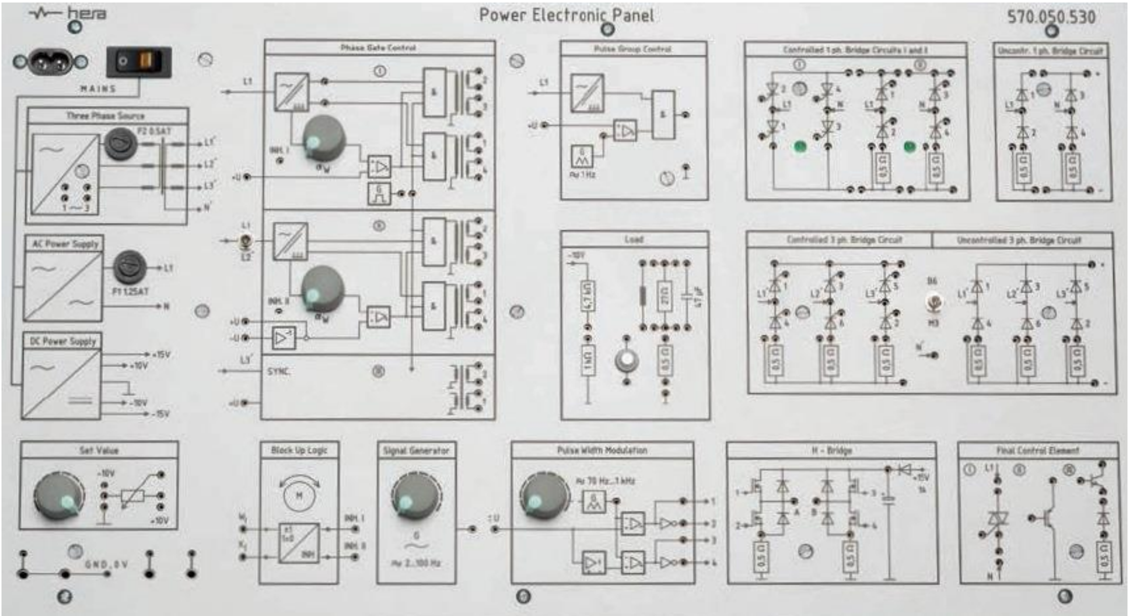

INSTRUCTOR MANUAL

PRINCIPLES OF POWER ELECTRONICS

Article No: 570.058.001

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Preamble

The manual

Principles of Power Electronics

is a support in doing tests in electrics and electric engineering with the hera training systems.

All topics are structured as follows:

- Fundamentals
- Tests, including problem (test) and test procedure

In chapter Fundamentals is a short description to the subject of the test following.
Due to the complexity of the subjects we try not to get too theoretical.

To deepen your theoretical foundations or to accompany your tests, we recommend technical literature from your local bookstore.

To control your answers to the problems and questions a CD with manual and key is included.

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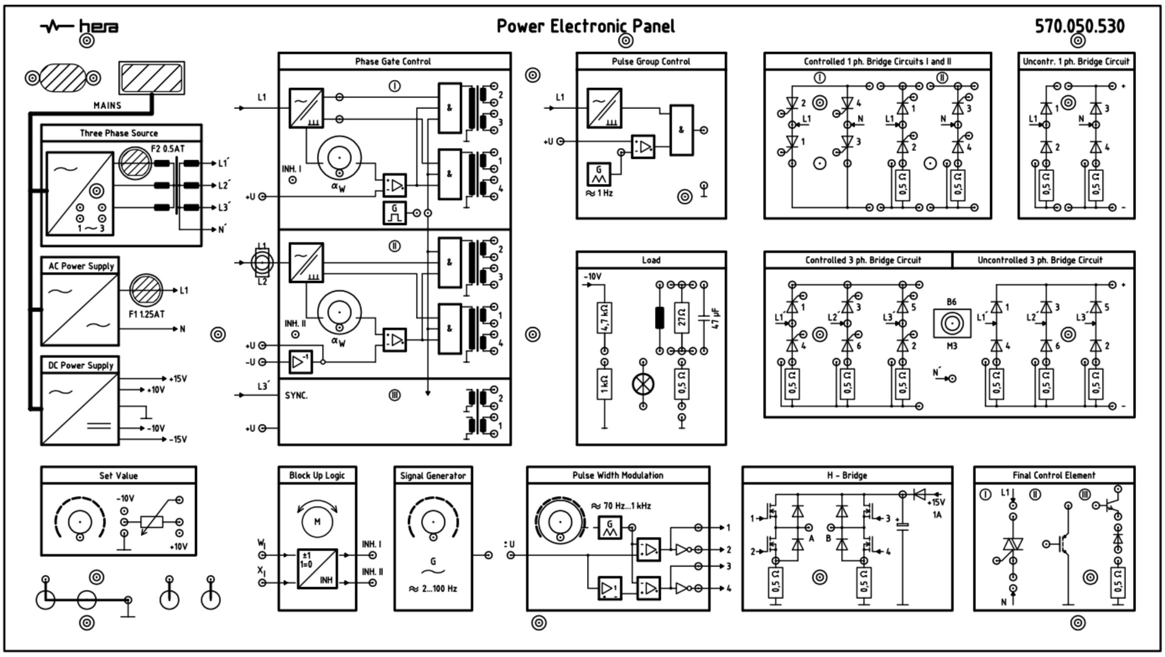
V1.1.0

Directory

1 Fundamentals of Power Electronics

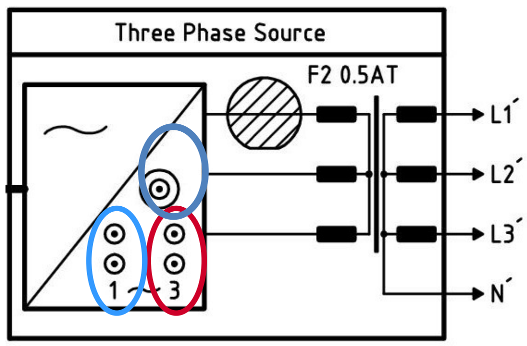
With reference to the Power Electronic Panel 570.050.530

1.1 General Set-Up of the Power Electronic Panel



pic. 1.1 Power Electronic Panel

1.1.1 Voltage Supplies

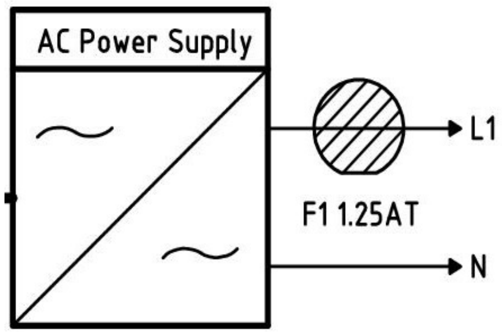


3phase AC Source

The voltage between the phases is approx. 20,5V and between phase and N approx. 12V.

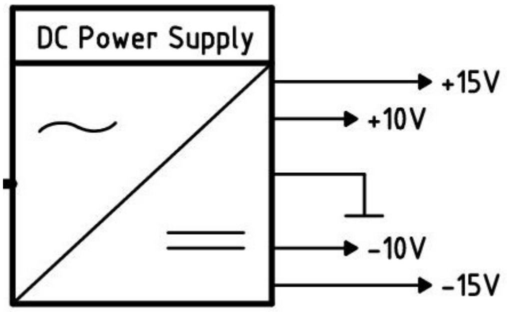
The AC source is galvanically isolated from the other power supplies on the POWER BOARD.

Phase L1' of the AC source lays on a transformer and is directly connected to mains, it is protected by a replaceable fuse F2 (0,5 A T).
If phase L2' and L3' are required, they can be connected at the input of the phase shifter with a 2mm connecting cable (red circle). Phase voltage in L2' and L3' is generated by phase shifter, power amplifier and output transformers with current limiter of approx. 0,5A. As the internal power system is heavily stressed by phase L2' and L3', they should only be connected if needed. This may even avoid errors caused by not required components and its feedback to the operating voltage.



