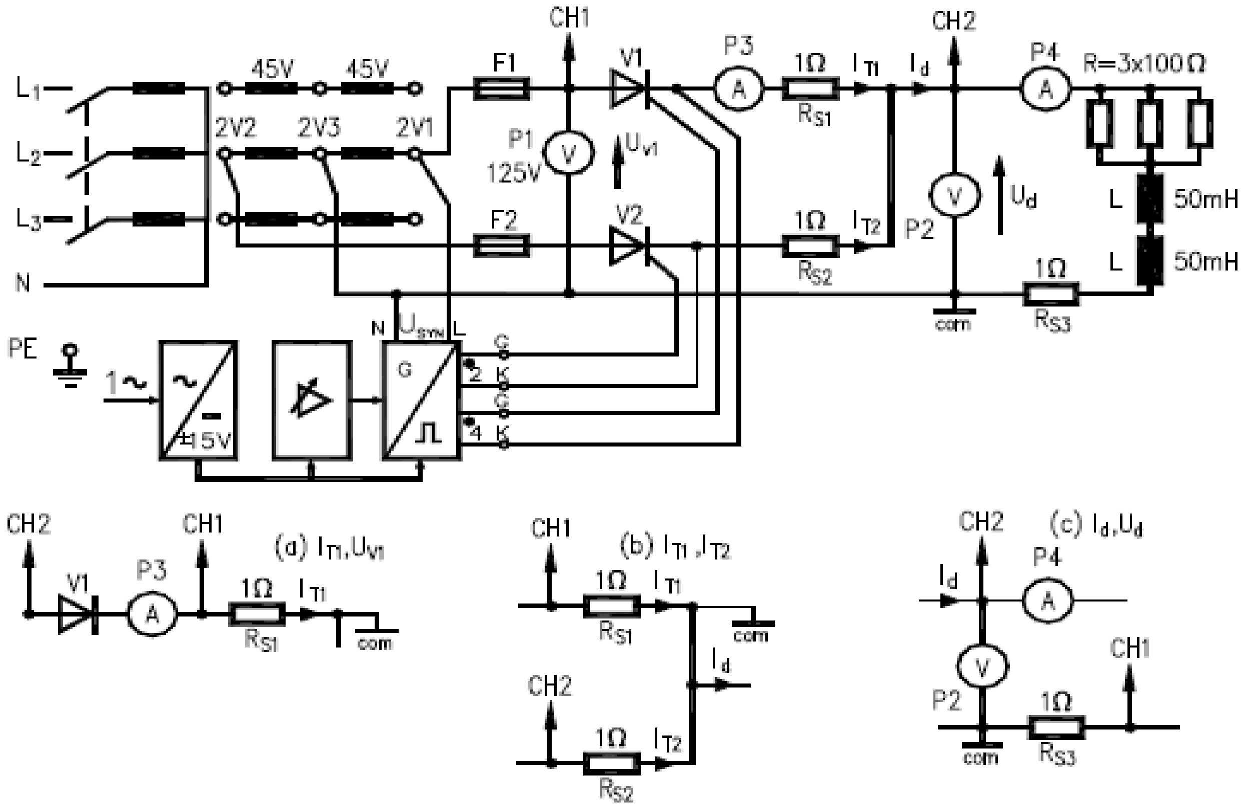
$$U_{dAV} = (U_{vM}/\pi)(1+\cos\alpha)$$

TWO-PULSE MIDPOINT CONVERTER OHMIC-INDUCTIVE LOAD

Objectives:

- Recording voltage and current time profiles
- Voltage and current measurements
- Determination of various characteristic data

Circuit diagram



Experiment procedure
Assemble the circuit according with the foregoing circuit diagram, disregarding details (a), (b) and (c) at first.
1) Connections
Connect the voltage reference generator DL2614 and control unit DL2616 to the power supply +15V/0/-15V.
Connect the output U_o of voltage generator to input U_c of the control unit.
Connect the terminals L/N (U_{SYN}) of the control unit respectively to terminals 2V1/2V3 of the transformer.
Connect pulse transformers 2 & 4 to gate/cathode circuit of SCRs V_2 & V_1: socket marked with a dot to the gate

2) Basic settings
2.1) Voltage reference generator DL2614
EXT/INT switch on INT position
(0/+10V)/(0/±10V) switch on (0/+10V) position.
Set point potentiometer to 10 V.
2.2) Control unit DL2616
Control angle αo switch on 0° position.
"Pulse shape" switch on pulse train position.
Inhibit voltage UINH = 15 V (open).

3) Supply the circuit and measure:
3.1) the rms value U_{v1} of the supply voltage by the voltmeter P1;
3.2) the average value U_{dAV} and the rms value U_{dRMS} of the output voltage by the voltmeter P2;
3.3) the average value I_{T1AV} and the rms value I_{T1RMS} of the SCR V_1 current by the ammeter P3;
3.4) the average value I_{dAV} and the rms value I_{dRMS} of the output current by the ammeter P4.
Enter the measured value as a function of gate angle α in the table below.

U_{v1} =

α (°)	**0**	α_1	α_2	α_3	α_4
U_{dAV} (V)					
U_{dRMS} (V)					
I_{dAV} (A)					
I_{dRMS} (A)					
I_{T1AV} (A)					
I_{T1RMS} (A)					

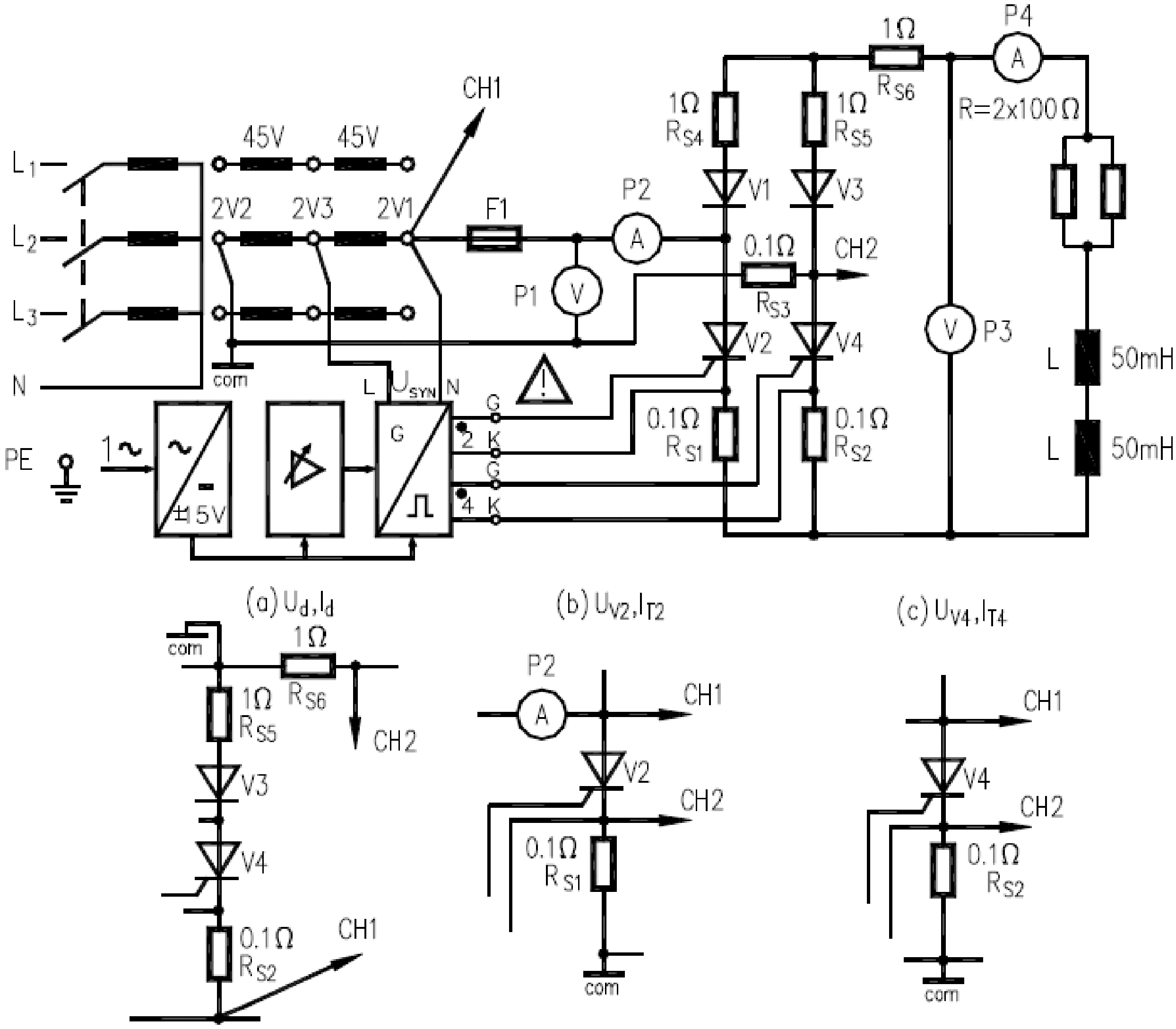
Evaluate the various characteristic data of the converter and compare these with the theoretical values.
Draw the transfer characteristic $U_{dAV}/U_{dAV0} = f(\alpha)$.

4) Recording on the oscilloscope **(Use α = 60°)**
4.1) Recording the supply U_{v1} and output U_d voltages.
Oscilloscope setting
DC coupling; Yt mode. Trigger: AC Line.
Channel 1 (voltage U_{v1}) and Channel 2 (voltage U_d)
4.2) Recording the current I_{T1} and the voltage U_{v1} at SCR V_1
Oscilloscope setting
Assemble the measuring circuit according with detail (a).
Channel 1 (current I_{T1} proportional to voltage at shunt $R_{S1} = 1\Omega$): 500 mV/div.
Channel 2 (U_{v1} voltage)
4.3) Recording the diode currents I_{T1} and I_{T2}
Oscilloscope setting
Assemble the measuring circuit according with detail (b).
Channel 1 (current I_{T1} proportional to voltage at shunt $R_{S1} = 1\ \Omega$): 1 V/div.
Channel 2 (current I_{T2} proportional to voltage at shunt $R_{S2} = 1\ \Omega$): 1 V/div.
4.4) Recording the current I_d and the voltage U_d.
Oscilloscope setting
Assemble the measuring circuit according with detail (c).
Channel 1 (current I_d proportional to voltage at shunt $R_{S3} = 1\ \Omega$): 1 V/div.
Channel 2 (U_d voltage)

HALF-CONTROLLED BRIDGE, OHMIC-INDUCTIVE LOAD (TOPOLOGY 1)

Objectives:

- Recording voltage and current time profiles
- Voltage and current measurements
- Determination of various characteristic data



Experiment procedure
Assemble the circuit according to the foregoing circuit diagram, disregarding details (a), (b) and (c) at first.
1) Connections
Connect the voltage reference generator DL2614 and control unit DL2616 to the power supply +15V/0/-15V.
Connect the output U_o of voltage generator to input U_c of the control unit.
Connect the terminals L/N (U_{SYN}) of the control unit respectively to terminals 2V3/2V1 of the transformer.
Connect pulse transformers 2 & 4 to gate/cathode circuit of SCRs V_2 & V_4: socket marked with a dot to the gate

2) Basic settings
2.1) Voltage reference generator DL2614
EXT/INT switch on INT position
(0/+10V)/(0/±10V) switch on (0/+10V) position.
Set point potentiometer to 10 V.
2.2) Control unit DL2616
Control angle α_o switch on 0° position.
"Pulse shape" switch on pulse train position.
Inhibit voltage UINH = 15 V (open).

3) Supply the circuit and measure:
3.1) the rms value U_v of the supply voltage by the voltmeter P1;
3.2) the rms value I_v of the supply current by the ammeter P2;
3.3) the average value U_{dAV} and the rms value U_{dRMS} of the output voltage by the voltmeter P3;
3.4) the average value I_{dAV} and the rms value I_{dRMS} of the output current by the ammeter P4.
Enter in the table the measured value as a function of gate angle α.

α (°)	**0**	α_1	α_2	α_3	α_4
U_v (V)					
I_v (A)					
U_{dAV} (V)					
U_{dRMS} (V)					
I_{dAV} (A)					
I_{dRMS} (A)					

Compare measurements with the expected theoretical values.

4) Recording on the oscilloscope **(Use α = 60°)**
4.1) Recording the supply voltage U_v and current I_v.
Oscilloscope setting
DC coupling; Yt mode. Trigger: AC Line.
Channel 1 (voltage U_v)
Channel 2 (current I_v proportional to voltage at shunt $R_{S3} = 0.1\ \Omega$)
4.2) Recording the voltage U_d and current I_d. Oscilloscope setting.
Assemble the measuring circuit according with detail (a).
Channel 1(U_d voltage)
Channel 2 (current I_d proportional to voltage at shunt $R_{S6} = 1\Omega$)
4.3) Recording the SCR V_2 voltage and current
Oscilloscope setting:
Assemble the measuring circuit according with detail (b).
Channel 1 (voltage U_{v2})
Channel 2 (current I_{T2} proportional to voltage at shunt $R_{S1} = 0.1\ \Omega$)
4.4) Recording the SCR V_4 voltage and current
Oscilloscope setting:
Assemble the measuring circuit according with detail (c).
Channel 1 (voltage U_{v4})
Channel 2 (current I_{T4} proportional to voltage at shunt $R_{S2} = 0.1\ \Omega$)

<u>**EXPERIMENT FOUR**</u>

THREE-PHASE BRIDGE CONVERTERS

INTRODUCTION

The three-phase fully-controlled bridge circuit is shown below

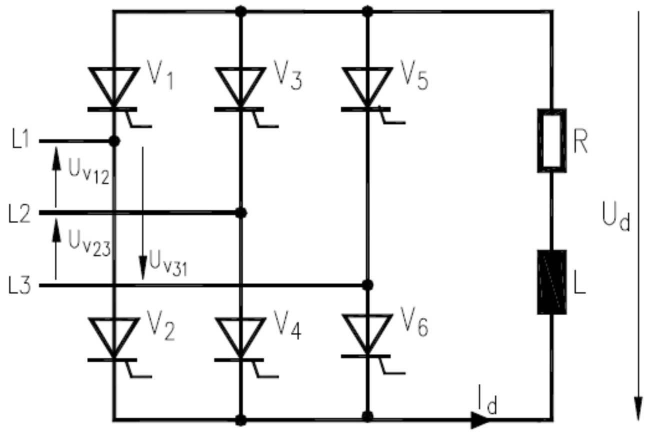


Fig. 1 Three-phase fully-controlled bridge converter with ohmic-inductive load

Two SCRs always conduct simultaneously and the trigger pulses have to be applied simultaneously to the two concerned SCRs, that in this way need double pulses: this means that each SCR requires two pulses (main and secondary pulse) which are phase shifted by 60° with respect to each other and that the secondary pulse must be synchronous with the trigger pulse of the following SCR.

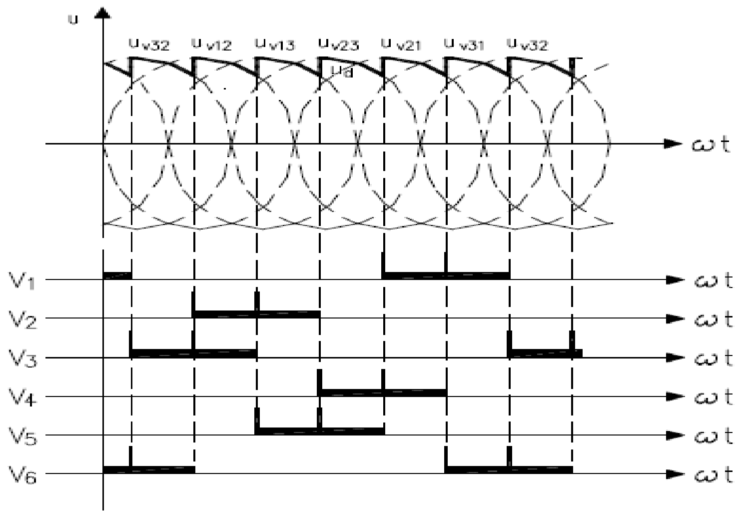


Fig. 2 Voltage time profile, 3-phase fully-controlled bridge converter with ohmic-inductive load

With ohmic load the conduction is not-intermittent for control angle up to 60° and becomes intermittent for control angles 60° < α < 120°: finally the direct voltage is zero for α > 120°.
The average output voltage is

$$U_{dAV} = 1.35\ U_{v12}$$

For an ohmic-inductive load the direct current is smoothed by the energy stored in the choke until intermittent operation occurs at limit control angle.
Beyond the control angle 60° the direct voltage has negative areas and the operation is said to be regenerative.