1phase AC Power Supply

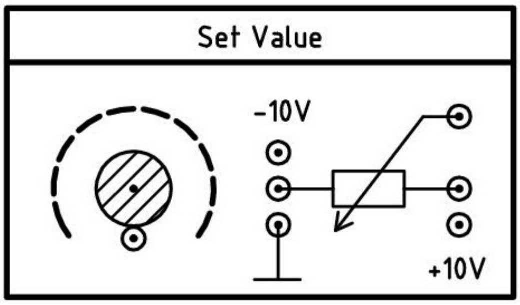
AC power supply for the 1phase inverters (L1, N) (13V AC / 1A) is also galvanically isolated from mains and on secondary side protected by a replaceable fuse F1 (1,25 AT).



DC Power Supply

DC source with 4 fixed voltages, isolated from mains.

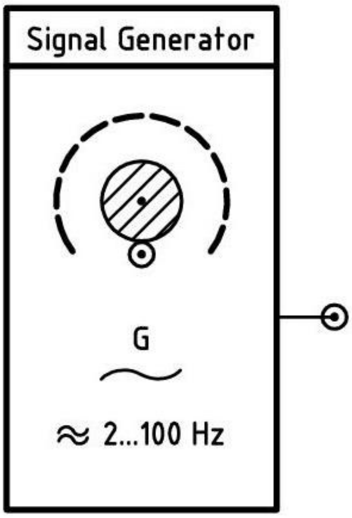
The voltages with reference to earth are +15V, +10V, -10V und -15V.



Control Potentiometer

This potentiometer generates the control voltages +U or ±U for phase gate control, for pulse group control and for PWM. If the reference point is connected to earth, the control voltage +U = 0 ... +10 V is generated, if reference point is at -10 V, control voltage of ±U = -10 V ... +10 V is generated.

Output voltages: 0 ... +10 V, -10 V ... +10 V



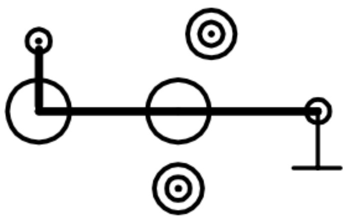
Signal Generator

This signal generator is adjustable by potentiometer for a sinusoidal PWM. The output voltage is not isolated to earth.

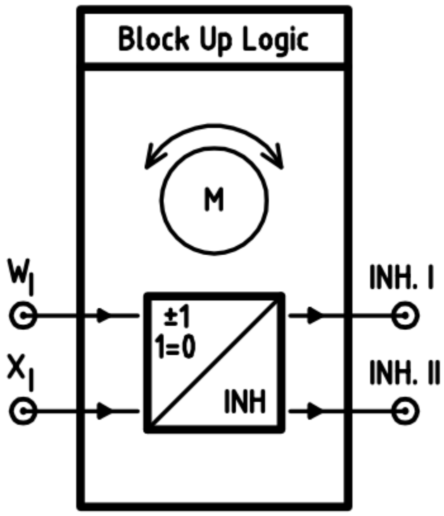
Frequency range: approx. 2 ... 100 Hz

Output resistance: approx. 3,9 Ω

1.1.1.1 Voltages and Reference Potentials

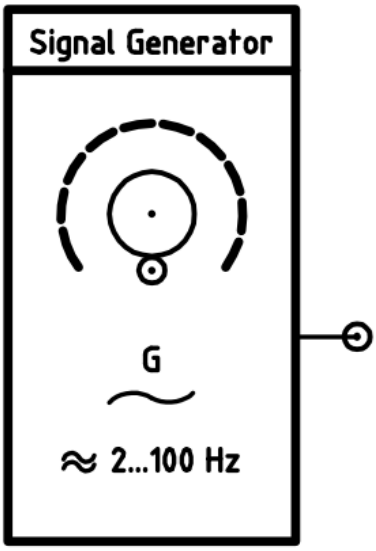


Reference Potential: GND

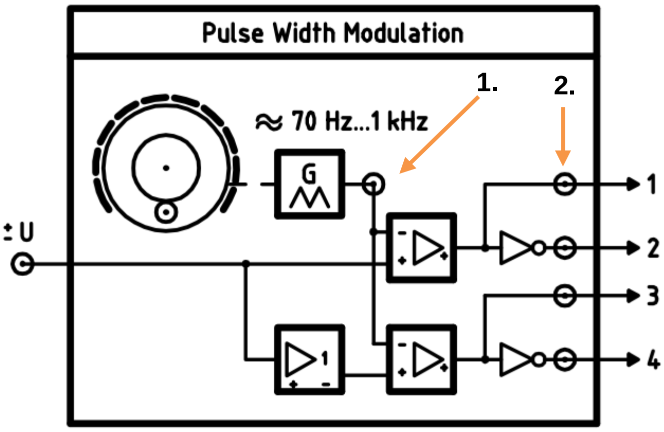


W_I:
Input Voltage: -10V / +10V
Reference Potential: GND
X_I:
Input Voltage: -10V / +10V
Reference Potential: GND

INH.I:
Output Voltage: GND / +15V
Reference Potential: GND
INH.II:
Output Voltage: GND / +15V
Reference Potential: GND

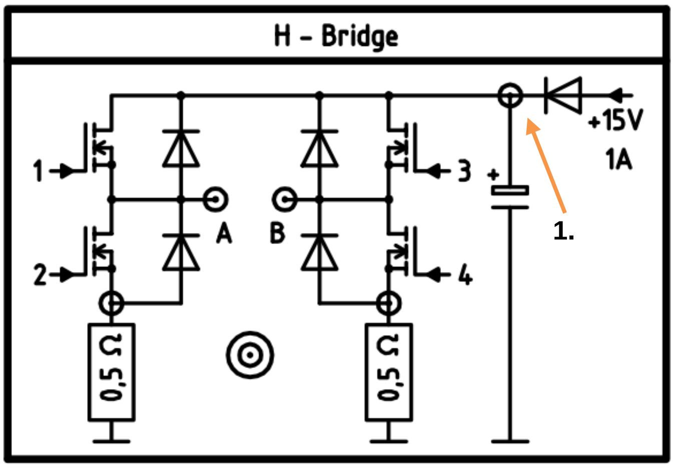


Output Voltage: +10V / -10V
Reference Potential: GND

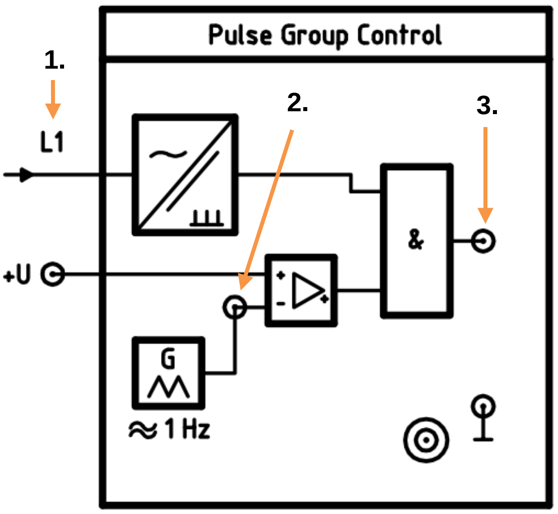


±U$_I$:
Input Voltage: -10 / +10V
Reference Potential: GND

1.
Output Voltage: +10V / - 10V
Reference Potential: GND
2.
Output Voltage: GND / +15V
Reference Potential: GND

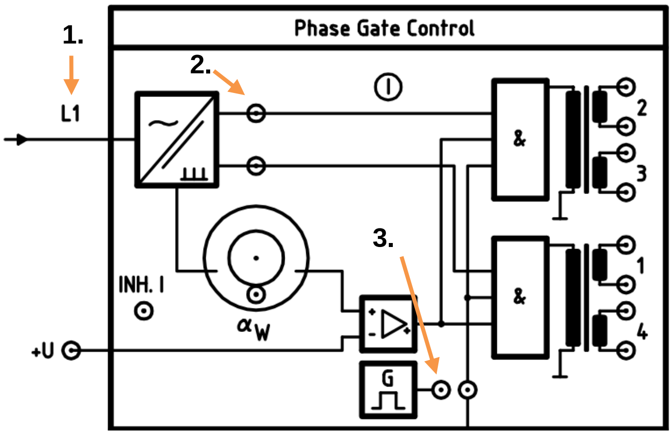


A-B:
Output Voltage: GND / +15V
Reference Potential: GND
1.
Output Voltage: +15V
Reference Potential: GND



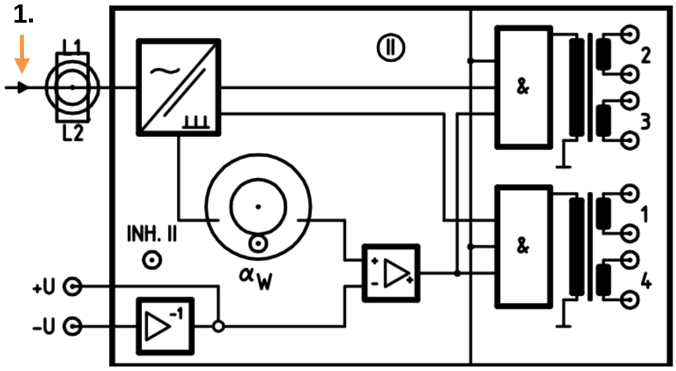
+U$_I$:
Input Voltage: GND / +10V
Reference Potential: GND
1.
For generating the pulse groups the zero passage of L1 is captured. This is done with an isolated transformer, so there is no connection to the DC supply.

2.
Output Voltage: +10V / - 10V
Reference Potential: GND
3.
Output Voltage: +15V
Reference Potential: GND

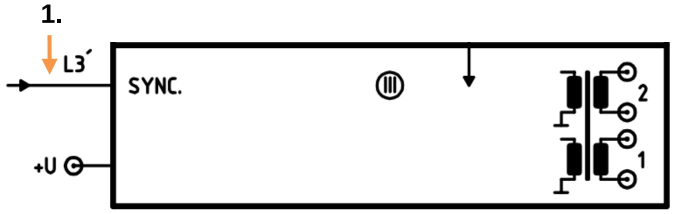


$+U_I$:
Input Voltage: GND / +10V
Reference Potential: GND
1.
To initiate the triggering pulse, the zero-passage of L1 is captured. This is done with an isolated transformer, so there is no connection to the DC supply.

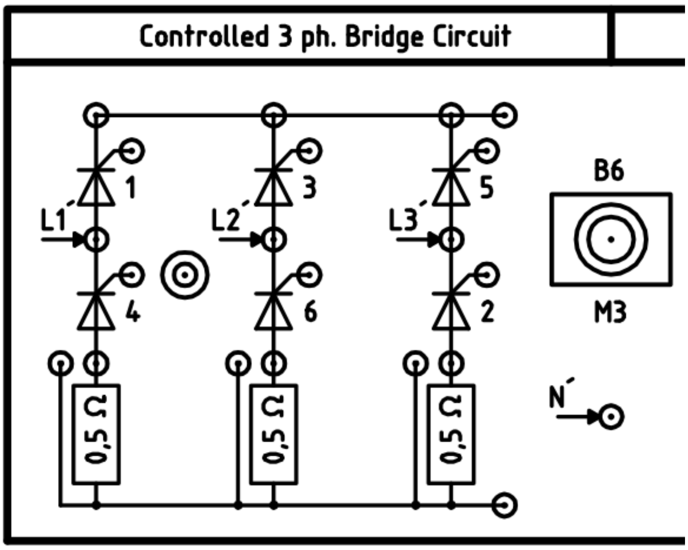
2.
Output Voltage: +15V / - 15V
Reference Potential: GND
3.
Output Voltage: +15V
Reference Potential: GND



$+U_I$:
Input Voltage: GND / +10V
Reference Potential: GND
$-U_I$:
Input Voltage: GND / +10V
Reference Potential: GND
1.
To initiate the triggering pulse, the zero-passage of L1 or L2 is captured. This is done with an isolated transformer, so there is no connection to the DC supply.



$+U_I$:
Input Voltage: GND / +10V
Reference Potential: GND
1.
To initiate the triggering pulse, the zero-passage of L3 is captured. This is done with an isolated transformer, so there is no connection to the DC supply.



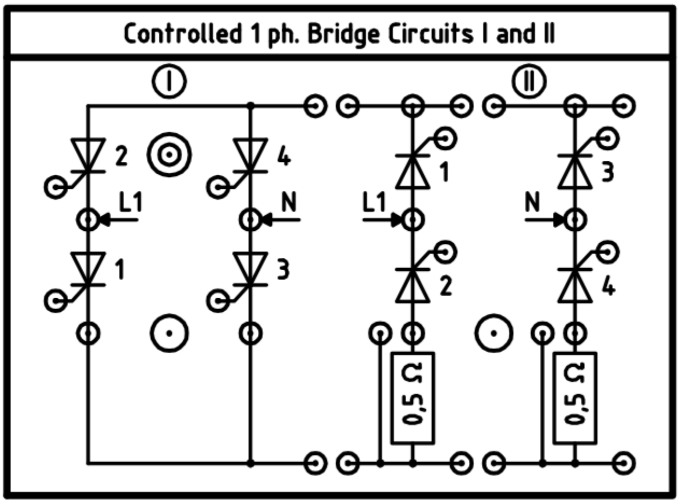
Switch Setting B6:
L1´- N´ & L2´- N´ & L3´- N´:
Output Voltage: approx.5,8V AC

Switch Setting M3:
L1´- N´ & L2´- N´ & L3´- N´:
Output Voltage: approx.11,5V AC

Switch Setting B6:
L1´- L2 & L2´- L3´ & L3´- L1´:
Output Voltage: approx.10V AC

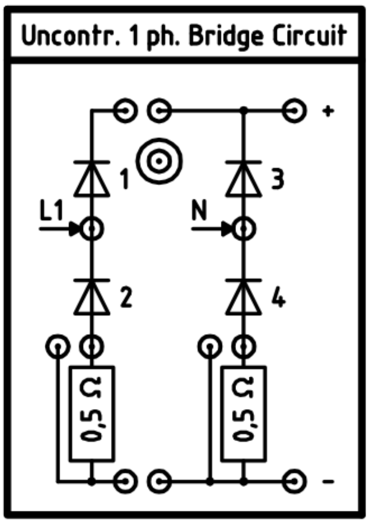
Switch Setting M3:
L1´- L2 & L2´- L3´ & L3´- L1´:
Output Voltage: ca.20V AC

Voltages L1 / N and L1´/ N´ are galvanically isolated.



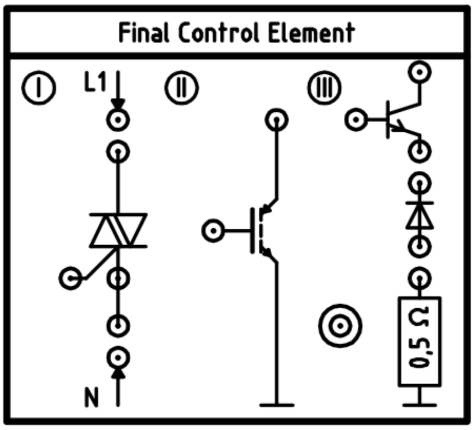
L1 - N:
Output Voltage: approx. 13V AC

Voltages L1 / N and L1´/ N´ are galvanically isolated.



L1 - N:
Output Voltage: approx. 13V AC

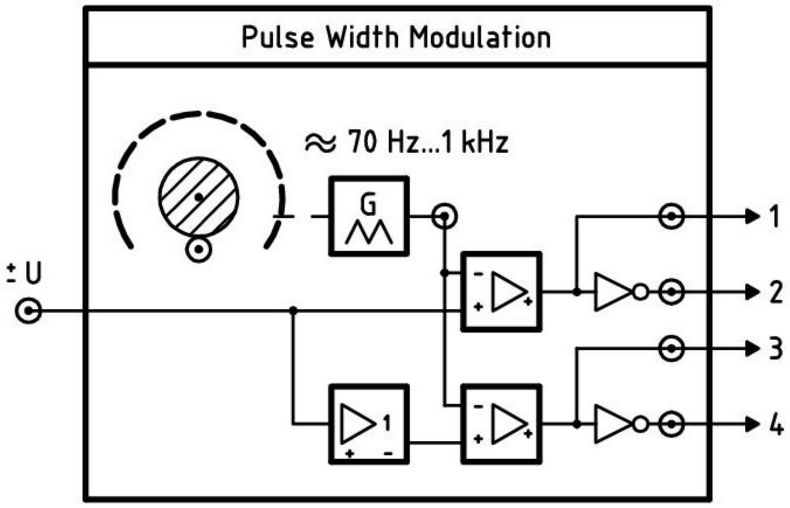
Voltages L1 / N and L1´/ N´ are galvanically isolated.