For continuous (non-intermittent) operation the average output voltage can be expressed as

$$U_{dAV} = (1.35\ U_{v12}) \cos\alpha$$

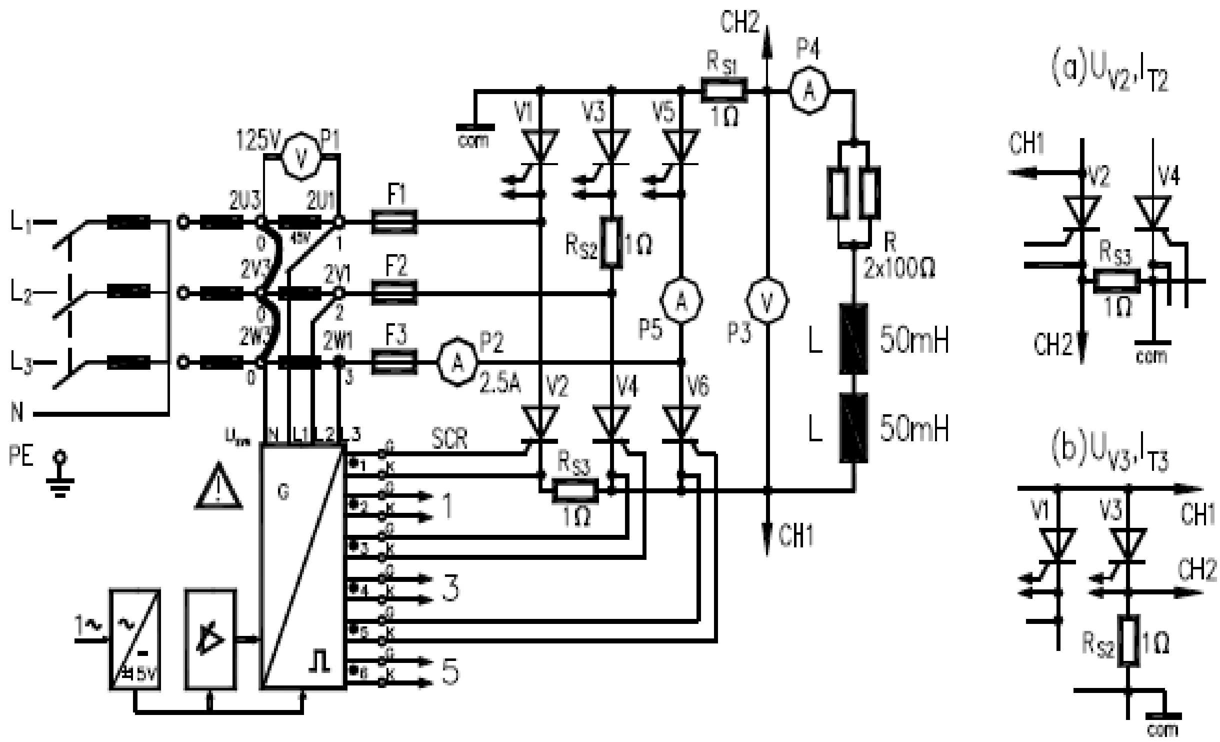
<u>**Note**</u>: Read the theoretical part of experiments 2 and 3.

THREE-PHASE FULLY-CONTROLLED BRIDGE, OHMIC-INDUCTIVE LOAD

Objectives:

- Recording voltage and current time profiles
- Voltage and current measurements
- Determination of various characteristic data

Circuit diagram



Experiment procedure

Assemble the circuit according with the foregoing topographic diagram, disregarding details (a) and (b) at first.

1) Connections

Connect the voltage reference generator DL2614 and control unit DL2617 to power supply +15V/0/-15V.

Connect the output U_o of voltage generator to input U_c of the control unit.

Connect terminals $L_1/L_2/L_3/N(U_{SYN})$ of control unit to transformer terminals 2U1/2V1/2W1/2U3 respectively.

Connect the pulse transformers 1, 2, 3, 4, 5 and 6 to gate/cathode circuit of the SCRs V_2, V_1, V_4, V_3, V_6 and V_5: socket marked with a dot to the gate.

2) Basic settings

2.1) Voltage reference generator DL2614

EXT/INT switch on INT position

(0/+10V)/(0/±10V) switch on (0/+10V) position.

Set point potentiometer to 10 V.

2.2) Control unit DL2617

Analog control switch on "∩" position

Control angle α_o switch on 30° position.

"Pulse shape" switch on single pulse position.

Select MAIN + SEC PULSE

Inhibit voltage UINH = 15 V (open).

2.3) Natural commutating point

In order to use the practically control the converter must set with the control angle α=0° at the natural commutating point with the reference voltage U_o = 10 V.

Set α_o = 30° and U_c = 10V.

Supply the circuit and check the correct phase sequence (green led lights).

If the oscilloscope displays a six-pulse rectified voltage the control angle is α = 0°.

3) Voltage and current measurements

Supply the circuit and measure:

3.1) the rms value U_{v3} of the phase voltage by the voltmeter P1;

3.2) the rms value I_{v3} of the line current by the ammeter P2;

3.3) the average value U_{dAV} and the rms value U_{dRMS} of the output voltage by the voltmeter P3;

3.4) the average value I_{dAV} and the rms value I_{dRMS} of the output current by the ammeter P4.

3.5) the average value I_{T5AV} and the rms value I_{T5RMS} of the SCR V_5 current by the ammeter P5.

Enter the measured value as a function of the gate angle α in the following table.

α (°)	**0**	**α_1**	**α_2**	**α_3**	**α_4**
U_{v3} (V)					
I_{v3} (A)					
U_{dAV} (V)					
U_{dRMS} (V)					
I_{dAV} (A)					
I_{dRMS} (A)					
I_{T5AV} (A)					
I_{T5RMS} (A)					

Draw the transfer characteristic $U_{dAV}/U_{dAV0} = f(\alpha)$. Compare measurements with expected theoretical values.

4) Recording on the oscilloscope **(Use α = 60°)**

4.1) Recording the output voltage U_d, and current I_d

Oscilloscope setting: DC coupling; Yt mode. Trigger: AC Line.

Channel 1 (U_d voltage); Channel 2 (current I_d proportional to voltage at shunt R_{S1} = 1 Ω): 1 V/div.

4.2) Recording the voltage U_{V2} and the current I_{T2} at SCR V_2

Oscilloscope setting: Assemble the measuring circuit according with detail (a).

Channel 1 (U_{V2} voltage); Channel 2 (current I_{T2} proportional to voltage at shunt R_{S3} = 1 Ω): 1 V/div.

4.3) Recording the voltage U_{V3} and the current I_{T3} at SCR V_3

Oscilloscope setting: Assemble the measuring circuit according with detail (b).

Channel 1 (U_{V3} voltage); Channel 2 (current I_{T3} proportional to voltage at shunt R_{S2} =1 Ω): 1 V/div.

EXPERIMENT FIVE

STEP-DOWN (BUCK) CONVERTER

INTRODUCTION

As the name implies, this converter produces a lower average output voltage than the dc input voltage. Its main application is in regulated dc power supplies and dc motor speed control.
The basic circuit is shown in Fig.1, where pulse-width modulation (PWM) control is presumed.

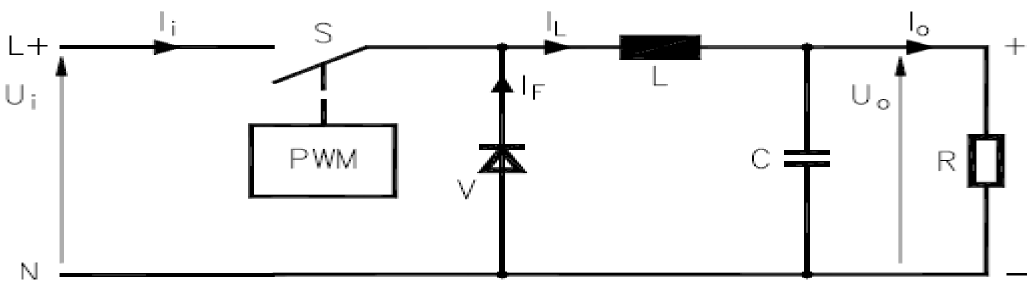


Fig. 1 Step-down (buck) converter

The controllable switch S supplies the LC low-pass filter with a voltage U_i while the fast diode V allows the free-wheeling flow of the current during the blocking phase of the switch.
The typical voltage and current characteristics are shown in Fig.2.

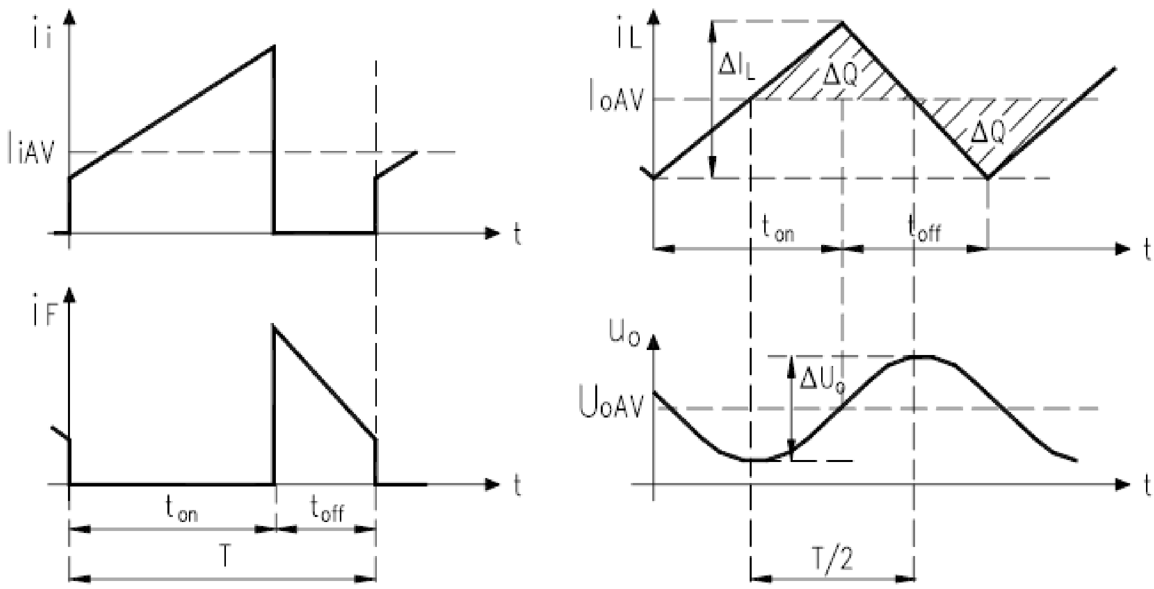


Fig. 2 Voltage and current characteristics, step-down converter

During the interval when the switch S is on, the diode becomes reverse biased and the input provides energy to the load R as well as to the inductor L.
The voltage across the inductor L is U_i - U_{oAV} and causes a linear increase in the inductor current I_L equal to:

$$(\Delta I_L)_{\text{rising}} = (U_i - U_{oAV})\, t_{on}/L$$

During the interval when the switch S is off, the inductor current flows through the diode, transferring some of its stored energy to the load R. The voltage across the inductor is $-U_{oAV}$ now and causes a linear decrease of the inductor current I_L equal to:

$$(\Delta I_L)_{\text{falling}} = U_{oAV}\, t_{off}/L$$

Since in the steady-state operation the variations of the current I_L must be equal this implies that:

$$U_{oAV} = U_i\, t_{on}/T = U_i\, D$$

The average value I_{oAV} of the current flowing through the load R is equal to the average value I_{LAV} of the inductor current. From Fig.2 we observe that

$$I_{iAV}T = I_{LAV}t_{on}$$

So

$$I_{oAV} = I_{LAV} = I_{iAV}T/t_{on} = I_{iAV}/D$$

The peak-to-peak ripple in the output voltage can be calculated by considering the waveforms shown in Fig.2 for a continuous conduction mode of operation. Assuming that all the ripple component of the inductor current I_L flows through the capacitor C and its average value flows through the load R, since the shaded area represents the additional charge ΔQ, it results

$$\Delta U_o = \Delta Q/C = (\Delta I_L T)/(8C)$$

During t_{off} interval it results

$$\Delta I_L = (U_{oAV})(t_{off}/L) = U_{oAV}(1-D)T/L$$

Therefore, replacing into the previous equation, we have

$$\Delta U_o = U_{oAV}(1-D)/(8f^2LC)$$

Where f = 1/T is the switching frequency

Remark

The conduction mode of the converter can be continuous or discontinuous, based on the inductor current value. Being at the boundary between the continuous and the discontinuous mode, by definition, the inductor current goes to zero at the end of the t_{off} interval.

At this boundary (subscript B), the average inductor current is:

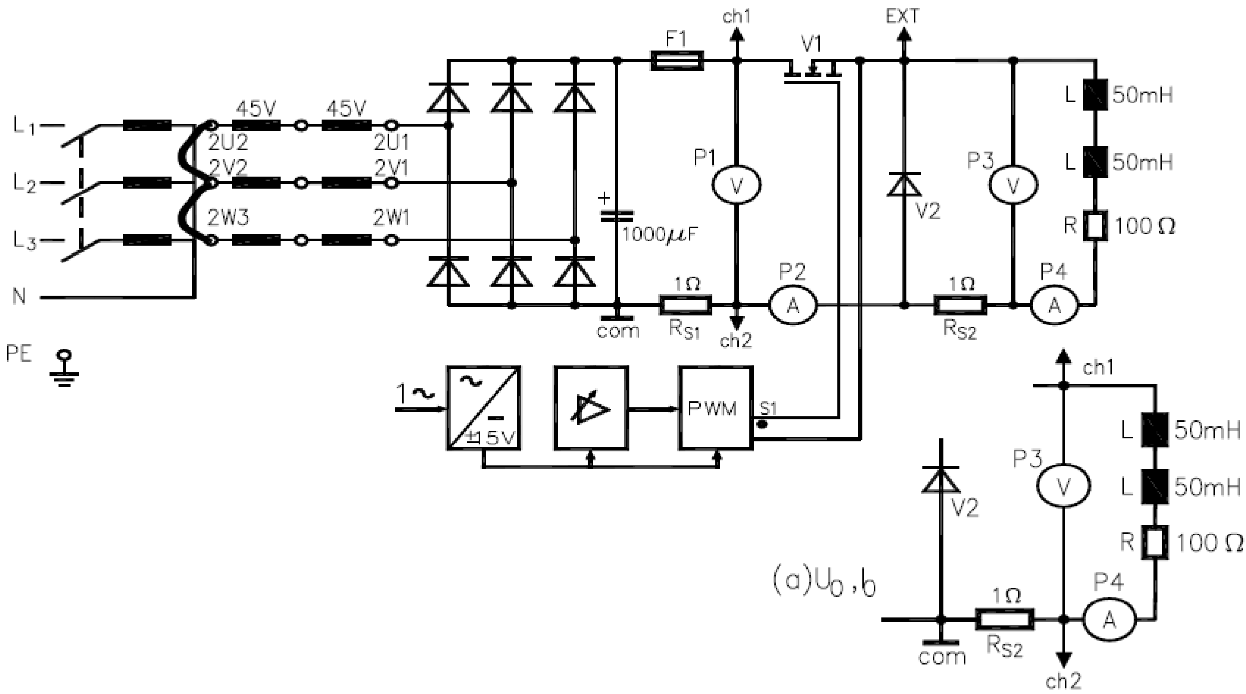
$$I_{LBAV} = \Delta I_L/2 = (U_i-U_{oAV})D/(2fL) = I_{oBAV}$$

and so, if during an operating condition it results $I_{oAV} < I_{LBAV}$ then the operation will become discontinuous.

STEP-DOWN CONVERTER WITH MOSFET

Objectives:
• Measurement and recording of the input and output variables of the converter.
• Control characteristic.
• Ripple of the output current.

Circuit diagram



Experiment procedure
Assemble the circuit according to the foregoing circuit diagram, disregarding detail (a) at first.
1) Connections
Connect the voltage reference generator DL2614 and PWM control unit DL2619 to power supply +15V/0/-15V.
Connect the output U_o of voltage generator to input U_c of the control unit.
Connect the pulse output S_1 to gate/source circuit of the MOSFET V_1: socket marked with a dot to the gate.

2) Preliminary calculations
2.1) Input voltage of the converter
Star connected transformer: $U_{vo} = 2x45 = 90$ V.
Rectified voltage and dc input voltage of the converter:
$U_{dAV} = U_{iAV} = 2.342\ U_{v0} = 2.342x90 \cong 210.8$ V.
2.2) Input current of the converter
The current on every line supplying the bridge flows for 2/3 of the period and so, being the permissible current I_v =1.5 A on the secondary phase winding of the mains transformer, the permissible rectified current is $(3/2)^{0.5}$x1.5 = 1.224x1.5 = 1.84 A but, as a precaution, the permissible input current is assumed equal to 1.5 A
2.3) Output voltage of the converter
When the switching frequency is f = 4000 Hz and the control voltage U_c = 3.5 V approx, the duty ratio is 50%
The output voltage of the converter is $U_{oAV} = U_{iAV}\ D = 210.8x0.5 = 105.4$V
2.4) Output current of the converter
The permissible output current of the converter depends on the permissible currents for the used components.
MOSFET: 10 A.
Load inductance: 2.5 A.
Load resistance 100 Ω: 1 A.
The input current of the converter is smaller than the output current in accordance with the duty ratio and so, if a load resistance 100 Ω is assumed the output current is 105.4/100=1.05A

3) Basic settings
3.1) Voltage reference generator DL2614
EXT/INT switch on INT position
(0/+10V)/(0/±10V) switch on (0/+10V) position.
Set point potentiometer to 3.5 V.
3.2) Control unit DL2619
Connect the PWM output to input U_i of the output amplifier.
Switching frequency f = 4000 Hz: coarse adjustment "x100" and fine adjustment "40".
Inhibit voltage UINH = 15 V (open).
3.3) Meters
Set AV/AC+DC measurements for voltmeters P1/P3 and ammeters P2/P4.
Voltmeters P1/P3: measuring range 300 V.
Ammeters P2/P4: measuring range 3 A (1 A).
3.4) MOSFET
Connect the RCD suppressor circuit.
3.5) Free-wheeling diode
Connect the RCD suppressor circuit.

4) Initial activation of the converter
First switch on the control unit and only afterwards should the mains transformer be switched on.

5) Voltage and current measurements
Measure:
5.1) the input voltage U_{iAV} by the voltmeter P1;
5.2) the input current I_{iAV} by the ammeter P2;
5.3) the output voltage U_{oAV} by the voltmeter P3;
5.4) the output current I_{oAV} by the ammeter P4;
Enter the measured values in the following table.

U_{iAV} (V)	I_{iAV} (A)	U_{oAV} (V)	I_{oAV} (A)

6) Recording on the oscilloscope

6.1) Recording the U_i voltage and Ii current at the input of the converter

Oscilloscope setting

DC coupling; Yt mode. Trigger: EXT.

EXT SYNC input (output U_o of the converter).

Channel 1 (voltage U_i)

Channel 2 (current I_i proportional to voltage at shunt R_{S1} =1 Ω)

6.2) Recording the U_o voltage and Io current at the output of the converter

Oscilloscope setting

Assemble the measuring circuit according with detail (a).

EXT SYNC input (output U_o of the converter).

Channel 1 (voltage U_o)

Channel 2 (current I_o proportional to voltage at shunt R_{S2} = 1 Ω)

7) Control characteristic

The control characteristic $U_o = f(t_{on})$ at constant load resistance describes the real behaviour of the converter

7.1) Basic settings

7.1.1) Voltage reference generator DL2614

EXT/INT switch on INT position

(0/+10V)/(0/±10V) switch on (0/+10V) position.

Set point potentiometer to 3.5 V.

7.1.2) Control unit DL2619

Connect the PWM output to input U_i of the output amplifier.

Switching frequency f = 4000 Hz: coarse adjustment “x100” and fine adjustment “40”.

Inhibit voltage UINH = 15 V (open).

7.1.3) Meters

Set AV/AC+DC measurements for voltmeters P1/P3 and ammeters P2/P4.

Voltmeters P1/P3: measuring range 300 V.

Ammeters P2/P4: measuring range 3 A (1 A).

7.2) Oscilloscope setting

DC coupling; Yt mode. Trigger: Ch1.

Channel 1 (voltage U_o)

Channel 2 (current I_o proportional to voltage at shunt R_{S2} = 1 Ω)

7.3) Activation of the converter

First switch on the control unit and only afterwards should the mains transformer be switched on.

7.4) Prearrangement

Adjust the scope time base so that only one period of the output voltage is displayed: time base = 25 μs/div. If necessary adjust the set point value of the switching frequency f=100 Hz (fine control) so that the period T=1/f= 250 μs covers a screen width of ten divisions and the control voltage U_c so that the time t_{on} = 150 μs.

7.5) Reduce the control voltage U_c in order to carry out the suggested t_{on} times (measure t_{on} at the oscilloscope) and enter the measured values in the following table.

t_{on} (μs)	**U_{iAV} (V)**	**I_{iAV} (A)**	**U_{oAV} (V)**	**I_{oAV} (A)**

Draw the control characteristic $U_o = f(t_{on})$ of the converter and the curve $U_i = f(t_{on})$. Compare measurements with the expected theoretical values.

8) Ripple of the output current
Due to the switching operation of the converter the output voltage is comprised of the direct voltage component and the spurious, non-sinusoidal, alternating voltage component. At the output side of the converter the smoothing is carried out by a smoothing inductor connected in series with the load.

8.1) Basic settings
Load resistance R = 100 Ω.
Filter capacitor C = 1000 μF.
8.1.1) Voltage reference generator DL2614
EXT/INT switch on INT position
(0/+10V)/(0/±10V) switch on (0/+10V) position.
Set point potentiometer to 3.5 V.
8.1.2) Control unit DL2619
Connect the PWM output to input U_i of the output amplifier.
Switching frequency f= 4000 Hz: coarse adjustment “x100” and fine adjustment “40”.
Inhibit voltage UINH =15 V (open).
8.1.3) Meters
Set AV/AC+DC measurements for voltmeters P1/P3 and ammeters P2/P4.
Voltmeters P1/P3: measuring range 300 V.
Ammeters P2/P4: measuring range 3 A (1 A).

8.2) Oscilloscope setting
AC coupling; Yt mode. Trigger: Ch1.
Channel 1 (voltage U_o)
Channel 2 (current Io proportional to voltage at shunt $R_{S2} = 1\Omega$)

8.3) Activation of the converter
First switch on the control unit and only afterwards should the mains transformer be switched on.

8.4) Measurement
Measure the ripple in the output current on the oscilloscope screen.

EXPERIMENT SIX

STEP-UP (BOOST) CONVERTER

INTRODUCTION

As the name implies this converter produces a greater average output voltage than the dc input voltage. Its main application is in regulated dc power supplies and the regenerative braking of dc motors. The basic circuit is shown in Fig.1, where the filter capacitor C is assumed to be very large to ensure a constant output voltage value while PWM control is presumed (a switch-on duration t_{on} = 100% must avoided).

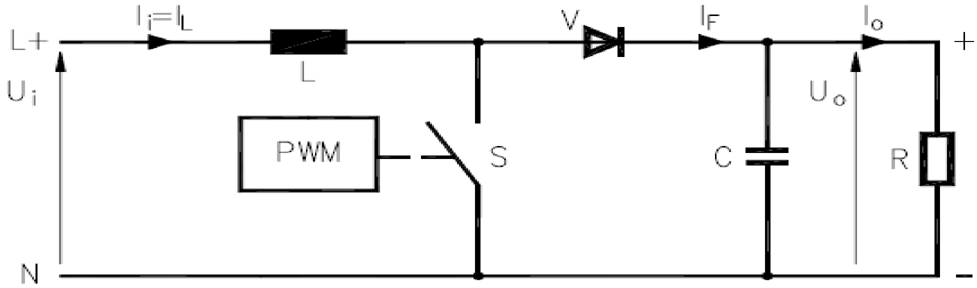


Fig. 1 Step-up (boost) converter

The typical voltage and current characteristics are shown in the following Fig. 2

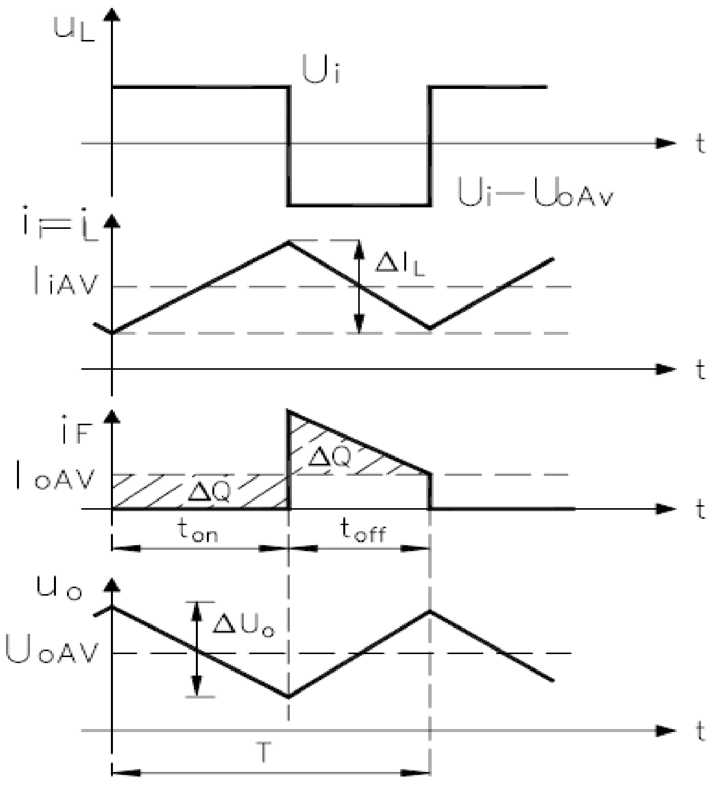


Fig. 2 Voltage and current characteristics, step-up converter

When the switch S is on, the diode V is reverse biased, thus isolating the output stage.
The input supplies energy to the inductor L and causes a linear increase in the inductor current I_L equal to:

$$(\Delta I_L)_{rising} = (U_i/L)t_{on}$$

When the switch S is off, the load receives energy from the inductor L as well as from the input.
This causes a linear decrease of the inductor current equal to:

$$(\Delta I_L)_{falling} = (U_{oAV}-U_i)t_{off}/L$$

Since in steady-state operation the variations of current I_L must be equal, this implies

$$U_{oAV} = U_i(1+t_{on}/t_{off}) = U_i T/t_{off} = U_i/(1-D)$$

The average value I_{oAV} of the current flowing through the load R is equal to the average value I_{FAV} of the diode current. From Fig.2 we observe that

$$I_{FAV}\ T = I_{iAV}\ t_{off}$$

So

$$I_{oAV} = I_{iAV}\ (1\text{-}D)$$

The peak-to-peak ripple in the output voltage can be calculated by considering the waveforms shown in Fig.2 for a continuous conduction mode of operation. Assuming that all the ripple component of the diode current I_F flows through the capacitor C, and its average value flows through the load R, since the shaded area represents the additional charge ΔQ, it results

$$\Delta U_o = \Delta Q/C = I_{oAV} t_{on}/C = U_{oAV} DT/(RC) = U_{oAV} D/(fRC)$$

where f = 1/T is the switching frequency

Remark

The conduction mode of the converter can be continuous or discontinuous, based on the inductor current value. Being at the boundary between the continuous and the discontinuous mode, by definition, the inductor current goes to zero at the end of the t_{off} interval.

At this boundary (subscript B), the average inductor current is:

$$I_{LBAV} = \Delta I_L/2 = U_{oAV} D(1\text{-}D)/(2fL)$$

while the corresponding average value of output current is

$$I_{oBAV} = U_{oAV} D(1\text{-}D)^2/(2fL)$$

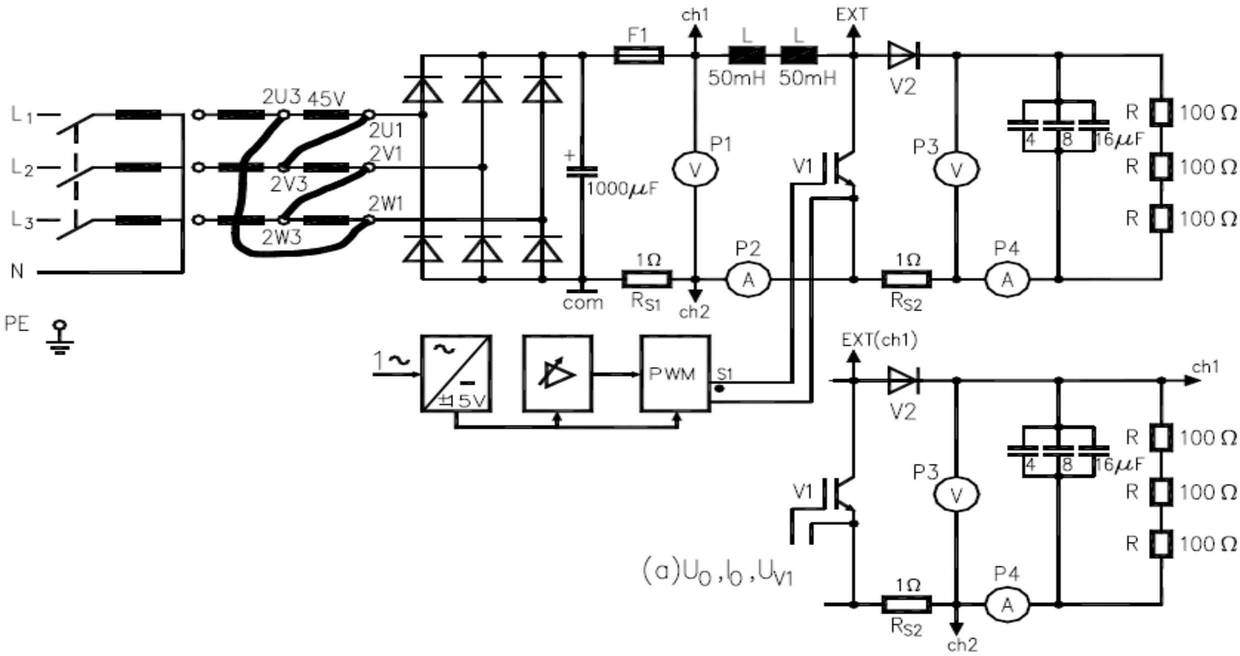
and so, if during an operating condition it results $I_{oAV} < I_{LBAV}$ (and hence $I_{LAV} < I_{LBAV}$)then the operation will become discontinuous.

STEP-UP CONVERTER WITH IGBT AND PWM CONTROL

Objectives:

- Measurement and recording of the input and output variables of the converter.
- Control characteristic.

Circuit diagram



Experiment procedure

Assemble the circuit according with the foregoing topographic diagram, disregarding detail (a) at first.
1) Connections
Connect voltage reference generator DL2614 and PWM control unit DL2619 to the power supply +15V/0/-15V.
Connect the output U_o of voltage generator to input U_c of the control unit.
Connect the pulse output S_1 to gate/emitter circuit of the IGBT V_1: socket marked with a dot to the gate.

2) Preliminary calculations
2.1) Input voltage of the converter
Mesh connected transformer: $U_v = 45 = 45$ V.
Rectified voltage and dc input voltage of the converter:
$U_{dAV} = U_{iAV} = 1.35\ U_v = 1.35x45 = 60.75$ V.
2.2) Input current of the converter
The current on every line supplying the bridge B6U flows for 2/3 of the period and so, being the permissible current $I_v = 1.5$ A on the secondary phase winding of the mains transformer, the permissible rectified current is $I_{dAVmax} = 1.23\ \sqrt{3}\ I_v = 1.23x\sqrt{3}x1.5 = 3.2$ A, but in the presence of the series inductor (Imax = 2.5 A), the permissible input current of the converter is assumed equal to $I_{iAVmax} = 2.5$ A
2.3) Output voltage of the converter
With the switching frequency f = 1000 Hz and duty ratio D = 80% the output voltage is 60.75/0.2 = 304V.
2.4) Output current of the converter; load.
The permissible output current of the converter depends on the permissible current for the relevant used components.
IGBT: 24 A; Load resistance 100 Ω: 1 A.
The input current of the converter is higher than the output current in accordance with the duty ratio and so, if a load resistance 300 Ω is assumed the output current is 304/300 = 1.01A

3) Basic settings
3.1) Voltage reference generator DL2614
EXT/INT switch on INT position
(0/+10V)/(0/±10V) switch on (0/+10V) position.
Set point potentiometer to 0 V.
3.2) Control unit DL2619
Connect the PWM output to input U_i of the output amplifier.
Switching frequency f = 1000 Hz:
Coarse adjustment “x10” and fine adjustment “100”.
Inhibit voltage UINH = 15 V (open).
3.3) Meters
Set AV/AC+DC measurements for voltmeters P1/P3 and ammeters P2/P4.
Voltmeters P1/P3: measuring range 300 V (100 V).
Ammeters P2/P4: measuring range 3 A (1 A).
3.4) IGBT
Connect the RCD suppressor circuit.
3.5) Free-wheeling diode
Connect the RCD suppressor circuit.

4) Initial activation of the converter
4.1) First switch on the control unit and only afterwards should the mains transformer be switched on.
4.2) As long as the IGBT remains disabled ($U_c = 0$ V) the input voltage U_i feeds the ohmic load via the series inductor and the free-wheeling diode V2.
4.3) Measure and enter the measured values in the following table.
4.3.1) the input voltage U_{iAV} by the voltmeter P1;
4.3.2) the input current I_{iAV} by the ammeter P2;
4.3.3) the output voltage U_{oAV} by the voltmeter P3;
4.3.4) the output current I_{oAV} by the ammeter P4.

U_{iAV} (V)	I_{iAV} (A)	U_{oAV} (V)	I_{oAV} (A)

Compare measurements with the expected theoretical values.

5) Increase the control voltage ($U_c \cong 5$ V): the converter chops.

Adjust the control voltage and the frequency fine regulation in order to achieve a switching frequency f = 1000 Hz and $t_{on} = t_{off} = 500$ µs. Enter the voltage and current measured values in the following table.

U_{iAV} (V)	**I_{iAV} (A)**	**U_{oAV} (V)**	**I_{oAV} (A)**

6) Recording on the oscilloscope

6.1) Recording the U_i voltage and I_i current at the input of the converter

Oscilloscope setting

DC coupling; Yt mode. Trigger: EXT.

EXT SYNC input (voltage U_{V1} of the IGBT).

Channel 1 (voltage U_i): 20 V/div; probe x100.

Channel 2 (current Ii proportional to voltage at shunt $R_{S1} = 1\ \Omega$): 0.5 V/div; probe x1.

6.2) Recording the U_o voltage, and I_o current at the output of the converter, and the voltage U_{V1} at IGBT.

Oscilloscope setting:

Assemble the measuring circuit according with detail (a); in order to record the voltage U_{V1} connect channel 1 to collector of the IGBT corresponding to the EXT SYNC connection.

EXT SYNC input (voltage U_{V1} of the IGBT).

Channel 1 (voltage U_o): 100 V/div; probe x100.

Channel 1 (voltage U_{V1}): 100 V/div; probe x100.

Channel 2 (current I_o proportional to voltage at shunt $R_{S2} = 1\ \Omega$): 0.5 V/div; probe x1.

7) Control characteristic

7.1) Basic settings:

7.1.1) Voltage reference generator DL2614

EXT/INT switch on INT position

(0/+10V)/(0/±10V) switch on (0/+10V) position.

Set point potentiometer to 5 V.

7.1.2) Control unit DL2619

Connect the PWM output to input Ui of the output amplifier.

Switching frequency f = 1000 Hz:

Coarse adjustment “x10” and fine adjustment “100”.

Inhibit voltage UINH = 15 V (open).

7.1.3) Meters

Set AV/AC+DC measurements for voltmeters P1/P3 and ammeters P2/P4.

Voltmeters P1/P3: measuring range 300 V (100).

Ammeters P2/P4: measuring range 3 A (1 A).

7.2) Oscilloscope setting:

DC coupling; Yt mode. Trigger: Ch1.

Channel 1 (voltage U_{V1}): 200 V/div ; probe x100.

Channel 2 (current Io proportional to voltage at shunt $R_{S2} = 1\ \Omega$): 1 V/div ; probe x1.

7.3) Activation of the converter

First switch on the control unit and only afterwards should the mains transformer be switched on.

7.4) Prearrangement

If necessary adjust the set point value of the switching frequency f = 100 Hz (fine control) in order to achieve a switching frequency f = 1000 Hz.

7.5) Adjust the control voltage U_c in order to carry out the <u>suggested</u> t_{on} times (measure ton at the oscilloscope) and enter the measured values in the following table.

t_{on} (µs)	**U_i (V)**	**I_i (A)**	**U_o (V)**	**I_o (A)**

Draw the control characteristic $U_o = f(t_{on})$ of the converter and the curves $U_i = f(t_{on})$ and $I_i = f(t_{on})$

Compare the measured results with the theoretical predictions.