L1 - N:
Output Voltage: approx. 13V AC

Voltages L1 / N and L1´/ N´ are galvanically isolated.

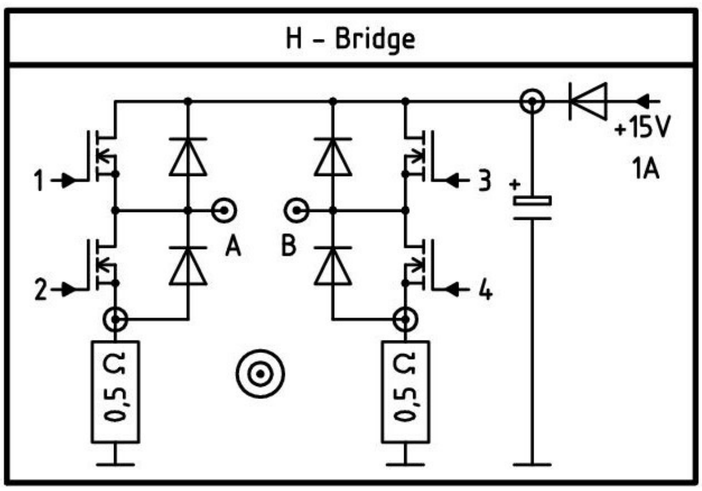
1.1.2 Signal Generator, Load and Electric Components



PWM Signal Generator

The pulse width modulation supplies the control signals to the H-bridge. The modulation of signal 1…4 is basically done by time shifted pulse width modulation. The outputs are internally connected to the MOS-FET-bridge. For examination of the smoothing factor with constant inductivity in a basic frequency is the PWM adjustable.

Input resistance at the inputs ±U:	approx. 10 kΩ
Output resistance at the outputs 1-4:	approx... 3,9 kΩ
Adjustable range of the frequency:	approx. 70 Hz ... 1 kHz



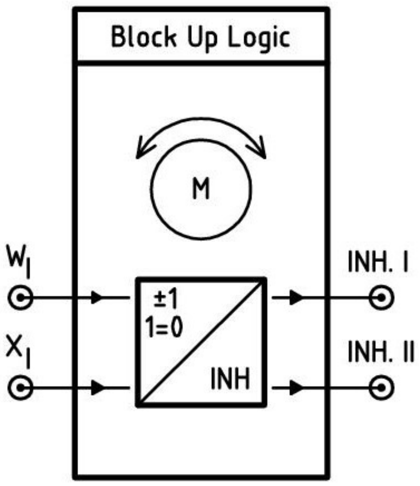
H-Bridge

The H-bridge enables the operation of DC motors in four quadrants mode. It is connected to a capacitive buffered DC link, which is decoupled form the supply unit by diode.

The H-bridge gets its signals internally by PWM. The principle of time-shifted pulse width modulation affects, that the switching frequency appearing at the diagonal bridge section is twice as much as the switching frequency of the capacitors.

The bridge is powered by a DC link with current limitation of approx. 1A. The voltage of this link could be tapped off at the jack, which could also be used for measurements with the GTO thyristor or the bipolar capacitor. The low ohmic output voltages of bridge section A and B could be used for control of the GTO thyristor or of the bipolar capacitors.

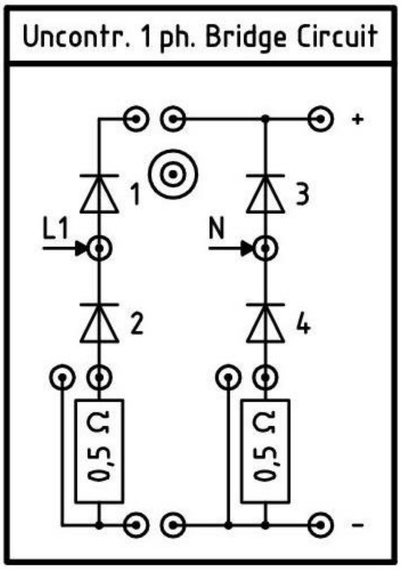
max. permitted current within the diagonal bridge section:	Imax. = approx. 1 A
max. permitted link voltage:	UZK max. = approx. 16 V
tolerance of measuring resistors:	±10 %



Block Up Logic

With the block up logic of the 1phase bridge circuit and a DC motor a four quadrants operation could be realized. With the both inhibit lines (INH) it will choose the right phase gate control I or II and controls the status LEDs of the both 1phase bridge circuits.

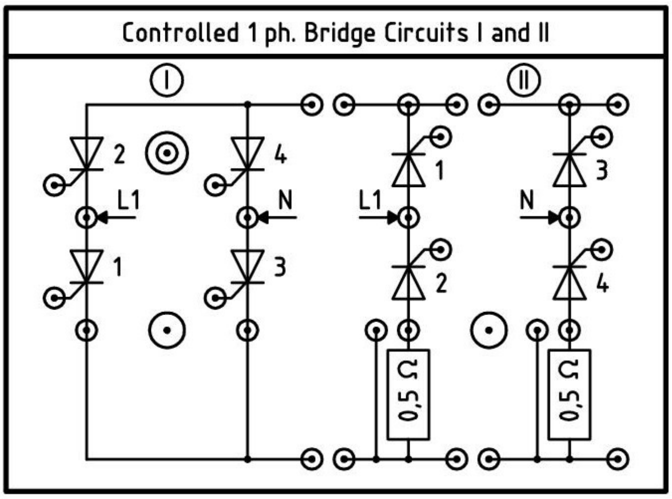
Input resistance at input WI: approx. 10 kΩ
Input resistance at input XI: approx. 10 kΩ



Uncontrolled 1phase Bridge Circuit

This circuit is permanently wired to L1 and N, it is isolated feed by the power transformer. Depending on the experiment, neutral conductor N' or plus or minus jacks could be used for reference point and therefore be connected to ground.
Both bridge sections could be separated, so a half-wave rectifier could be realized with a diode. Bridgeable shunts (0,5 Ω) are integrated into the bridge circuit. For current measurement the 2mm connecting leads have to be removed.

max. permitted current: $I_{max.}$ = approx. 1 A
Tolerance of shunts: ±10 %

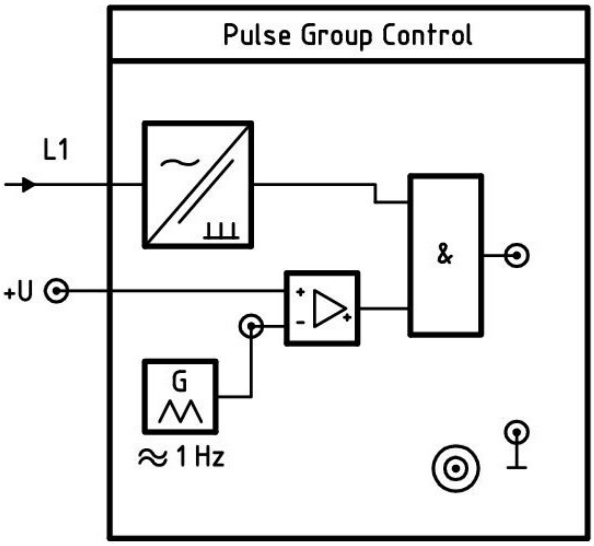


Controlled 1phase Bridge Circuit

Both circuits are permanently wired to L1 and N and are isolated feed by the power transformer. Depending on the experiment, neutral conductor N' or plus or minus jacks could be used for reference point and therefore be connected to ground. Both sections of bridge I could be separated, thus the thyristors could be used separately. With 2mm connecting leads a half-controlled bridge could be realized from a combination of one uncontrolled and one controlled bridge section.