EXPERIMENT SEVEN

SINGLE-PHASE FULLY-CONTROLLED RECTIFIER IN THE INVERSION MODE

INTRODUCTION

Fig. 1 shows the fully-controlled bridge rectifier with a supplementary dc voltage E_0 in series with ohmic load. E_0 is in the direction of the direct current I_d.

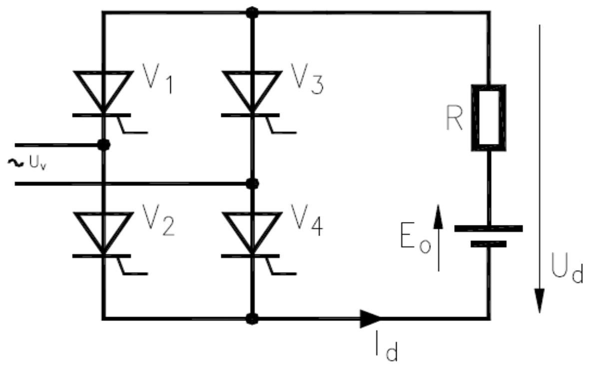


Fig. 1 Controlled rectifier with ohmic load and supplementary dc voltage

With control angle $0° < \alpha < 90°$ the direct voltage U_d and supplementary voltage E_0 are in series and a relatively high pulsating output current results: the average direct voltage value is positive.
With control angle $\alpha > 90°$ the operation is regenerative and the converter works in the inversion mode.
The converter can be continuously controlled from $\alpha = 0°$ to stability limit while the intermittent operation is avoided because of the sufficiently high supplementary voltage, as shown in Fig. 2.

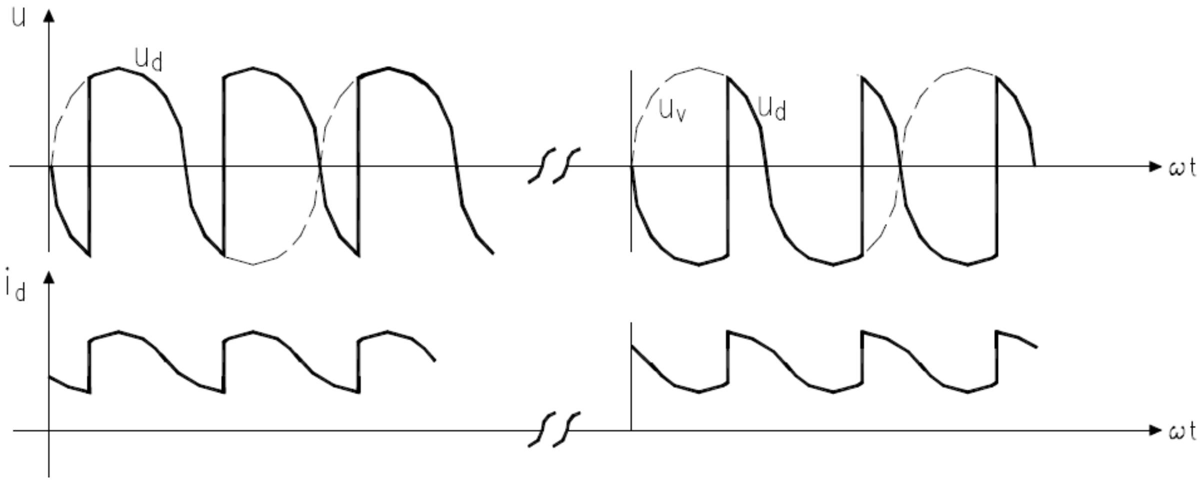


Fig. 2 Voltage and current time profiles

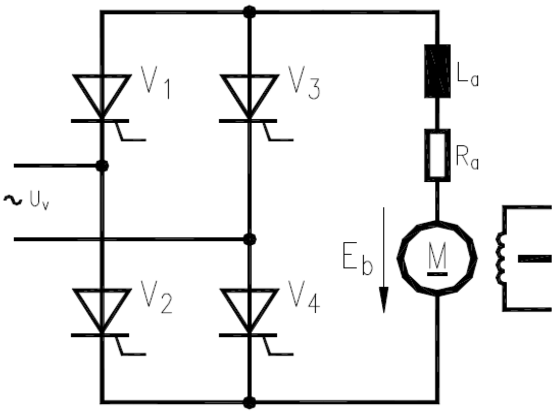


Fig. 3 Fully-controlled bridge, dc motor load

When converter is used in practice, ohmic-inductive load with back-e.m.f. E_b occurs when operating dc motors: E_b is an e.m.f. induced in the armature circuit, proportional to the speed, R_a is the armature winding resistance and L_a the leakage inductance.
For conducting SCRs the direct voltage follows the time profile of the supply ac voltage while for blocking SCRs the direct voltage is equal to the back-e.m.f., as shown in Fig. 4

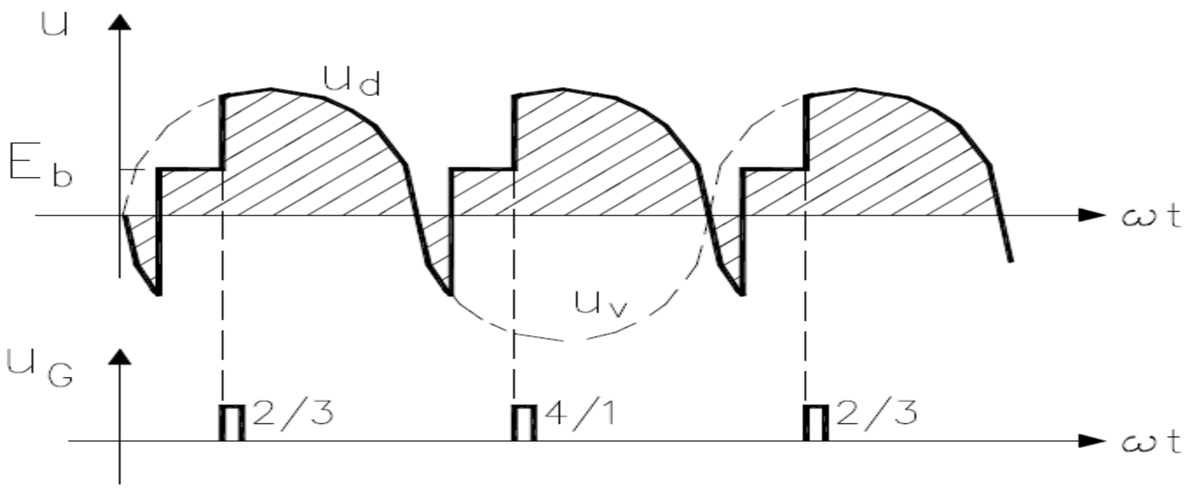


Fig. 4 Voltage time profiles

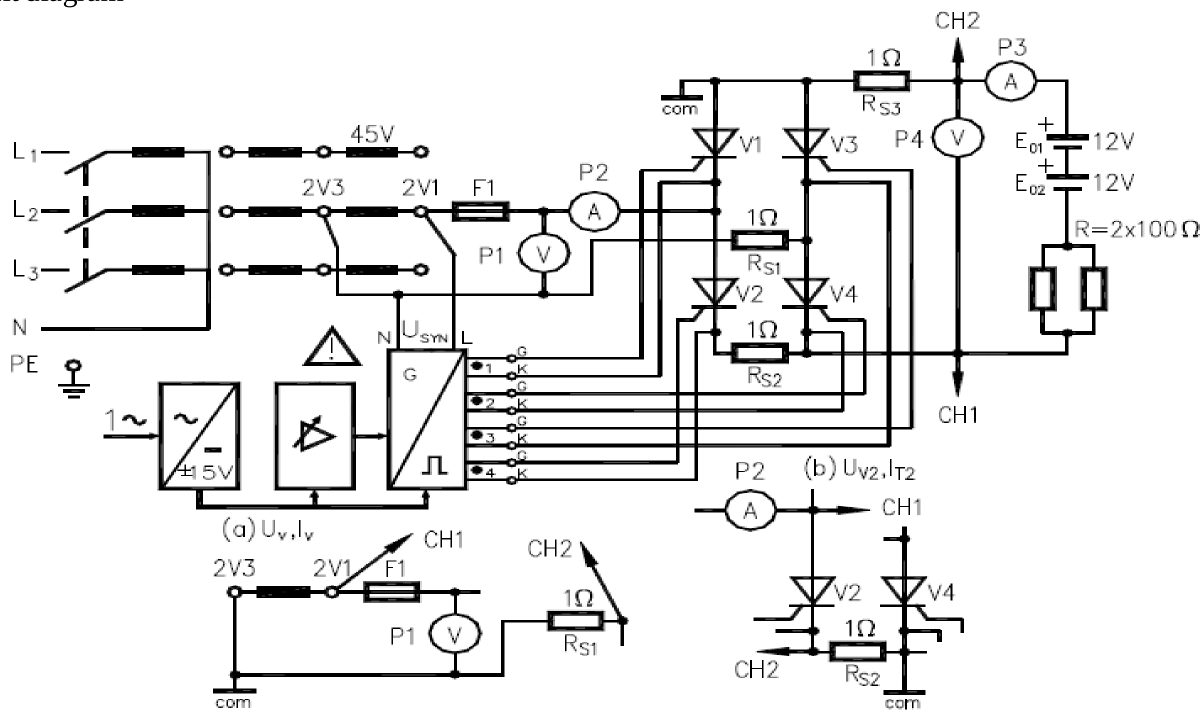
The SCRs can only be triggered when the instantaneous value of the ac supply voltage is higher than the back e.m.f.: in this case the control range of the converter is limited.
When the SCRs conduct the voltage U_d is formed from sections of the sinusoidal supply voltage; during the gaps in the current the voltage U_d is equal to the speed dependent back e.m.f.
The motor inductance is here insufficient to make a continuous load current.

FULLY-CONTROLLED BRIDGE, OHMIC LOAD AND SUPPLEMENTARY DC VOLTAGE

Objectives:

- Recording voltage and current time profiles
- Voltage and current measurements
- Determination of various characteristic data

Circuit diagram



Experiment Procedure

Assemble the circuit according with the foregoing topographic diagram, disregarding details (a) and (b) at first.

1) Connections

Connect the voltage reference generator DL2614 and control unit DL2616 to the power supply +15V/0/-15V.

Connect the output U_o of voltage generator to input U_c of the control unit.

Connect the terminals L/N (U_{SYN}) of the control unit respectively to terminals 2V1/2V3 of the transformer.

Connect the pulse transformers 1, 2 and 3, 4 to gate/cathode circuit of the SCRs V_1 ,V_4 and V_3 ,V_2 respectively: socket marked with a dot to the gate.

Connect the Power Analyzer to the input side of the circuit. Ask the instructor to show you how to do this.

2) Basic settings

2.1) Voltage reference generator DL2614

EXT/INT switch on INT position

(0/+10V)/(0/±10V) switch on (0/+10V) position.

Set point potentiometer to 10 V.

2.2) Control unit DL2616

Control angle α_o switch on 0° position.

“Pulse shape” switch on pulse train position.

Inhibit voltage UINH = 15 V (open).

3) Voltage and current measurements

Supply the circuit and measure:

3.1) the rms value U_v of the supply voltage by the voltmeter P_1;

3.2) the rms value I_v of the supply current by the ammeter P_2;

3.3) the average value U_{dAV} and the rms value U_{dRMS} of the direct voltage by the voltmeter P_3;

3.4) the average value I_{dAV} and the rms value I_{dRMS} of the direct current by the ammeter P_4;

3.5) the average and apparent input power

Enter the measured value as a function of the gate angles α in the following table.

α (°)	30	60	120	150
U_V (V)				
I_V (A)				
$U_{dAV\alpha}$ (V)				
$U_{dRMS\alpha}$ (V)				
$I_{dAV\alpha}$ (A)				
$I_{dRMS\alpha}$ (A)				
P_{in} (W)				
S (VA)				

Compare measurements with the expected theoretical values.

4) Recording on the oscilloscope (α = 60°)

4.1) Recording the direct voltage U_d and current I_d

Oscilloscope setting

DC coupling; Yt mode. Trigger: AC Line.

Channel 1(U_d voltage)

Channel 2 (current I_d proportional to voltage at shunt $R_{S3} = 1\ \Omega$): 1 V/div

4.2) Recording the supply voltage U_v and current I_v

Oscilloscope setting

Assemble the measuring circuit according with detail (a).

Channel 1 (voltage U_v)

Channel 2 (current I_v proportional to voltage at shunt $R_{S1} = 1\ \Omega$): 1 V/div

4.3) Recording the SCR V_2 voltage and current

Oscilloscope setting

Assemble the measuring circuit according with detail (b).

Channel 1 (voltage U_{V2})

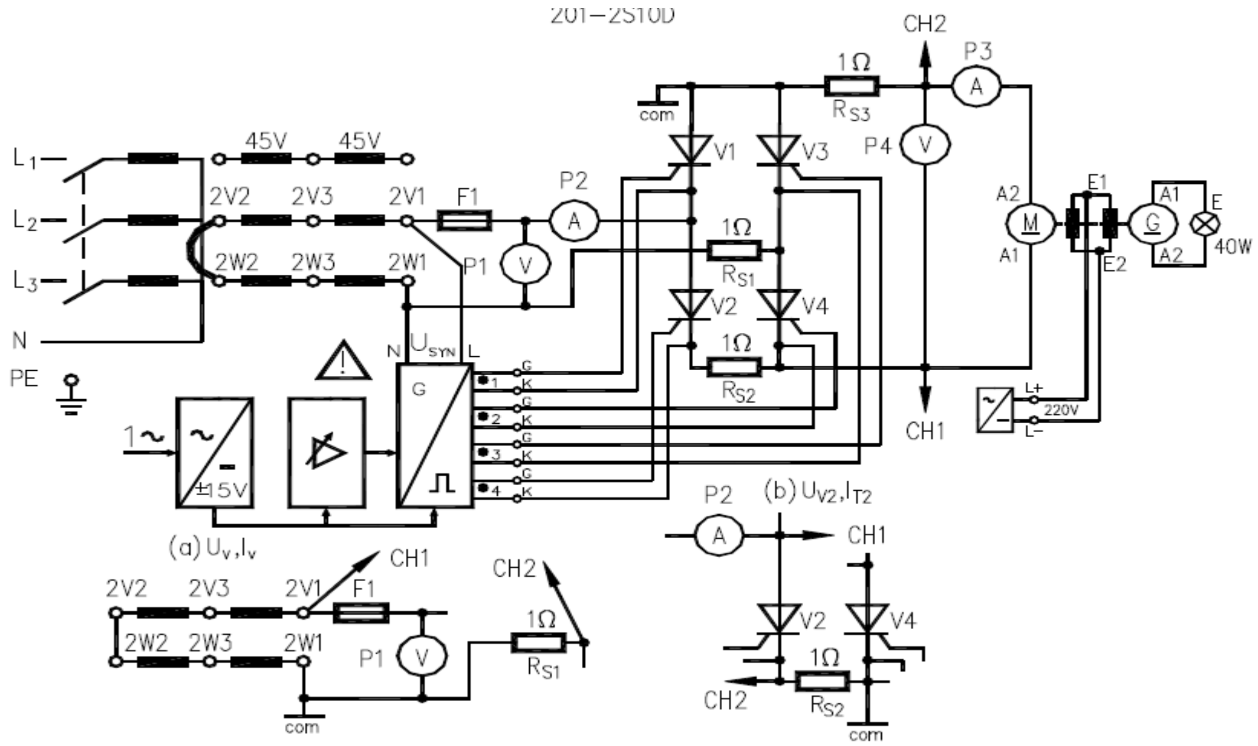
Channel 2 (current I_{T2} proportional to voltage at shunt $R_{S2} = 1\ \Omega$): 1 V/div.

FULLY-CONTROLLED BRIDGE, DC MOTOR LOAD

Objectives:

- Recording voltage and current time profiles
- Voltage and current measurements
- Determination of various characteristic data

Circuit diagram



Experiment procedure

Assemble the circuit according with the foregoing topographic diagram, disregarding details (a) and (b) at first.

1) Connections

Connect the voltage reference generator DL2614 and control unit DL2616 to the power supply +15V/0/-15V.
Connect the output U_o of voltage generator to input U_c of the control unit.
Connect the terminals L/N (U_{SYN}) of the control unit respectively to terminals 2V1/2W1 of the transformer.
Connect pulse transformers 1, 2 and 3, 4 to gate/cathode circuit of the SCRs V_1, V_4 and V_3, V_2 respectively: socket marked with a dot to the gate.

2) Basic settings

2.1) Voltage reference generator DL2614
EXT/INT switch on INT position
(0/+10V)/(0/±10V) switch on (0/+10V) position.
Set point potentiometer to 0 V.

2.2) Control unit DL2616
Control angle α_o switch on 0° position.
"Pulse shape" switch on pulse train position.
Inhibit voltage UINH = 15 V (open).

2.3) Motor
Supply the excitation winding of the machine before to supply the converter.

3) Voltage and current measurements

Supply the circuit and measure:
3.1) the rms value U_v of the supply voltage by the voltmeter P1;
3.2) the rms value I_v of the supply current by the ammeter P2;
3.3) the average value U_{dAV} and the rms value U_{dRMS} of the direct voltage by the voltmeter P3;
3.4) the average value I_{dAV} and the rms value I_{dRMS} of the direct current by the ammeter P4.
In addition measure the rotational frequency n.
Enter the measured value as a function of the gate angles in the following table.

α (°)	60	90
U_V (V)		
I_V (A)		
$U_{dAV\alpha}$ (V)		
$U_{dRMS\alpha}$ (V)		
$I_{dAV\alpha}$ (A)		
$I_{dRMS\alpha}$ (A)		
n (min^{-1})		

With control angle $\alpha < 60°$ the converter operation becomes unstable (pulsating motor speed).

4) Recording on the oscilloscope ($\alpha = 90°$)

4.1) Recording the direct voltage U_d and current I_d. Oscilloscope setting:
DC coupling; Yt mode. Trigger: AC Line.
Channel 1(U_d voltage): 100 V/div, probe x100.
Channel 2 (current I_d proportional to voltage at shunt $R_{S3} = 1\Omega$): 500 mV/div, probe x1.

4.2) Recording the supply voltage U_v and current I_v.
Oscilloscope setting
Assemble the measuring circuit according with detail (a).
Channel 1 (voltage U_v): 100 V/div; probe x100.
Channel 2 (current I_v proportional to voltage at shunt $R_{S1} = 1\ \Omega$): 1 V/div; probe x1.

EXPERIMENT EIGHT

SINGLE-PHASE SWITCHED-MODE INVERTER

INTRODUCTION

Inverters are converters used to convert the dc input into a sinusoidal ac output with variable frequency and amplitude. Dc-to-ac inverters are used in ac-motor drives and uninterruptible ac power supplies. To be precise, the switch-mode inverter is a converter through which the power flow is reversible.
Let us consider a single-phase inverter, which is shown in block-diagram form in Fig.1, where the input voltage is assumed to be a dc voltage U_d source and the output voltage U_o is filtered so that it can be assumed to be sinusoidal.

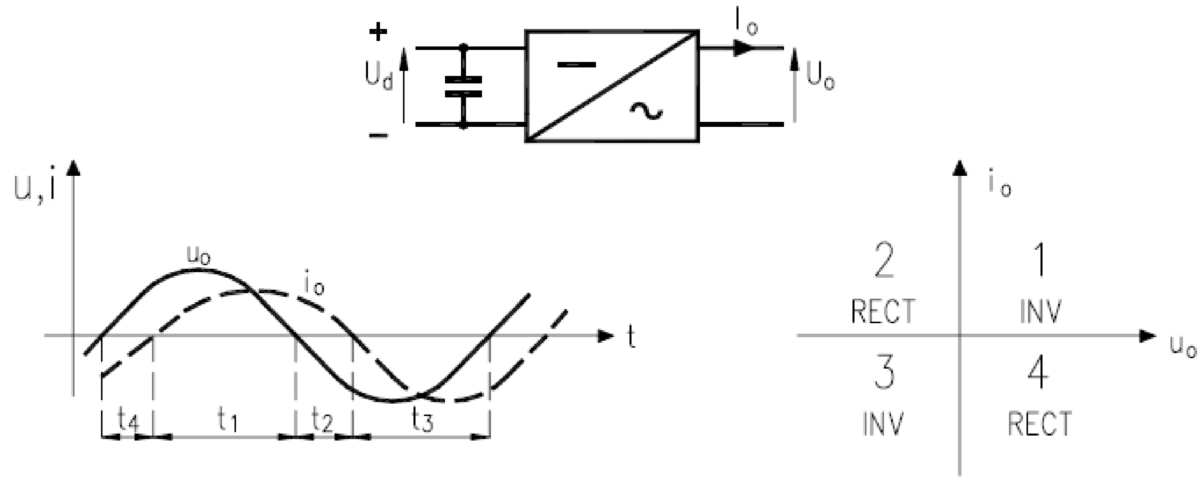


Fig. 1 Single-phase inverter block diagram and filtered output waveforms

The output waveforms show that during the intervals t_1 and t_3 the instantaneous power p_o=u_oi_o is positive and therefore it flows from the dc side to the ac side (inverter operation); in contrast, during the intervals t_2 and t_4 the power is negative and therefore it flows from the ac side to the dc side (rectifier operation).
A step-down converter is only suitable for single-quadrant operation.
A half-bridge circuit can be used to reverse the current if an active load is involved.
A genuine four-quadrant operation can be achieved with the help of a full-bridge: due to arrangement of their components, full-bridge is often termed H-bridge.

Single-phase half-bridge inverter

Figure 2 shows the basic half-bridge inverter, where we assume that the input dc voltage U_d is constant and that the potential at midpoint "O" remains essentially constant with respect to the negative dc bus N.

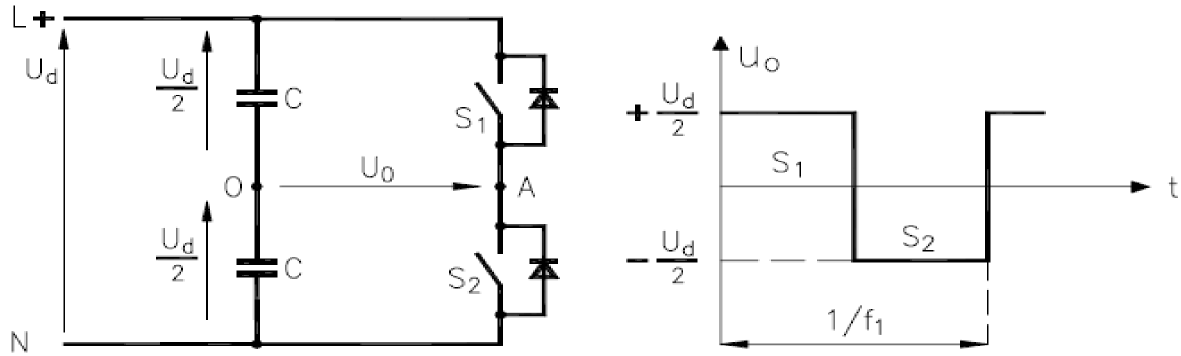


Fig. 2 Single-phase half-bridge inverter and output voltage waveform

Since the two switches S_1 and S_2 are never off simultaneously, the output voltage U_o fluctuates between the following values dictated by the switch states:

$U_d/2$ (S_1 on, S_2 off)
$-U_d/2$ (S_1 off, S_2 on)

When the switch S_1 is on the output current will flow through S_1 and the point A is at positive potential U_d.

Similarly when the switch S_2 is on the output current will flow through S_2 and the point A is at zero potential.
In the square-wave switching mode, each switch is on for one-half cycle (180°) of the desired frequency f_1 of the output sinusoidal voltage. From Fourier analysis of the output voltage waveform the peak values of the fundamental frequency f_1 and that of the harmonic components f_h (h takes only odd values) can be obtained.
In order to produce a sinusoidal output voltage waveform at a desired fundamental frequency f_1 it is necessary that the control signal of PWM switching be sinusoidal at the frequency f_1.

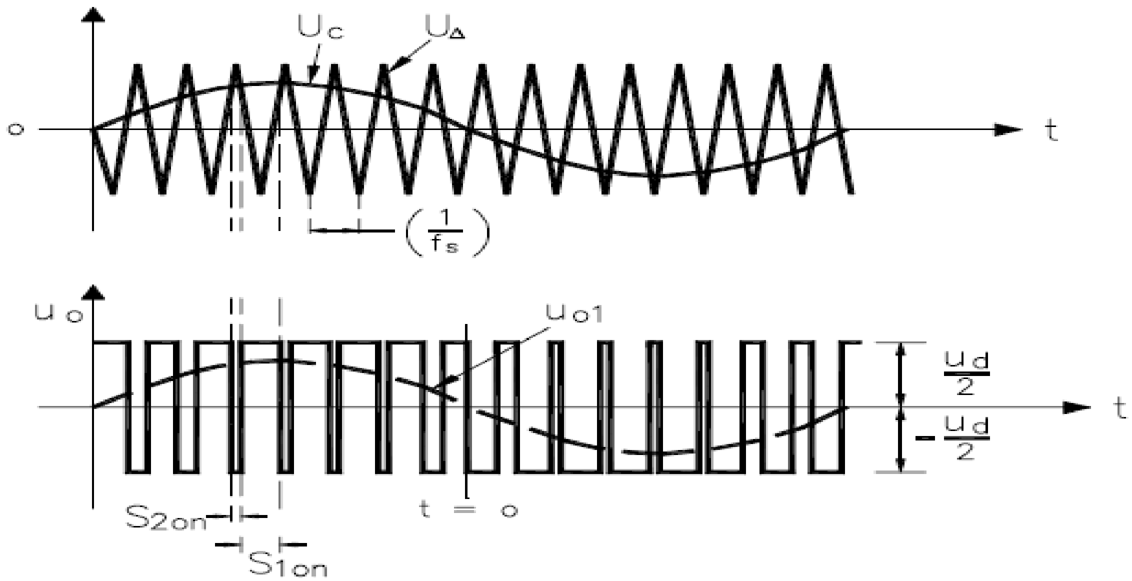


Fig. 3 Single-phase inverter output with sinusoidal PWM

The frequency of the triangular waveform establishes the inverter switching frequency f_s while the control voltage U_C is used to modulate the switch duty cycle.
The inverter output voltage will not be a perfect sine wave and will contain voltage components at harmonic frequencies of f_1.
The harmonic spectrum of the output voltage depends on the amplitude modulation ratio m_a and on the frequency modulation ratio m_f
The peak amplitude of the fundamental frequency component is ($m_a \leq 1$)
The harmonics in the output voltage appear as sidebands centered around the switching frequency and its multiples.
The frequency modulation ratio m_f should be an odd integer so only odd harmonics are present.
In most applications, the switching frequency f_s is selected to be either less than 6 kHz or greater than 20 kHz to be above the audible range.

Remark
The two switches are switched in such a way that when one of them is in its off state, the other switch is on: in practice they are both off for a short time interval (blanking time) to avoid short-circuit of the dc input.

Single-phase full-bridge inverter

A full-bridge inverter consists of two half-bridge inverters, as shown in the following Fig.4: with the same dc input voltage, the maximum output voltage is twice that of the half-bridge inverter.

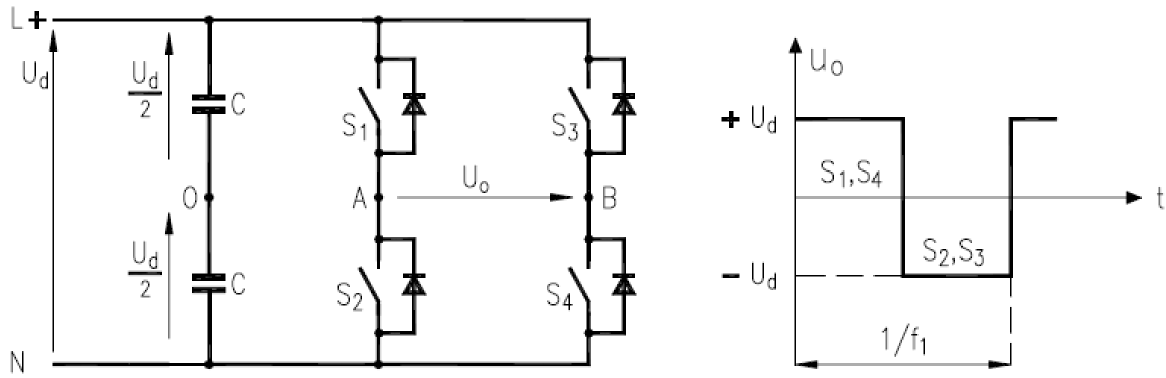


Fig. 4 Single-phase full-bridge (H-bridge) inverter and output voltage waveform

In this scheme, the diagonally opposite switches (S_1, S_4) and (S_2,S_3) are switched simultaneously and so, carrying out the same analysis as the half-bridge inverter, the output voltage fluctuates between the following values dictated by the switch states:

U_d (S_1 & S_4 on, S_2 & S_3 off)
$-U_d$ (S_1 & S_4 off, S_2 & S_3 on)

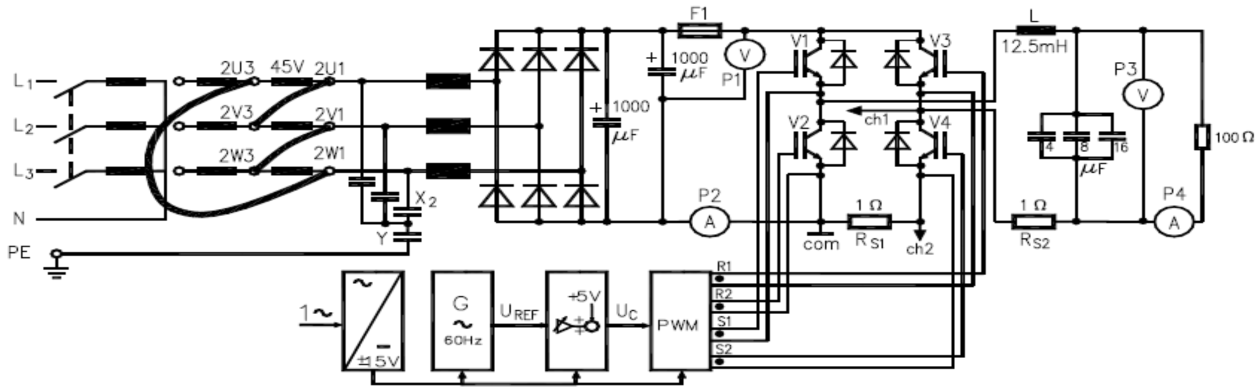
In the square-wave switching mode, each pair switch is on for one-half cycle (180°) of the desired frequency f_1 of the output sinusoidal voltage.

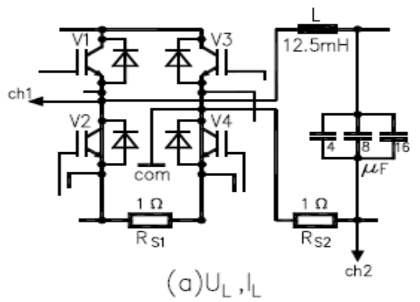
When sinusoidal PWM switching is used the same results apply as explained earlier. The output voltage, however, is twice that of the half-bridge inverter.

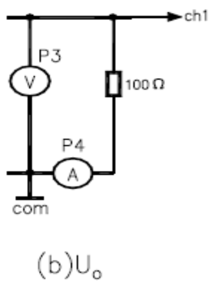
SINGLE-PHASE FULL-BRIDGE INVERTER WITH SINUSOIDAL PWM CONTROL

Objectives:
• Production of a sinusoidal voltage.
• Measurement and recording of the input and output variables of the inverter.

Circuit diagram







Experiment procedure

Assemble the circuit according with the foregoing topographic diagram, disregarding details (a) and (b) at first. Before you connect the function generator, the matching amplifier and control unit follow steps from 1) to 3).

1) Auxiliary power supply
Connect the function generator DL2633 and the matching amplifier DL2625 to the power supply +15V/0/-15V. At the moment do not supply the PWM control unit DL2619.

2) Basic settings
2.1) Function generator DL2633
Function: sinusoidal wave.
Signal frequency f = 60 Hz: coarse adjustment "x10" and fine adjustment "6".
LEVEL potentiometer to 50%.
Connect the output U_o to the input U_i of the matching amplifier.
2.2) Matching amplifier DL2625
Arrange the offset function: offset switch on "offset on" position and offset potentiometer to +5 V approx.
Amplification: gain = 0.5x1.
Time constant: $\tau = 0$.
Do not connect the output U_o to the input U_c of the PWM unit.
2.3) Control unit DL2619
Connect the PWM output to input U_i of the output amplifier.
Switching frequency f = 2 kHz:
coarse adjustment "x10" and fine adjustment "200" approx.
Inhibit voltage UINH = 15 V (open).
Connect the pulse outputs S_1-S_2 and R_1-R_2 to gate/emitter circuit of the IGBTs V_1-V_4 and V_2-V_3 respectively: socket marked with a dot to the gate.
2.4) Meters
Set AV/AC+DC measurements for meters P_1/P_2 and RMS/AC+DC measurements for meters P_3/P_4.
Voltmeters P_1/P_3: measuring range 100 V.
Ammeters P_2/P_4: measuring range 1 A.

3) Pre-arrangement of the control voltage of PWM unit.
The control unit PWM processes voltages in the range 0...+10 V so the control voltage must be matched conveniently.
3.1) Recording the reference voltage U_{REF} at the output of the function generator and the control voltage U_c at the output of the matching amplifier: use an oscilloscope.
Oscilloscope setting:
DC coupling; Yt mode. Trigger: Ch1.
Channel 1 (voltage U_{REF}): 10 V/div; probe x10.
Channel 2 (voltage U_c): 2 V/div; probe x1.
Common: 0 V.
3.2) Switch on the auxiliary power supply and the function generator.
Adjust the frequency f = 60 Hz (fine control) and the amplitude U_{REF} = 16 Vpp
(LEVEL potentiometer) of the square wave.
Adjust the control signal U_c at the output of the matching amplifier:
offset potentiometer (U_c = 5 VMEAN):
amplification "gain" (U_c = 8 Vpp).
3.3) Switch off the auxiliary power supply.

4) Connections
Complete the connections connecting the output U_o of the amplifier to input U_c of the control unit PWM.
Connect the control unit PWM to the power supply +15V/0/-15V.

5) Initial activation of the inverter.
5.1) First switch on the control unit and only afterwards should the mains transformer switched on.
5.2) Recording the U_{V4} voltage and I_{T4} current at the IGBT V_4.

Oscilloscope setting:
DC coupling; Yt mode. Trigger: Ch1.
Channel 1 (voltage U_{V4}): 50 V/div; probe x10.
Channel 2 (current I_{T4} proportional to voltage at shunt $R_{S1} = 1\ \Omega$): 2 V/div; probe x1.
If necessary adjust the set point value of the switching frequency f = 2 kHz (fine control).

6) Recording on the oscilloscope
6.1) Recording the U_L voltage across the bridge diagonal and the I_L inductor current.
Oscilloscope setting
Assemble the measuring circuit according with detail (a).
DC coupling; Yt mode. Trigger: Ch1.
Channel 1 (voltage U_L): 50 V/div; probe x10.
Channel 2 (current I_L proportional to voltage at shunt $R_{S2} = 1\ \Omega$): 2 V/div; probe x1.
6.2) Recording the U_o voltage at the output of the inverter.
Oscilloscope setting
Assemble the measuring circuit according with detail (b).
DC coupling; Yt mode. Trigger: Ch1.
Channel 1 (voltage U_o): 20 V/div; probe x10.