In bridge I, bridgeable shunts (0,5 Ω) are installed. For current measurement the 2mm connectors have to be removed.
The two LEDs are for rotation direction indication of an external panel, which is operated via H-bridge.

max. permitted current:	$I_{max.}$ = approx. 1 A
Tolerance of shunts:	±10 %



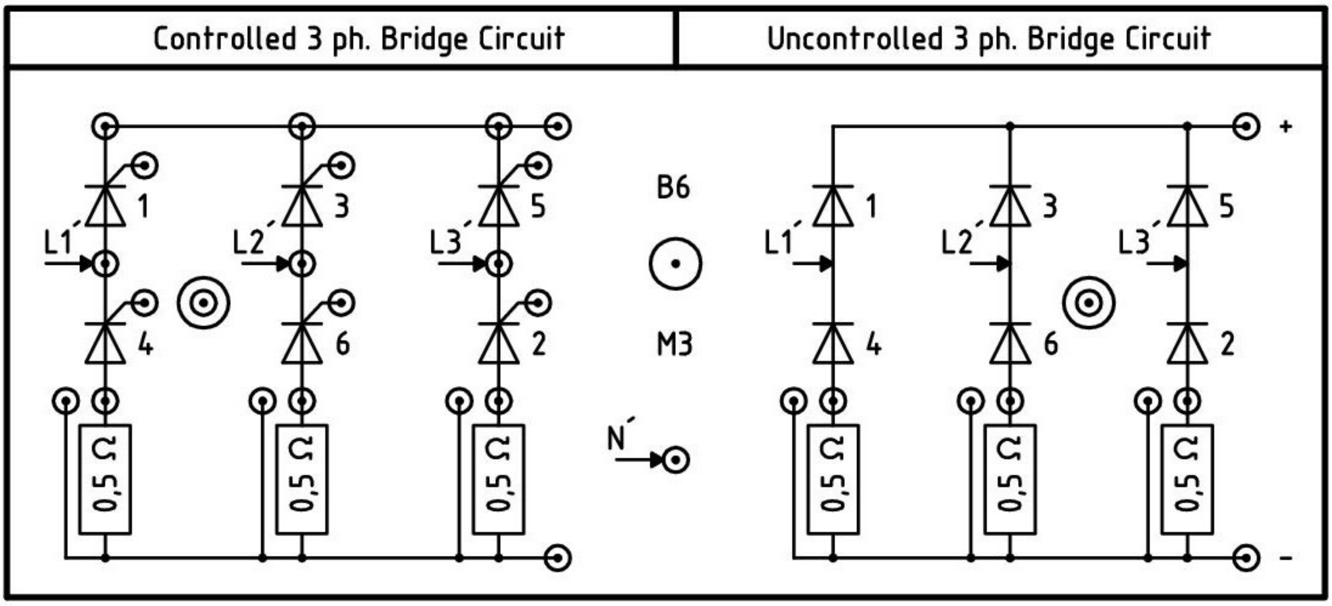
Pulse Group Control

For a complete group of waves, the pulse group control initiates the triggering pulse for the TRIAC, which blocks for a certain number of waves. The TRIAC will get conducting by the beginning of a positive half-wave and hold this for a group of full-waves. Then there is a pause for a group of several full-waves. The triggering pulse is set, so the TRIAC will always trigger when crossing zero. Control voltage U defines the duty cycle „conduct phase – block phase“ of the TRIAC.

Input resistance at the input +U:	approx. 10 kΩ
Basic frequency of the generator:	approx. 1 Hz

CAUTION: In switched state there is no galvanic isolation to ground potential (⊥).

Controlled and Uncontrolled 3phase Bridge Circuit



Controlled 3phase Bridge Circuit

The circuit is firmly connected to L1', L2', L3' and N', it is supplied by a floating AC source. Depending on the test, the neutral conductor N' or the plus – or minus jack could be used for reference. As the output voltage is doubled in a bridge circuit B6, when two circuits M3 (positive and negative bridge section) are connected, the input voltage has to be reduced by half, so the total output voltage is the same. This is done at the switch M3/B6. Bridgeable shunts (0,5 Ω) are integrated into the bridge circuit. For current measurement the 2mm connectors have to be removed.

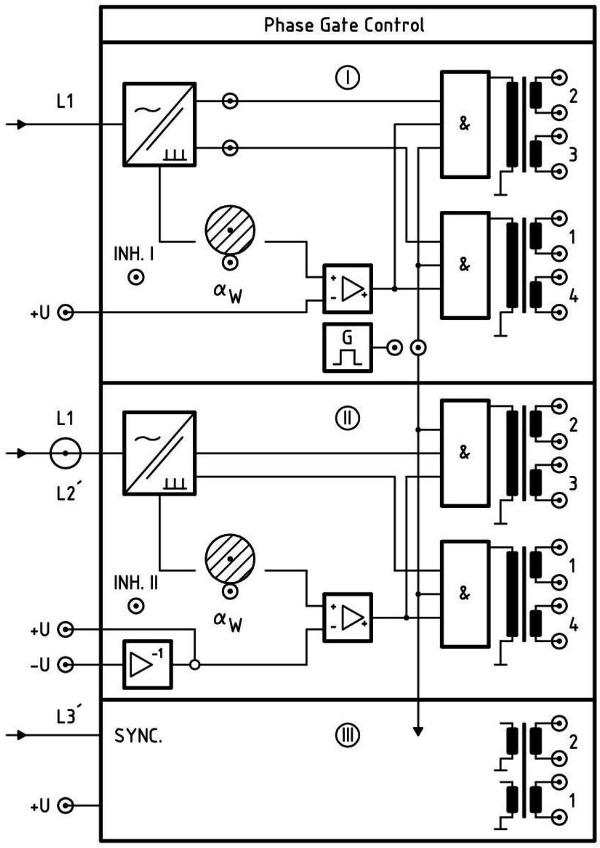
max. permitted current:	$I_{max.}$ = approx. 1 A
Tolerance of shunts:	±10 %

Uncontrolled 3phase Bridge Circuit

The circuit is firmly connected to L1', L2', L3' and N', it is supplied by a floating AC source. Depending on the test, the neutral conductor N' or the plus – or minus jack could be used for reference. As the output voltage is doubled in a bridge circuit B6, when two circuits M3 (positive and negative bridge section) are connected, the input voltage has to be reduced by half, so the total output voltage is the same. This is done at the switch M3/B6. Bridgeable shunts (0,5 Ω) are integrated into the bridge circuit. For current measurement the 2mm connectors have to be removed.

max. permitted current:	$I_{max.}$ = approx. 1 A
Tolerance of shunts:	±10 %

Block with Three Phase Gate Controls



Phase Gate Control I

Phase gate control I is required for tests in the one phase system. It could be utilized for single pulse or multi pulse operation. All essential measuring points are accessible by measuring jacks. In combination with phase gate control II the four- quadrant operation could be realized within a one phase system.
The phase gate control I initiates triggering signals for the controlled rectifier bridge I. The pulse initiators are numbered, so they are directly assigned to the thyristors of the single phase bridge circuit. Always the first (upper) connector of the pulse initiator is connected to the gate of the thyristor. For the operation of the 3phase bridge circuit only the control unit of the pulse initiators 1 and 2 are deployed.
Synchronization of L1 is inphase with L1'. In 3phase operation the phase gate control I supplies triggering signals 1 and 2 for the branch ¼.
For measurement of the phase gate control all signals could be taken at the 2mm jacks.
Each output of the pulse initiator possesses diodes for rectification and for protection in malfunctional circuits. These could be easily replaced if necessary.

Phase Gate Control II

Phase Gate Control II is with extra input for operation with negative set point. A four-quadrant drive is given in combination with the closed-loop system PID-C Motor Panel (Art. No. 570.030.520).
The Phase Gate Control II provides triggering pulses for the controlled rectifier bridge II, synchronization has to be done with L1 (selector L1/L2'). The pulse initiators are assigned to the thyristors by numbers. For 3-phase operation the synchronization has to be switched to L2‘, thus the control sends the triggering signals to branch of 3/6.
Phase angle control I and II are required to realize a four-quadrant mode in a one phase system. Control II also has to be synchronized by phase L1. For this the control voltage of control II has to be inverted after input “U”, so it reacts to negative values.
To adapt the phase control range for each mode of the phase angle, the limits of the inverter for control I and II could be adjusted with the potentiometer αW.

True for control I and II is:

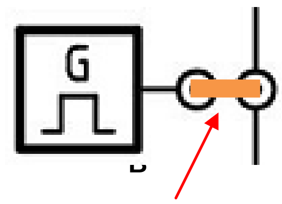
Input resistance for +U and -U:	approx. 10 kΩ
Adjustable range for αW:	approx. 150 ... 180°

Phase Gate Control III

Phase Gate Control III is only applicable for controlled 3phase bridges.
The control supplies triggering pulses for branch 5/2 of the 3phase bridge.
Synchronization is internally done by L3’. The inverter limit is firmly set.