The output voltage results in a sinusoidal characteristic with frequency equal to the reference signal frequency. The ripple of the output voltage depends on the filtration effect: the higher the capacitance the lower the voltage ripple. The higher the switching frequency the lower the ripple.

Note
Owing to the circuit unavoidable dissymmetry it is possible that the output voltage contains a dc component. You can perform any necessary adjustment using the offset control on the matching amplifier to maintain the dc component at a zero value.

7) Voltage and current measurements

U_i(V)	
I_i(A)	
U_o(V)	
I_i(A)	

8) Use the digital oscilloscope to perform FFT on the output voltage U_o. Plot the harmonic spectrum and make a record of your observations.

EXPERIMENT NINE

SINGLE-PHASE AC VOLTAGE CONTROLLER

INTRODUCTION

The continuous control of alternating electrical energy is normally performed by means of thyristors that are suitable for use as static switches on account of their extremely high switching capacity.
The thyristor family includes unidirectional devices as the SCRs and bidirectional devices as the TRIACs. As switch conducts current in both directions so two SCRs must always be connected back-to -back (pair of anti-parallel arms) while the TRIAC can be used instead of the two anti- parallel SCRs. A TRIAC can be considered as two parallel SCRs oriented in opposite directions and integrated into a semiconductor chip to provide symmetrical bidirectional characteristics.

SINGLE-PHASE AC CONTROLLER

The simplest device used to continuously adjust the ac power is shown in the following Fig.1, where two anti-parallel SCRs can be used instead of the TRIAC.

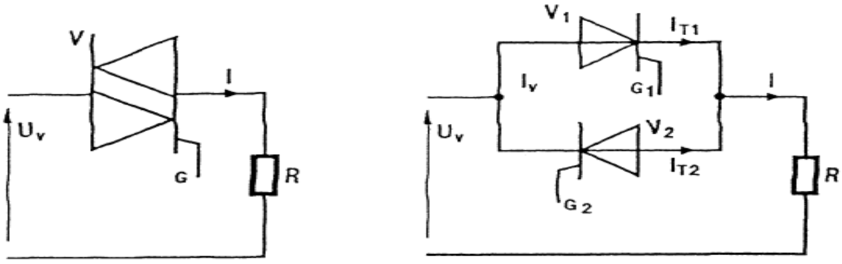


Fig. 1 Single-phase AC controller, ohmic load

The power regulation is accomplished by varying the control angle α of the TRIAC (of the two SCRs) during each half-period, as shown in the following Fig.2.

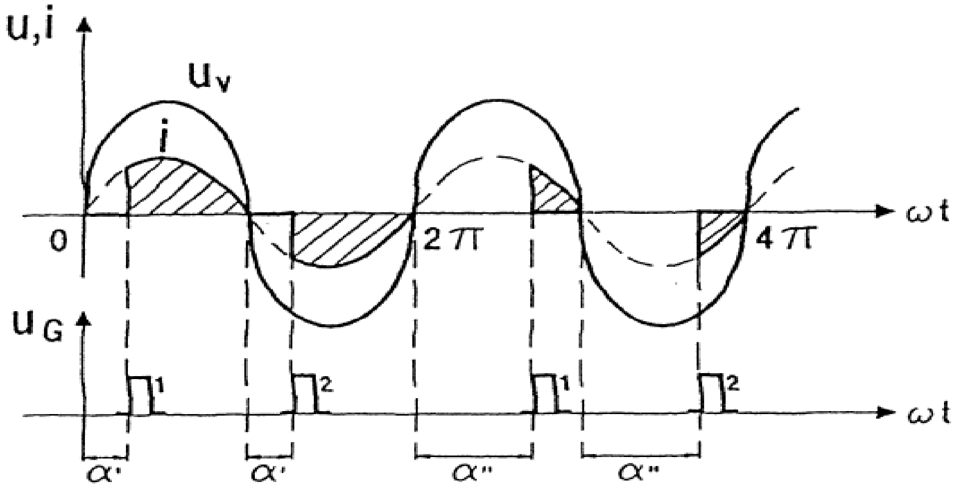


Fig.2 Voltage and current profiles

In the case of an ohmic load, the load current rises to the instantaneous value of the sinusoidal continuous current at the moment of firing angle and then flows in phase with the sinusoidal supply voltage until the zero transition is reached.
The load current can be continuously varied via the control angle α between the maximum value (α = 0°) and zero (α = 180°).
During the conduction phase the supply voltage is connected to the load; during the off-phase it is present at the controller as a reverse voltage.

All the following characteristics values apply to resistive load, neglecting losses in the controller.
Average value of SCR current

$$I_{TAV} = U_{vM}(1+\cos\alpha)/(2\pi R)$$

Rms value of SCR current

$$I_{TRMS} = (U_{vM}/R)[(\pi-\alpha+0.5\sin 2\alpha)/(4\pi)]^{0.5}$$

Rms value of load current

$$I_{RMS} = (2)^{0.5}(I_{TRMS}) = (U_{vM}/R)[(\pi-\alpha+0.5\sin 2\alpha)/(2\pi)]^{0.5}$$

The power transfer characteristic reflects the relationship between the load active power P and control angle α, as illustrated in Fig.3, where $P_o = U^2_v /R$ is the full drive power for the gate control angle $\alpha = 0°$.

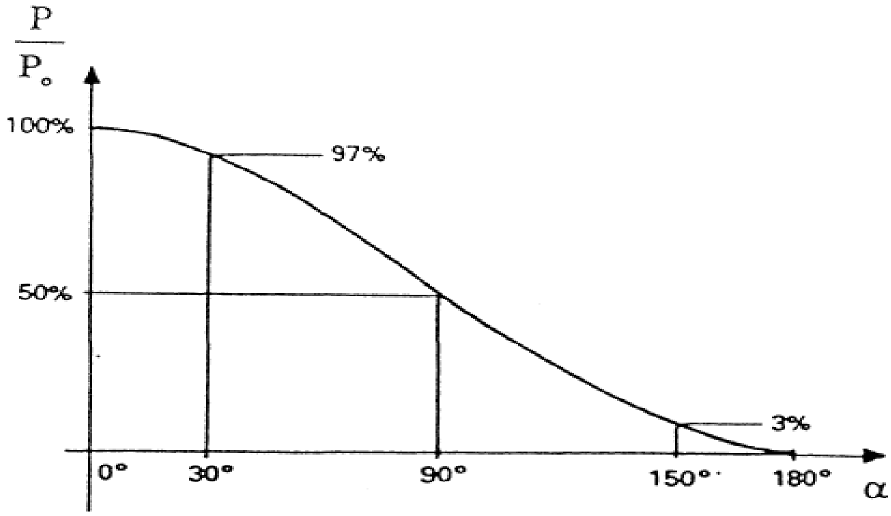


Fig. 3 Power transfer characteristics, AC controller with ohmic load

In addition the power factor PF on the supply side is

$$PF = P/S = P/(U_v I)$$

and results inductive even in circuits with ohmic load.

Ohmic-inductive load
Circuits containing resistance and inductance in series are a load type frequently found in practice.

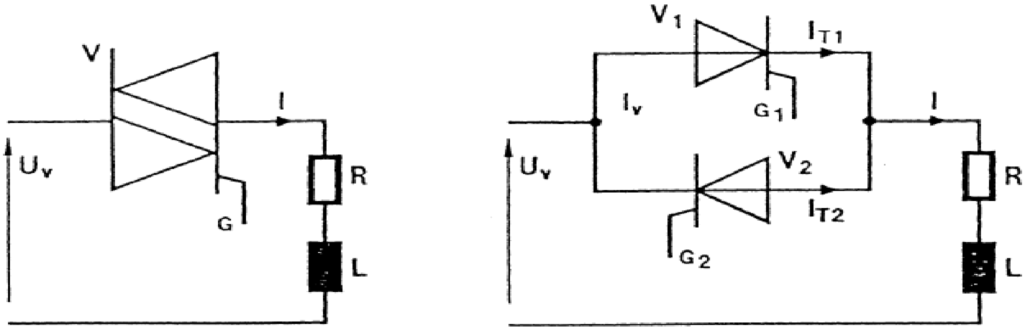


Fig. 4 Single-phase AC controller, ohmic-inductive load

The ohmic-inductive load represents a load case between ohmic and purely inductive load. Full drive is obtained when $\alpha = \varphi = \arctan(\omega L/R)$ and so the controller control range is between $\alpha = \varphi$ and 180°.

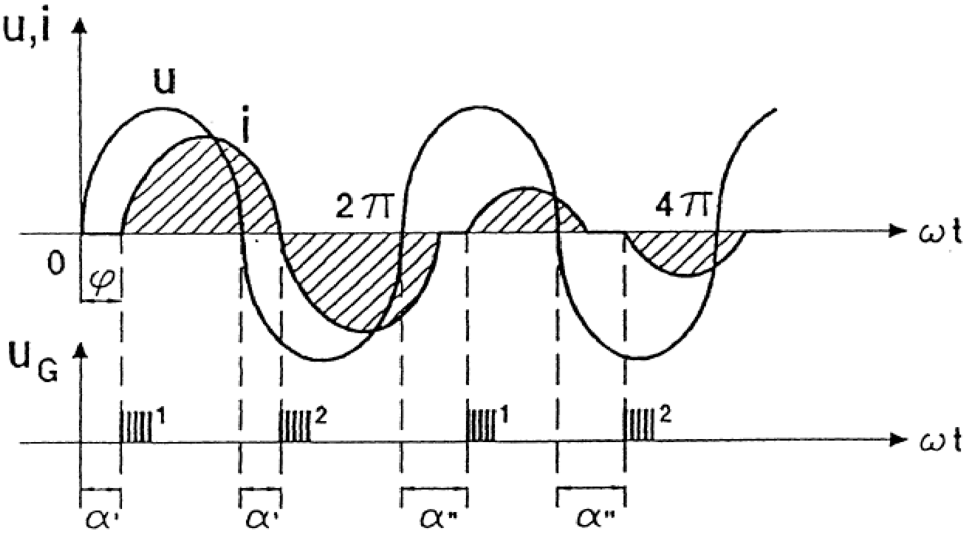


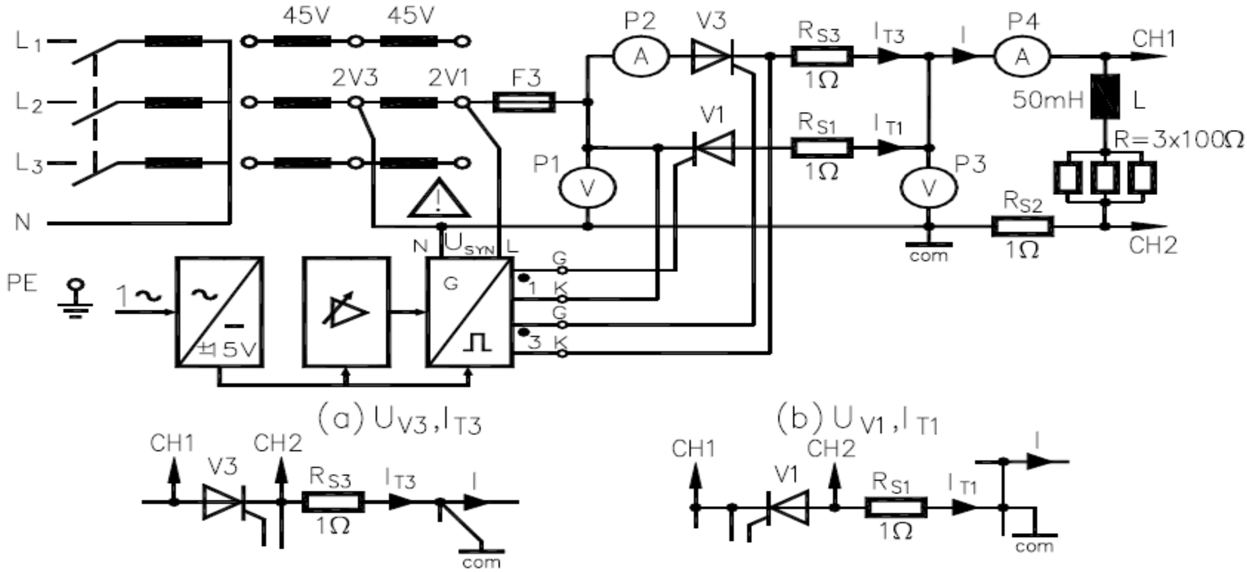
Fig.5 Voltage and current profiles

The load current is no longer sinusoidal but is made up of sinusoidal continuous current and superimposed equalizing current decreasing with the time constant $\tau = L/R$.
During the conduction phase the supply voltage is connected to the load; during the off-phase it is present at the controller as a reverse voltage.

SINGLE-PHASE AC CONTROLLER, OHMIC-INDUCTIVE LOAD

Objectives:
- Recording voltage and current time profiles
- Voltage and current measurements
- Determination of various characteristic data

Circuit diagram



Experiment procedure
Assemble the circuit according with the foregoing topographic diagram, disregarding details (a) and (b) at first.
1) Connections
Connect the voltage reference generator DL2614 and control unit DL2616 to the power supply +15V/0/-15V.
Connect the output U_o of voltage generator to input U_c of the control unit.
Connect the terminals L/N (U_{SYN}) of the control unit respectively to terminals 2V1/2V3 of the transformer.
Connect the pulse transformers 1 and 3 to gate/cathode circuit of the SCRs V_1 and V_3 respectively: socket marked with a dot to the gate.

2) Basic settings
2.1) Voltage reference generator DL2614
EXT/INT switch on INT position
(0/+10V)/(0/±10V) switch on (0/+10V) position.
Set point potentiometer to 0 V.
2.2) Control unit DL2616
Control angle α_o switch on 0° position.
"Pulse shape" switch on train pulse position.
Inhibit voltage UINH = 15 V (open).

3) Voltage and current measurements
Supply the circuit and measure:
3.1) the rms value U_v of the supply voltage by the voltmeter P_1;
3.2) the average value I_{T3AV} and the rms value I_{T3RMS} of the SCR V_3 current by the ammeter P_2.
3.3) the rms value U_{RMS} of the load voltage by the voltmeter P_3;
3.4) the rms value I_{RMS} of the load current by the ammeter P_4.
Enter measured values as a function of the gate angle α in 30° steps between 0° and 180°in the following table.

Control range: Load current lags behind the voltage by an angle φ=arctan ($\omega L/R$) and for this reason the controller can only be controlled between φ and 180°.
Increase the control voltage U_c until the oscilloscope shows the load voltage U and current I in a sinusoidal continuous form; at this point slowly decrease the control voltage U_c until the oscilloscope shows the full drive of both SCRs at the gate angle corresponding to the load phase angle φ.

α (°)	φ	30	60	90	120	150	180
$U_{v\alpha}$ (V)							
$U_{RMS\alpha}$ (V)							
$I_{RMS\alpha}$ (A)							
$I_{T3AV\alpha}$ (A)							
$I_{T3RMS\alpha}$ (A)							

Evaluate the various characteristic data of the controller and compare these with the theoretical values.

4) Recording on the oscilloscope (α = 90°)
4.1) Recording the load U voltage and I current.
Oscilloscope setting
DC coupling; Yt mode. Trigger: AC Line.
Channel 1 (voltage U): 50 V/div; probe x10.
Channel 2 (current I proportional to voltage at shunt R_{S2} = 1 Ω): 2 V/div; probe x1.
4.2) Recording the SCR V_3 voltage U_{V3} and current I_{T3} .
Oscilloscope setting:
Assemble the measuring circuit according with detail (a).
Channel 1 (U_{V3} voltage): 50 V/div; probe x10.
Channel 2 (current I_{T3} proportional to voltage at shunt R_{S3} = 1 Ω): 2 V/div; probe x1.
4.3) Recording the SCR V_1 voltage U_{V1} and current I_{T1} .
Oscilloscope setting:
Assemble the measuring circuit according with detail (b).
Channel 1 (U_{V1} voltage): 50 V/div; probe x10.
Channel 2 (current I_{T1} proportional to voltage at shunt R_{S1} = 1 Ω): 2 V/div; probe x1

EXPERIMENT TEN

FLYBACK CONVERTER

INTRODUCTION

The basic circuit of the flyback converter is shown in the following Fig.1.

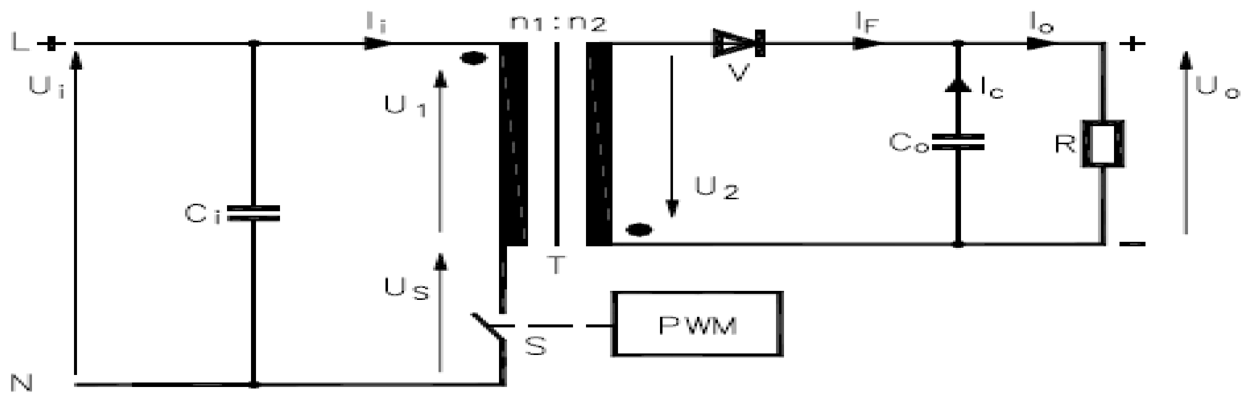


Fig.1 Flyback converter

When the switch S is ON, energy is stored in the primary of the transformer (primarily in the air gap of the ferrite core) while the diode V is reverse biased , the capacitor C_o discharges into the load R. When the switch S is turned off the voltage across the secondary winding rises until the diode V becomes conductive and therefore the energy stored in the transformer causes the current to flow in the secondary and consequently the capacitor C_o recharges. The magnetizing current I_m can have continuous (flyback with trapezoid characteristic) or discontinuous (flyback with triangular characteristic) flow depending on the control or the transformer load. Figure 2 shows the steady-state waveforms for continuous flow where the magnetic current I_m flows continuously.

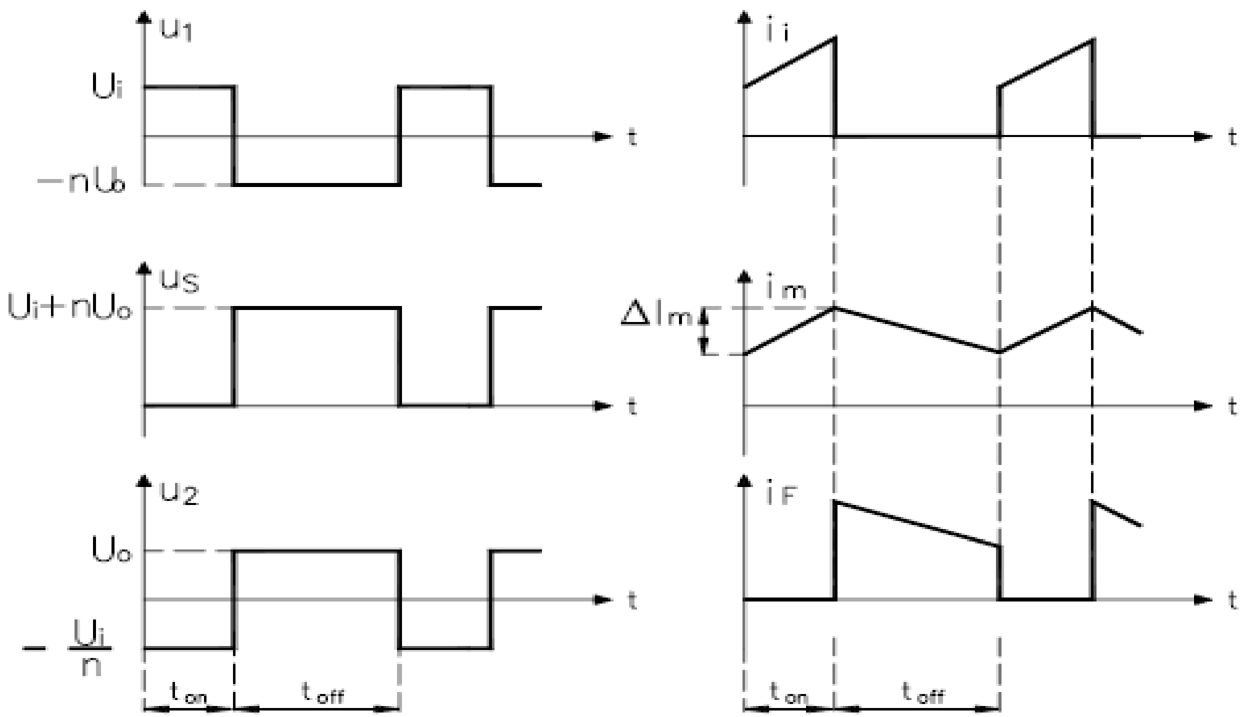


Fig.2 Flyback converter waveforms

During the t_{on} period the primary winding conducts the magnetization current that shows a linear increase equal to
$\Delta I_m = (U_i/L_1)t_{on}$

where L_1 is the inductance of the primary winding.

When the switch S is turned off the voltage across the windings reverses and it results

$u_2 = U_o + U_F \cong U_o$
$u_1 = - nU_o$

where $n = n_1/n_2$ is the transformer ratio.

During the t_{off} period the magnetization current has a linear decrease equal to

$\Delta I_m = (nU_o/L_1)t_{off}$

Since in the steady-state operation the variations of the current I_m must be equal, this implies

$(U_i/L_1)t_{on} = (nU_o/L_1)t_{off}$

and so

$U_{oAV} = (U_i/n)(t_{on}/t_{off}) = U_i(n_2/n_1)(D/(1-D))$

where $D = t_{on}/T$ is the duty cycle

The output voltage changes when the duty cycle is changes and approaches infant as D = 1. This must be prevented by means of a suitable control.

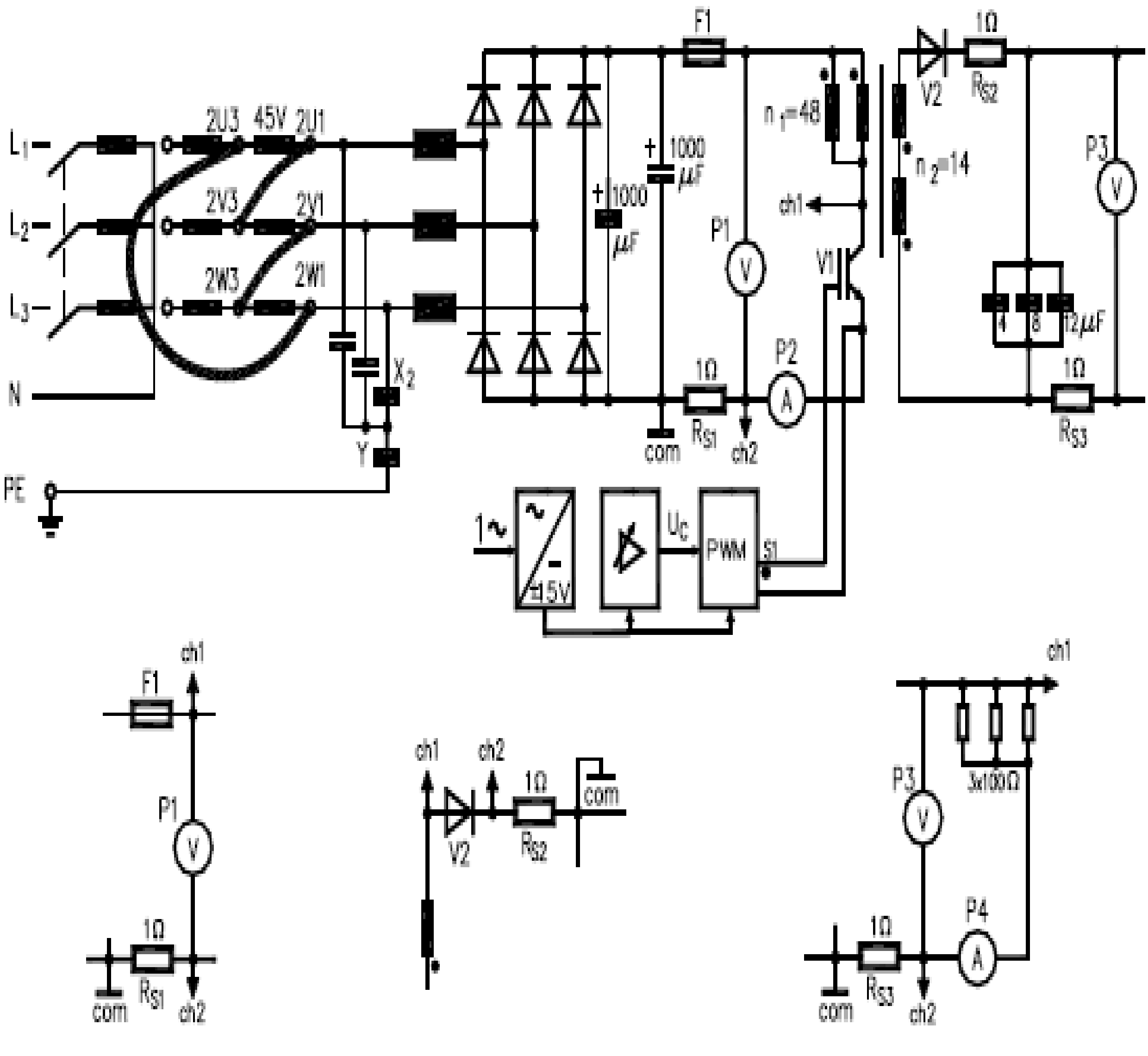
The voltage across the switch during the off interval is

$U_s = U_i + nU_o = U_i/(1-D)$

FLYBACK CONVERTER WITH IGBT (PWM CONTROL)

Objectives:
• Measurement and recording of the input and output variables of the converter.
• Control characteristic.

Circuit diagram



(a)U_i, I_i (b)U_{V2}, I_{F2} (c)U_o, I_o

Experiment procedure
Assemble the circuit according to the foregoing circuit diagram, <u>with the load being three 100 Ω resistors in parallel</u>. <u>Use an external DC power supply instead of the rectified mains</u>.

1) Connections
Connect the voltage reference generator DL2614 and PWM control unit DL2619 to power supply +15V/0/-15V.
Connect the output U_o of voltage generator to input U_c of the control unit.
Connect the pulse output S_1 to gate/emitter circuit of the IGBT V_1: socket marked with a dot to the gate.

2) Basic settings
2.1) Voltage reference generator DL 2614
EXT/INT switch on INT position
(0/+10V)/(0/±10V) switch on (0/+10V) position
Set point potentiometer to 0 V.

2.2) Control unit DL 2619
Connect the PWM output to input U_i of the output amplifier.
Switching frequency f = 15 kHz:
Coarse adjustment "x100", and fine adjustment "150" approx.
Inhibit voltage U_{INH} = 15 V (open).

2.3) Meters
Set AV/AC+DC measurements for voltmeters P1/P3 and ammeters P2/P4.
Voltmeters P1/P3: measuring range 100 V (30 V).
Ammeters P2/P4: measuring range 1 A (0.3 A).

2.4) IGBT
Connect the RCD suppressor circuit.

2.5) Silicon diode
Do not connect the RCD suppressor circuit
3) Initial activation of the converter:
3.1) First, switch on the control unit and only afterwards should the mains transformer be switched on.
3.2) Increase slowly the control voltage U_c = 4 V approx.
Warning
Do not exceed the Uc = 5 V value otherwise the switching transformer core becomes magnetically saturated: this reduces the inductance so that the current rises and triggers the thermal protection of the transformer.
The switching transformer used in this experiment allows the transmission of low power levels as it is designed and optimized for forward converters and only achieves its rated performance with them: nevertheless, the operating principle of the flyback converter can be demonstrated.
Voltage and current measurements
Measure:
4.1) the input voltage U_{iAV} by the voltmeter P1;
4.2) the input current I_{iAV} =IT1 by the ammeter P2;
4.3) the output voltage U_{oAV} by the voltmeter P3;
4.4) the output current I_{oAV} by the ammeter P4.
Enter the measured values in the following table.

U_{iAV} (V)	**I_{iAV} (A)**	**U_{oAV} (V)**	**I_{oAV} (A)**

5) Recording on the oscilloscope

Note
Since the basic instrument set does not normally allow simultaneous measurements, the measures may have to be carried out successively.

5.1) Recording the U_{V1} voltage and I_i current at the IGBT
Oscilloscope setting:
DC coupling; Yt mode. Trigger: Ch2.
Channel 1 (voltage U_{V1}): 50 V/div; probe x100.
Channel 2 (current I_i proportional to voltage at shunt R_{S1} = 1 Ω): 2 V/div; probe x1.

5.2) Recording the U_i voltage and I_i current at the input of the converter
Oscilloscope setting:
Assemble the measuring circuit according with detail (a).
DC coupling; Yt mode. Trigger: Ch2.
Channel 1 (voltage U_i): 50 V/div; probe x100.
Channel 2 (current I_i proportional to voltage at shunt R_{S1} = 1 Ω): 2 V/div; probe x1.

5.3) Recording the U_{V2} voltage and I_{F2} current at the diode V_2
Oscilloscope setting:
Assemble the measuring circuit according with detail (b).
DC coupling; Yt mode. Trigger: Ch2.
Channel 1 (voltage U_{V2}): 20 V/div; probe x100.
Channel 2 (current I_{F2} proportional to voltage at shunt $R_{S2} = 1\ \Omega$): 2 V/div; probe x1.

5.4) Recording the U_o voltage and I_o current at the output of the converter
Oscilloscope setting:
Assemble the measuring circuit according with detail (c).
DC coupling; Yt mode. Trigger: Ch1.
Channel 1 (voltage U_o): 5 V/div; probe x100.
Channel 2 (current Io proportional to voltage at shunt $R_{S3} = 1\ \Omega$): 1 V/div; probe x1.

6) Control characteristics

With $U_i = 66$ V and T = 66 µs, adjust the control voltage U_c in order to obtain the tabulated values (reading on graduated scale) and enter the measured values in the following table (measure t_{on} on the oscilloscope).
Draw the control characteristics $U_o = f(D)$ of the converter and the curve $I_i = f(D)$.

U_c (V)	**t_{on} (µs)**	**D**	**I_{iAV} (A)**	**U_{oAV} (V)**	**I_{oAV} (A)**
1.5	11	0.166			
2	16	0.242			
2.5	17	0.257			
3	20	0.3			
3.5	24	0.364			
4	26	0.394			
4.5	37	0.56			

EXPERIMENT 11

Generation of electric energy from photovoltaic panels and its inlet in the mains network

Photovoltaic (PV) cells work according to a basic physical phenomenon called 'photoelectric effect'. When the energy of photons hitting a semiconductor plate is high enough it can be absorbed by electrons on the surface of the semiconductor plate exposed to such radiation. The absorption of additional energy enables the (negatively charged) electrons to set free from their atoms. The electrons become mobile, and the space which is left behind is filled by another electron from a deeper part of the semiconductor. As a consequence, one side of the wafer (thin slice of a semiconductor material) has a higher concentration of electrons than the other, which creates a voltage between the two sides. Joining the two sides with an electrical wire enables the electrons to flow to the other side of the wafer which is electrical current. PV modules built from PV cells have humble efficiency of approx. 15%.

Characteristics of a solar cell

A solar cell is defined by its *I-V* curve. A typical *I-V* characteristic of the cell for a certain irradiation *G* and a certain fixed temperature *T* is shown in Fig. 1. For a resistive load, the load characteristic is a straight line with slope $I/V=1/R$. the power delivered to the load depends on the value of the resistance only. However, if the load *R* is small, the cell operates in the region M-N of the curve where the cell behaves as a constant current source, almost equal to the short circuit current I_{SC}. On the other hand, if *R* is large, the cell operates on the regions P-S of the curve, the cell behaves more as a constant voltage source, almost equal to the open-circuit voltage V_{OC}.

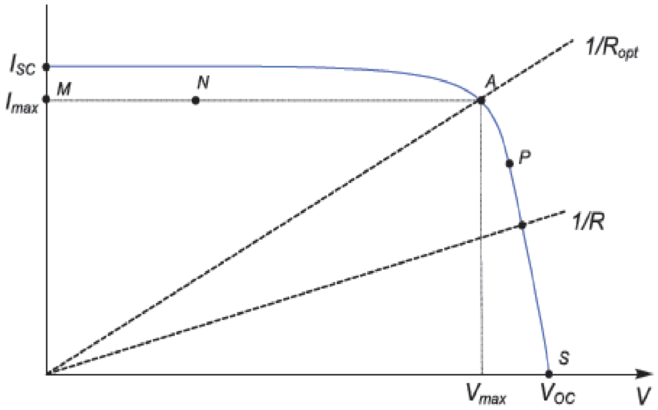


Fig.1

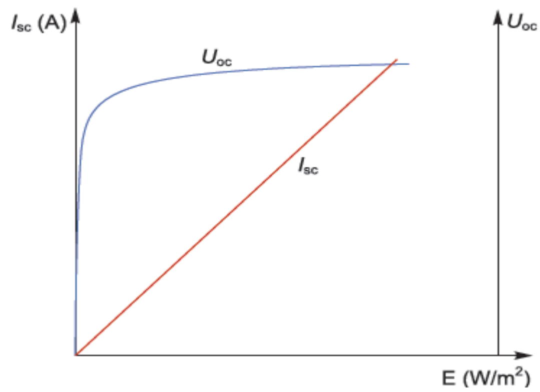


Fig.2

A real solar cell can be characterized by the following fundamental parameters, sketched in Fig. 1:

• Short-circuit current I_{SC} is the greatest value of current generated by a cell. It is produced when voltage is $V = 0$.

• Open-circuit voltage V_{OC} corresponds to the voltage when the cell current is $I = 0$.

$$V_{oc} = \frac{kT}{e} \ln\left(\frac{I_{sc}}{I_o} + 1\right)$$

Where *k* is the Boltzmann constant (1.38 X 10^{-23} J/°K), and *T* is the temperature (°K), *e* is electron charge (1.6 X 10-19 Coul.), and I_O is the saturation current (A)

• Maximum power point is the operating point marked A in the figure, where $P_{max} = V_{max} \cdot I_{max}$

• Maximum efficiency is the ratio between the maximum power and the incident light power.

$$\eta = \frac{P_{max}}{P_{in}} = \frac{I_{max}V_{max}}{AG_a}$$

Where G_a is the irradiation and *A* is the cell area

• Fill factor is the ratio of the maximum power that can be delivered to the load and he product of I_{SC} and V_{OC}

$$FF = \frac{P_{max}}{V_{oc}I_{sc}} = \frac{I_{max}V_{max}}{V_{oc}I_{sc}}$$

The fill factor is a measure of the real *I-V* characteristic. Its value is higher than 0.7 for good-quality cells. The fill factor diminishes as cell temperature is increased. The open circuit voltage increases logarithmically with the irradiation, while the short circuit current is a linear function of the irradiation, as shown in Fig. 2.The dominant effect with increasing cell's temperature is the linear decrease of the open circuit voltage, the cell being thus less efficient. The short circuit current increases with the cell temperature.