Input resistance for +U:	approx. 10 kΩ
Inverter limit: αW:	approx. 180°

Generator:
If the B6C circuit is applied, always one thyristor of above bridge half and one thyristor of the lower bridge half has to be conducting. Thus it is essential to trigger both thyristors with the first triggering pulse. To activate the circuit anytime, it is essential to bridge from generator to AND-gate. This triggers all connected thyristors with a frequency of approx. 10 kHz (multi-operation).

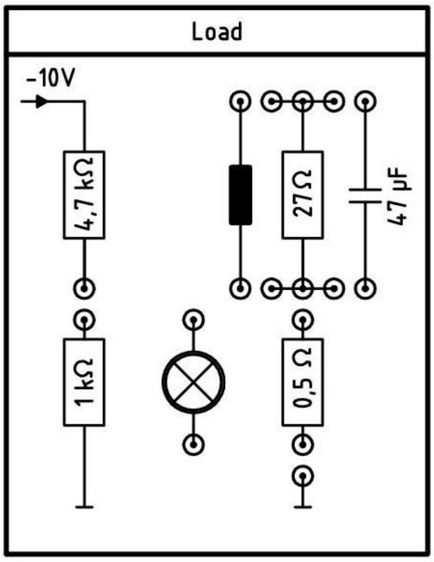


Bridge

Generally:

The pulse initiator transforms the 1phase AC voltage into two time-shifted trigger voltages. The trigger angle (time between trigger pulses) could be modified by potentiometer αW.
Generator and AND-gate are a gate-control, so the signal is transmitted to the initiator to the exact time.

Block with Different Loads



This block offers different loads for connection.

Measuring Resistance
Resistance 0,5 Ω / 2 W for the measurement of currents in load circuits.
Tolerance: ±10 %

Resistance
Resistor connected to ground (1 kΩ / 0,25 W), which is used as divider resistance for the LDR resistor if the temperature and light controlled system is plugged in.

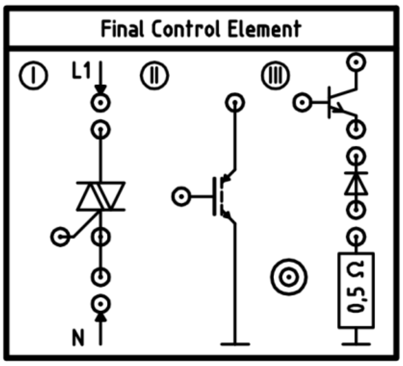
Load
Load resistance 27 Ω / 5 W for test proceedings.

Capacitor
Capacitive load (47 µF) for test proceedings.

Coil
Inductive load (20 mH) for test proceedings.
max. permitted current: Imax. = approx. 1 A

Voltage Divider Resistance
This resistor (4,7 kΩ), with internally applied DC voltage of -10 V, supplements the PTC resistor of the temperature and light controlled system in a way, that temperature alternations are converted into voltage alternations.

Final Control Block



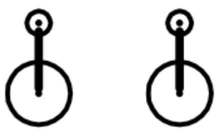
This block offers some more components for the test proceedings.

Bipolar Transistor
Bipolar transistor for tests to PWM and power control.
max. permitted current: $I_{max.}$ = approx. 1 A

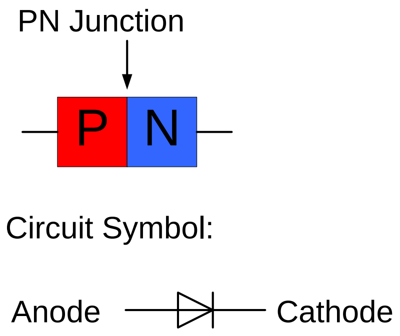
Free-Wheeling Diode
Free-wheeling diode with measuring resistance for tests to PWM.
max. permitted current: $I_{max.}$ = approx. 1 A
Tolerance measuring resistance: ±10 %

TRIAC
TRIAC for the examination of AC power controllers. The TRIAC receives its triggering pulses from the 1phase bridge circuit I or the pulse group control.
max. permitted current: $I_{max.}$ = approx. 1 A

2/4mm Adapters

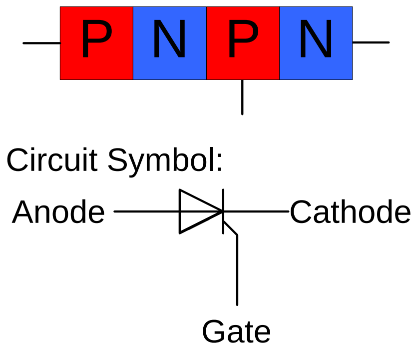


These connectors adapt 4mm measuring leads to 2mm measuring leads.



The Diode:

Diodes are semiconductors with two poles. A semi-conducting diode consists of a semiconductor crystal (Silicon, Germanium), one side is P- and the other side is N-doped. A barrier layer is between the PN junction. The different doped layers are equipped with ohmic contacts and can be connected to different components.
By applying voltage, the blocking effect could be removed or increased. The semiconductor diode blocks in one direction and conducts in the other one.

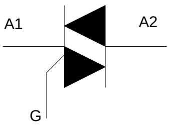


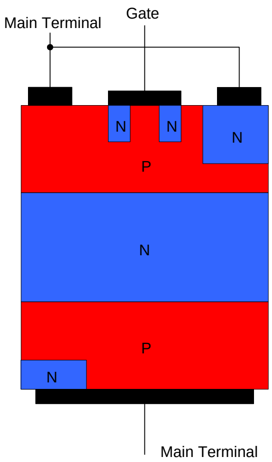
The Thyristor:

Thyristors consist of silicon wafers, which are divided in 4 sections with alternating P- and N-doping. The inner two layers form a barrier layer, which conducts if gate current is applied. Any other PN junctions function like semiconductor diodes.

If AC voltage is applied to a thyristor and it gets a pulse to the gate, it will be conducting until current drops below holding current.

Circuit Symbol





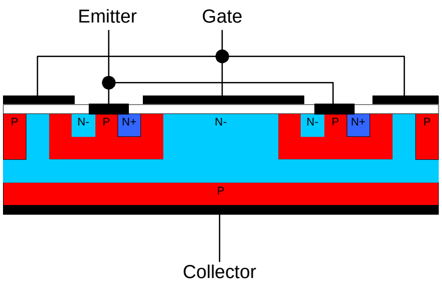
The TRIAC

The TRIAC has a control electrode G (gate) and two main electrodes M1 and M2 (main terminal), the main terminal MT2 is normally directly connected to the housing. So one gate is sufficient for both thyristors, the TRIACs are equipped with two triggering – or auxiliary thyristor controls, so it can be switched into low-resistance state with positive and negative pulse.

A TRIAC could be triggered with positive and negative gate current. However, it has to be considered, that the triggering sensibility depends on the polarity of gate current and the polarity of MT1 and MT2. The triggering types are named I+, I-, III+ and III- with regard to the respective output characteristics. The most sensible triggering characteristics have TRIACs with normally positive gate voltage, means type I+ and III-.

TRIACs are not available for very high currents, for this reason thyristors are still used in the field of power electronics.

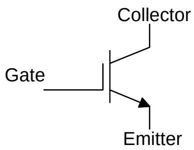
The IGBT



The IGBT (IGBT = Insulated Gate Bipolar Transistor) combines the advantages of power-field effect transistors and bipolare transistors.

powerless control
good conductance

Circuit Symbol



1.2 Details to Tests

The tests with the Power Electronic Panel are to deepen and check the acquired knowledges from the theoretical part. All necessary circuit diagrams are shown in the tests.

Switching of Individual Components

If certain components e. g. diodes, should be switched into present circuits, they have to be individually selected at the Power Electronic Panel, if not specified in the circuit diagram.

Three Phase Source

Make sure to select the correct phase mode for each of the tests. The jumper has to be placed at the correct position. For 3phase operation the jumper has to be in position “3”, for 1phase operation the jumper has to be in position “1”.

1.2.1 Measurement with the Oscilloscope

Earth contact (reference potential) of all input jacks (measuring sockets) are interconnected at the oscilloscope.
If the oscilloscope is powered by mains, there is also a connection between earth and protective conductor. As the measuring voltages of the panel are floating, there is no need to operate the oscilloscope at an isolated transformer.

If more voltage curves have to be examined, you have to make sure that the set-up is not short-circuited due to common earth. For this reason there should be just one earth connection from oscilloscope to test set-up

If oscilloscope settings for signal presentation are stated, e.g. voltage value (V/div. = Volt per division), you have to take these. If no settings are given, you have to choose own values and add to the chart, so the curve progression of each parameter could be clearly indicated.

Due to low-voltage operation, high-frequency peaks may occur when triggering the thyristor. If measuring instruments of latest technology are applied, you should switch to „Hi Resolution” (or similar) mode, so those peaks are not measured. This may simplify reading the diagrams.

1.3 Arithmetic Average and Root Mean Square

Normally the effective value of a rectifier is stated with the AC input voltage, while the output voltage is stated with the arithmetic average (DC part).

Arithmetic Average

The arithmetic average (linear average) indicates the DC part of a mixed AC/DC voltage. The arithmetic average of AC voltage is 0 V. The mathematical definition of the arithmetic average is the quotient from the total of all individual values and the number of individual values.

Root Mean Square

The effective value (RMS) is the root mean square of a time-variable signal. This effective value indicates the value of a DC voltage, which converts in the same time the same amount of energy (power) at an ohmic load. The root mean square is affected by the peak value and the curve form.

1.3.1 The Choice of Suitable Measuring Instruments

For correct measurements, you have to choose suitable measuring instruments for each application.

Measurement of Root Mean Square of Sinusoidal Voltages and Currents

- Moving Iron Instruments
- Multimeter with Root Mean Square (RMS)
- Thermo-Cross with DC Voltage Movement
- Measuring Instrument with Moving Coil in the Alternating Range

Measurement of Root Mean Square of NOT Sinusoidal Voltages and Currents

- Moving Iron Instruments
- Multimeter with Root Mean Square (RMS)
- Thermo-Cross with DC Voltage Movement

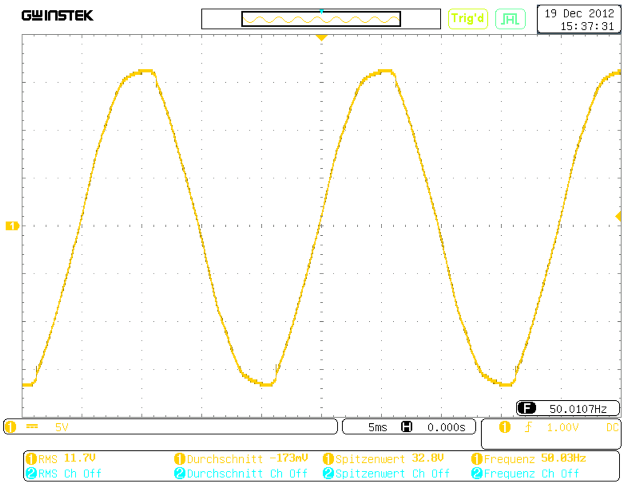
Arithmetic Average of Sinusoidal and NOT Sinusoidal Voltages and Currents

- Moving Iron Instruments
- Standard Multimeter in DC Ranges
- Oscilloscope

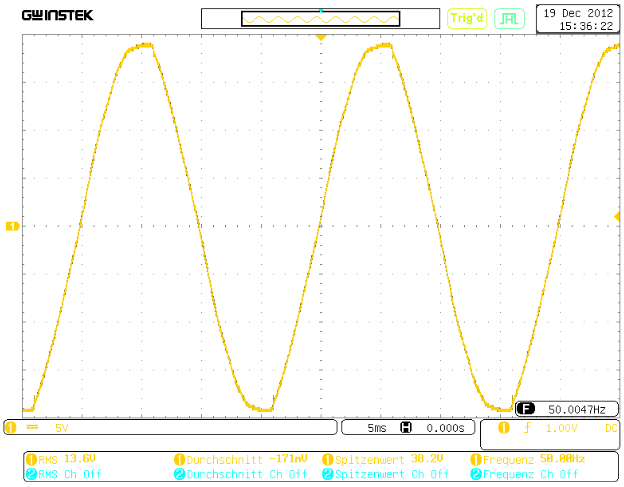
1.3.2 Controlling the Input Voltages without Load

Before each test, the input voltage should be measured and compared.

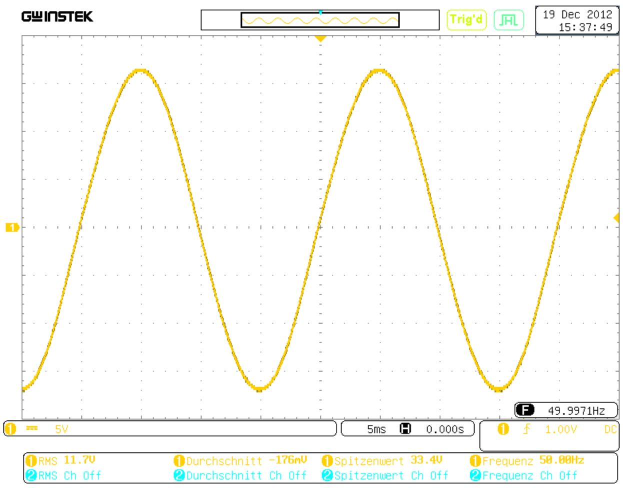
Caution! Selector Switch B6-M3 must be at M3!



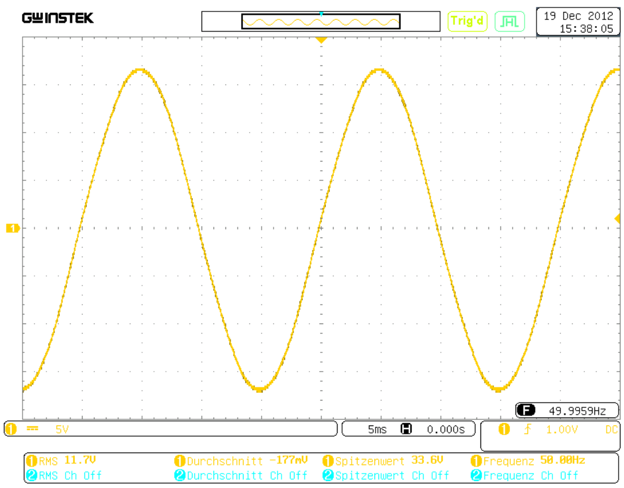
L1 - N



L1‘ – N‘



L2‘ – N‘



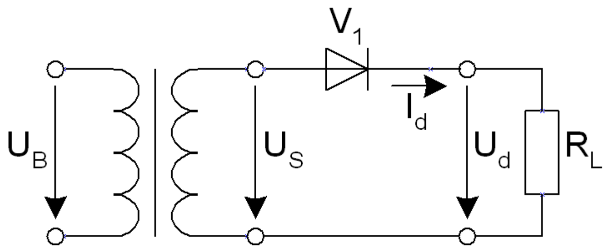
L3‘ – N‘

2 Uncontrolled Rectifier

2.1 Uncontrolled Single-Pulse Center Tapped Circuits M1U

For the conversion of AC and DC current, the blocking and conducting characteristics of diodes could be used. The simplest kind of rectification is done with just one diode.

Circuit:



pic. 2.1.0 M1U circuit

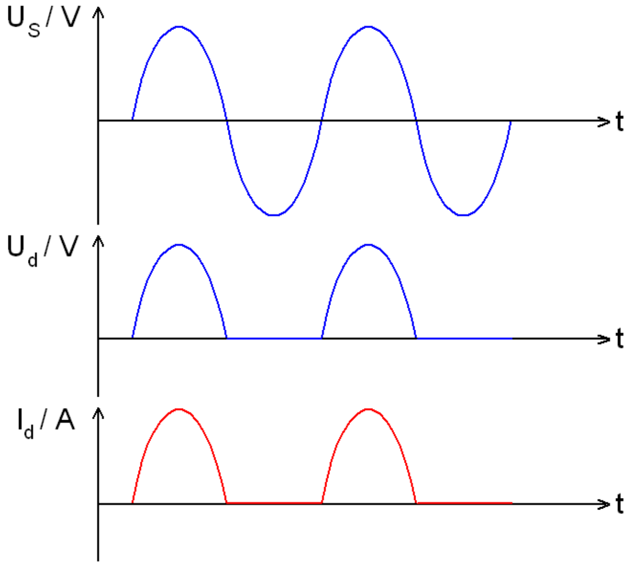
Function:

If the applied voltage U_S exceeds the threshold voltage of the diode V_1, it will conduct. In the phase of conduction, the current I_d passes the diode and the load resistor R_L. If the applied voltage U_S drops below the threshold voltage of the diode V_1, the diode blocks and electrical current is interrupted.