Irradiation and Temperature Measurements

Required equipment: Solar panel, DC power source (DL9032), solar panel measuring unit (DL9021)

Exercise 1: Setting the solar panel to the most irradiated position
1. Connect the module according to Fig. 3.
2. Find the position in which the solar panel provides highest irradiation using the built-in angle-meter.
3. Read the solar panel temperature.

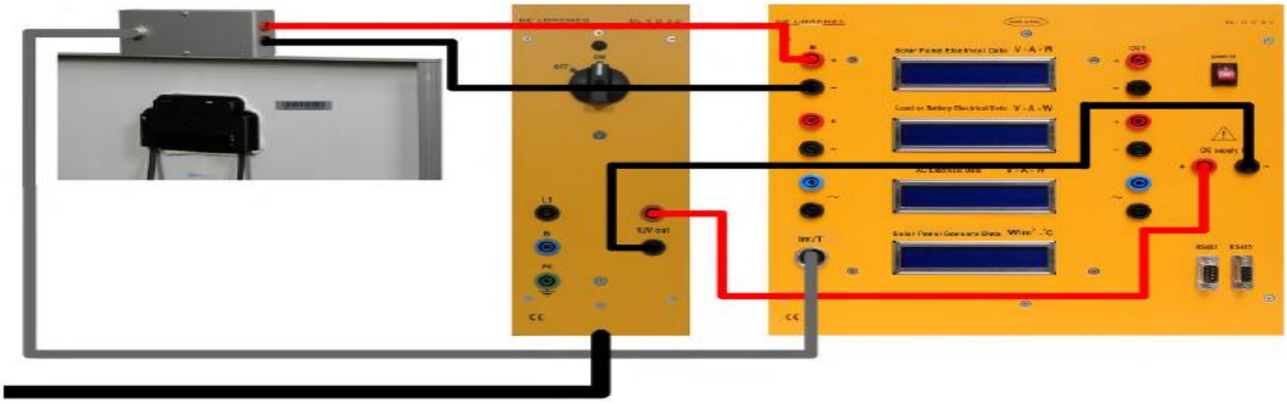


Fig. 3

Exercise 2: Changing the inclination of the solar panel
1. Change the inclination of the solar panel and fill in the following table.
2. Draw the inclination/irradiation graph based upon measurements.

Inclination (°)	0	10	20	30	40	50	60	70	80	90
Irradiation (W/m^2)										

Solar Panel Voltage-Irradiation Curve, Current-Irradiation Curve and Resistance of the Solar Panel

Exercise 1: Obtaining the solar panel voltage-irradiation curve
1. Connect the module according to the Fig. 3.
2. Find the position in which the solar panel provides highest irradiation using the built-in angle-meter.
3. Change the inclination and direction of the solar panel in order to obtain at least 8 different irradiation values (between zero and maximum irradiation value). Fill in the output voltage of the panel for each of them in the table.
4. Draw the voltage-irradiation graph.
5. Find the position in which the solar panel provides highest irradiation again.
6. Measure the open-circuit voltage.

Irradiation (W/m^2)										
Voltage (V)										

Exercise 2: Calculating the inner resistance of the solar panel
1. Connect the module according to Fig.3.
2. Find the position in which the solar panel provides highest irradiation using the built-in angle-meter
3. Change the inclination and direction of the solar panel in order to obtain at least 8 different irradiation values (between zero and maximum irradiation value). Fill in the short-circuit current of the panel for each in the table.
4. Draw the current-irradiation graph.
5. Find the position in which the solar panel provides highest irradiation again.
6. Measure the short-circuit current.
7. Using the open-circuit voltage from point 6 of the previous exercise, calculate the solar panel inner resistance.

Irradiation (W/m^2)										
Resistance (Ω)										

Current-Voltage Characteristics of the Solar Panel

Required equipment: Solar panel, DC power source DL9032, rheostat DL9018, panel measuring unit DL9021

Exercise: Obtaining the solar panel current-voltage curve

The circuit diagram of this exercise is provided in Fig. 4, while Fig. 5 provides a detailed circuit.

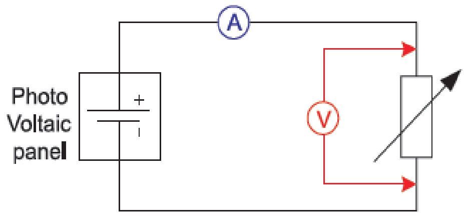


Fig. 4

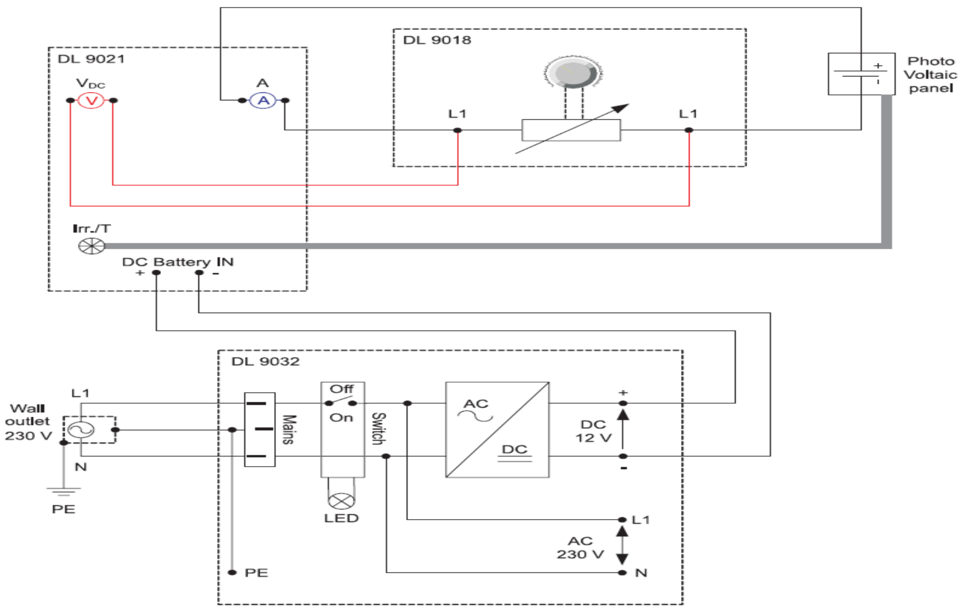


Fig. 5

Connect the modules according to Fig. 5

1. Find the position in which the solar panel provides highest irradiation using the built-in angle-meter.
2. Set the rheostat to the maximum resistance position.
3. Fill in the values of voltage and current into the table.
4. Lower the resistance of the rheostat to app. 90% and fill in the values of voltage and current into the table.
5. Repeat point 4 in 10% steps until reaching the minimum resistance position of the rheostat.
6. Change the inclination and direction of the solar panel in order to obtain app. 75% of the maximum irradiation. Repeat the procedure described in points 2-5.
7. Change the inclination and direction of the solar panel in order to obtain app. 50% of the maximum irradiation. Repeat the procedure described in points 2-5.
8. Change the inclination and direction of the solar panel in order to obtain app. 25% of the maximum irradiation. Repeat the procedure described in points 2-5.
9. Draw the current-voltage graph for all 4 irradiation scenarios.

Resistance of the Rheostat (% of the maximum value)	100	90	80	70	60	50	40	30	20	10	0
Current (A)											
Voltage (V)											

Solar Panel Electricity Delivered to the Mains Grid

DL9013G grid tie power inverter

The main difference between a standard power inverter and a grid tie power inverter is that the latter also ensures that the power supplied will be in phase with the grid power. This allows individuals with surplus power (wind, solar, etc.) to sell power back to utility in the form of net metering or the arrangement local power utility offers. The traditional grid tie inverters are in the high output, about 1-10 kW, they are very heavy and expensive. Therefore, most people interested in green energy generation cannot afford it. DL9013G micro grid tie inverter is very economical, easy to install, convenient and reliable. DL9013G has 12 V solar panel input, ground terminal and AC terminals. Power grid voltage should be connected to "Mains" terminals to ensure that power supplied will be in phase with grid. "Mains" terminals should also be connected to the load (lamp for example) that is supposed to be powered from solar panel connected to the PV input. Power inverter in module DL9013G is programmed to supply load from PV source and surplus energy is sent to the grid. If PV source cannot produce enough energy for the load, then mains grid supplies the load. The result is that the load is always supplied with electrical energy. If "Mains" terminals are disconnected from power grid then Island Protection LED glows red.

Required equipment

Solar panel, DC power source (DL9032), protective module (DL9031), solar panel measuring unit (DL9021), grid tie power inverter (DL9013G), AC measurement module (DL9030)

Exercise: Measuring the electricity delivered to the mains grid

The circuit diagram of this exercise is provided in Fig. 6.

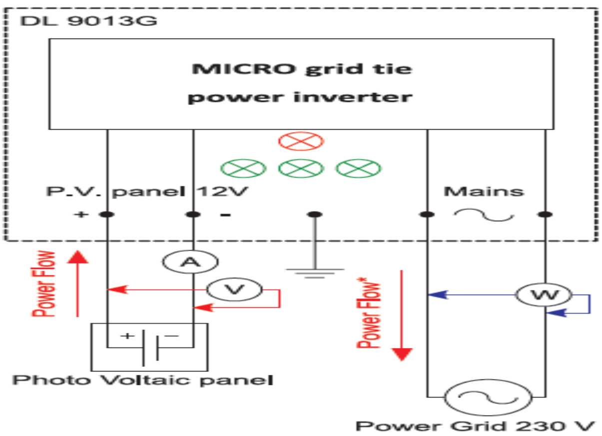


Fig. 6

Connect the modules according to Fig. 6.

1. Find the position in which the solar panel provides highest irradiation.
2. Using DL9030 read the value of electricity being delivered to the mains grid.
3. Fill in this value into the table.
4. Set the panel such that irradiation is app. 90% of its highest value and fill in the appropriate row in the table.
5. Repeat point 4 in 10% steps until reaching the minimum irradiation is reached, i.e. 0 W/m^2
6. Draw the delivered electricity-irradiation graph.

Irradiation (W/m^2)											
Current (A)											
Voltage (V)											
Delivered Power (W)											

Solar Panel Supplying Load

Required equipment

Solar panel, DC power source (DL9032), protective module (DL9031), solar panel measuring unit (DL9021), loads module (DL9017), grid tie power inverter (DL9013G), AC measurement module (DL9030)

Exercise 1: Measuring the electricity produced by the solar panel and delivered/taken from the mains

The circuit diagram of this exercise is provided in Fig. 7.

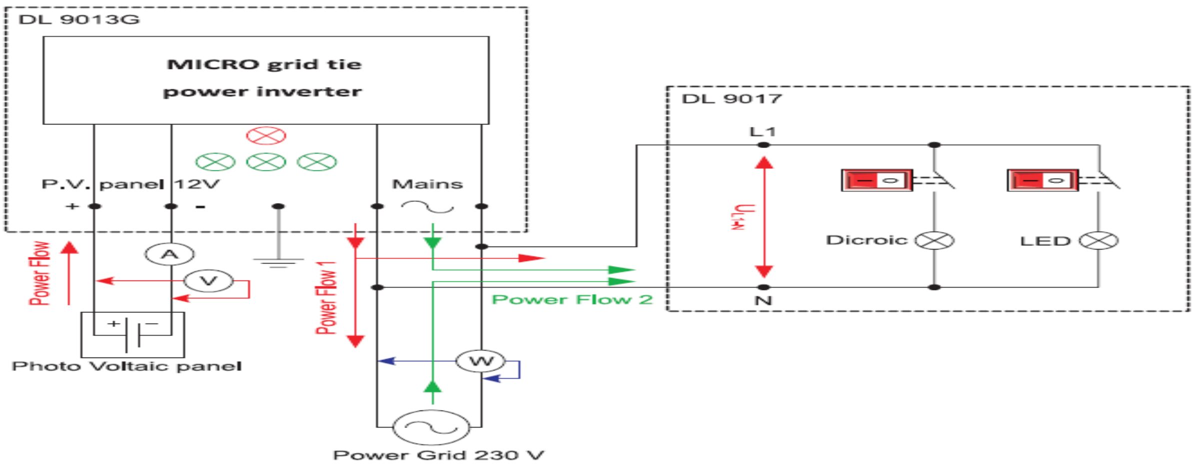


Fig. 7

Connect the modules according to Fig. 7.

1. Find the position in which the solar panel provides highest irradiation.
2. Switch on the LED lamp on DL9017 module.
3. Use DL9021 to read the power produced by the panel and DL9030 to read the power being delivered to the grid.
4. Fill in the produced and delivered electricity values in case of LED lamp turned on in first row of the table.
5. Switch off the LED lamp and turn on the dichroic lamp on DL9017 module.
6. Use DL9021 to read the power produced by the panel and DL9030 to read the power being delivered to the grid.
7. Fill in the produced and delivered electricity values in case of dichroic lamp turned on in first row of the table.
8. Switch on both the LED lamp the dichroic lamp on DL9017 module.
9. Use DL9021 to read the power produced by the panel and DL9030 to read the power being delivered to the grid.
10. Fill in the produced and delivered electricity values in case of both LED lamp and dichroic lamp turned on in first row of the table.
11. Set the panel such that irradiation is app. 90% of its highest value and fill in the appropriate row in the table.
12. Repeat points 2-10 in 10% steps until reaching the minimum irradiation is reached, i.e. 0 W/m^2.
13. Draw the produced electricity-irradiation and delivered electricity-irradiation graphs for all three cases.

Note: DL9021 contains AC wattmeter, and solar panel produced DC power. Therefore, we cannot measure the solar panel power directly. The power is calculated by multiplying voltage and current measured with DL9021 module.

Irradiation (W/m^2)	LED lamp		Dichroic lamp		LED and Dichroic	
	Produced electricity (W)	Delivered electricity (W)	Produced electricity (W)	Delivered electricity (W)	Produced electricity (W)	Delivered electricity (W)

<u>Exercise 2:</u> Measuring the electricity produced by the solar panel, delivered/taken from the mains grid, and the loading of DL9017 lamps

The circuit diagram of this exercise is provided in Fig. 8.

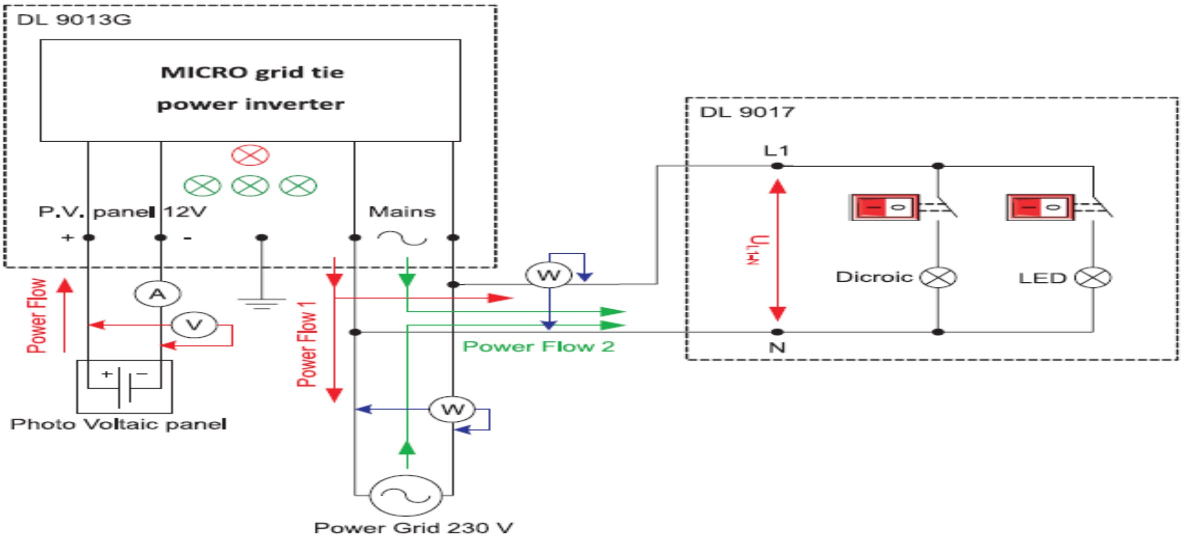


Fig. 8

Connect the module according to Fig. 8.
1. Find the position in which the solar panel provides highest irradiation.
2. Switch on the LED lamp on DL9017 module.
3. Use DL9021 to calculate the power produced by the panel (use ammeter and voltmeter), and to read the value of DL9017 loading. Use DL9030 to read power delivered to the grid.
4. Fill in the table the produced electricity, loading value and delivered electricity to the grid in case of LED lamp turned on
5. Switch off the LED lamp and turn on the dichroic lamp on DL9017 module.
6. Use DL9021 to calculate the power produced by the panel (use ammeter and voltmeter), and to read the value of DL9017 loading. Use DL9030 to read the power delivered to the grid.
7. Fill in the table the produced electricity, loading value and delivered electricity to the mains grid in case of dichroic lamp turned on
8. Switch on both the LED lamp the dichroic lamp on DL9017 module.
9. Use DL9021 to calculate the value of power produced by the solar panel (use ammeter and voltmeter), and to read the value of DL9017 loading. Use DL 9030 to read the value of power delivered to the grid.
10. Fill in the produced electricity, loading value and delivered electricity to the grid in case of both LED lamp and dichroic lamp turned on in the table.
11. Set the panel such that irradiation is app. 90% of its highest value and fill in the appropriate row in the table.
12. Repeat points 2-10 in 10% steps until reaching the minimum irradiation is reached, i.e. 0 W/m^2.
13. Draw the produced electricity- irradiation, delivered electricity-irradiation and loading-irradiation graphs for all three cases.

Irradiation (W/m^2)	LED lamp			Dichroic lamp			LED and Dichroic		
	Produced electricity (W)	Loading (W)	Delivered electricity (W)	Produced electricity (W)	Loading (W)	Delivered electricity (W)	Produced electricity (W)	Loading (W)	Delivered electricity (W)