Current I_d flows only at the positive half-wave of the supply voltage U_S. The amplitude of the current is dependent on the load resistor R_L.

Signal Curve:

The form of the signal curve I_d is identical to U_S.



pic. 2.1.0.1 signal curve

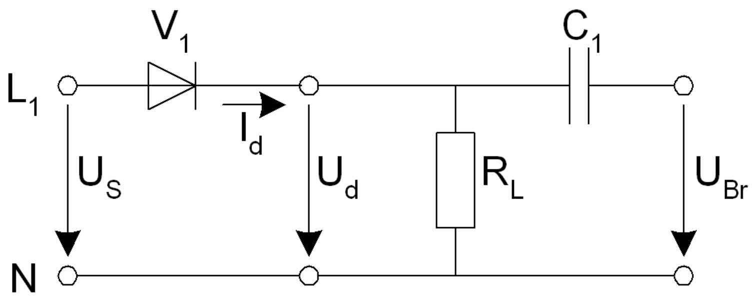
Ripple

The ripple w (stated in %) is significant for the quality of a rectifier circuit. The ripple shows the ratio of ripple portion (effective value of ripple voltage $U_{Br\,eff}$) and DC portion (arithmetic average $U_{d\,ar}$), it is calculated as follows:

$$w = \frac{U_{Br\,eff}}{U_{d\,ar}}$$

Root Mean Square Ripple Voltage

For determination of the ripple voltages' RMS, it is essential to separate the DC voltage from the rectifiers' output voltage U_d. The simplest way to do so is with a capacitor (C_1) at the output of the circuit.



pic. 2.1.0.2 circuit for ripple voltage measurement

Pulse Rate

The pulse rate p often is stated as additional quality criteria for rectifier circuits. This indicates the frequency of ripple voltage f_{Br}.

The pulse rate indicates the number of DC blocks occurring in one period of the applied AC voltage.

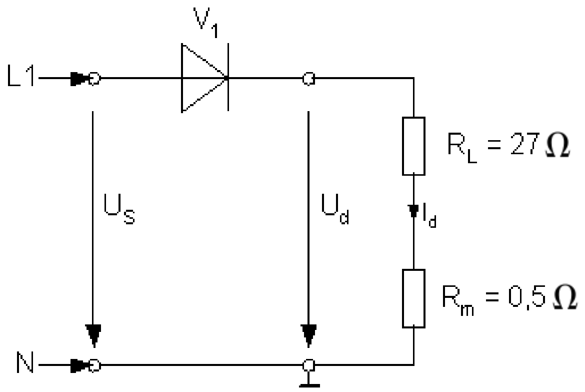
2.1.1 Test 1

Currents and voltages in uncontrolled single-pulse center tapped circuits M1U at **ohmic load**.

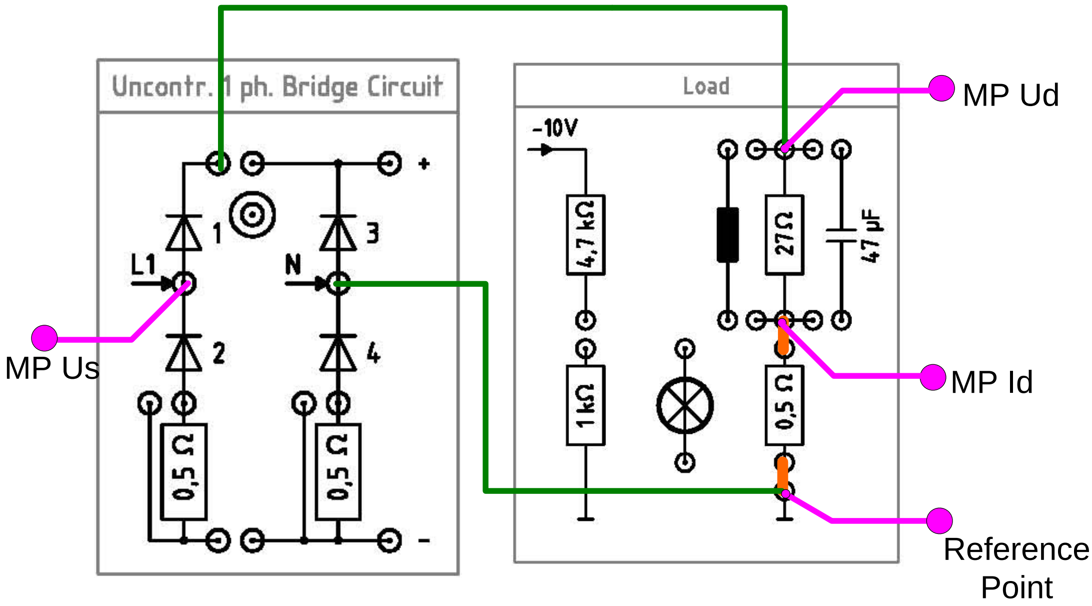
Test Configuration & Test Procedure

- Build up the circuit in pic. 2.1.1.0 with your Power Electronic Panel pic. 2.1.1.1.

.



pic. 2.1.1.0 circuit

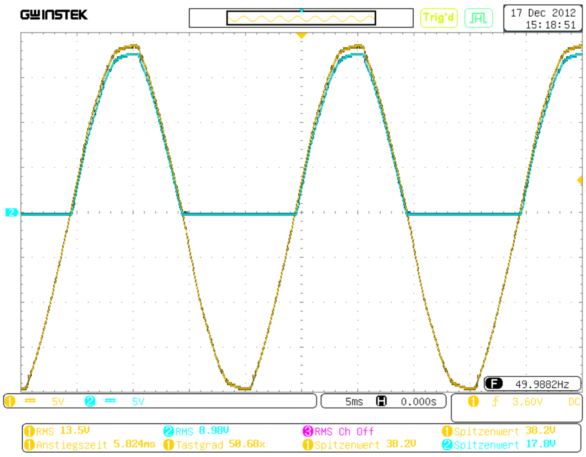


pic. 2.1.1.1 circuit at Power Electronic Panel

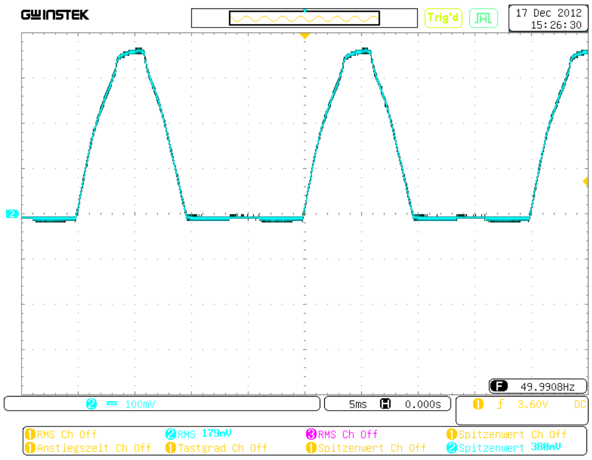
- Trigger the oscilloscope internally to mains (line/~).

- Measure following parameters with the oscilloscope:
  - Mains Voltage U_S,
  - Output Voltage of the Rectifier $U_{d,}$,
  - Output Current I_d (voltage drop across R_m)

- Draw the curves into pic. 2.1.1.2. and pic. 2.1.1.3.



pic. 2.1.1.2



pic. 2.1.1.3

Oscilloscope settings::

Mains Voltage U_S: 5 V / div.
Output Voltage U_d: 5 V / div.
Time t: 5 ms / div.

Oscilloscope settings:

This oscillogram requires current setting to 0,2 A / div. (requirement R_m = 0,5 Ω). Calculate the set value.

U = R × I = 0,5 Ω * 0,2 A / div
= 0,1 V / div <=> 0,2 A / div.

Output Current I_d: 0,2 A/div. = 0,1V/div.

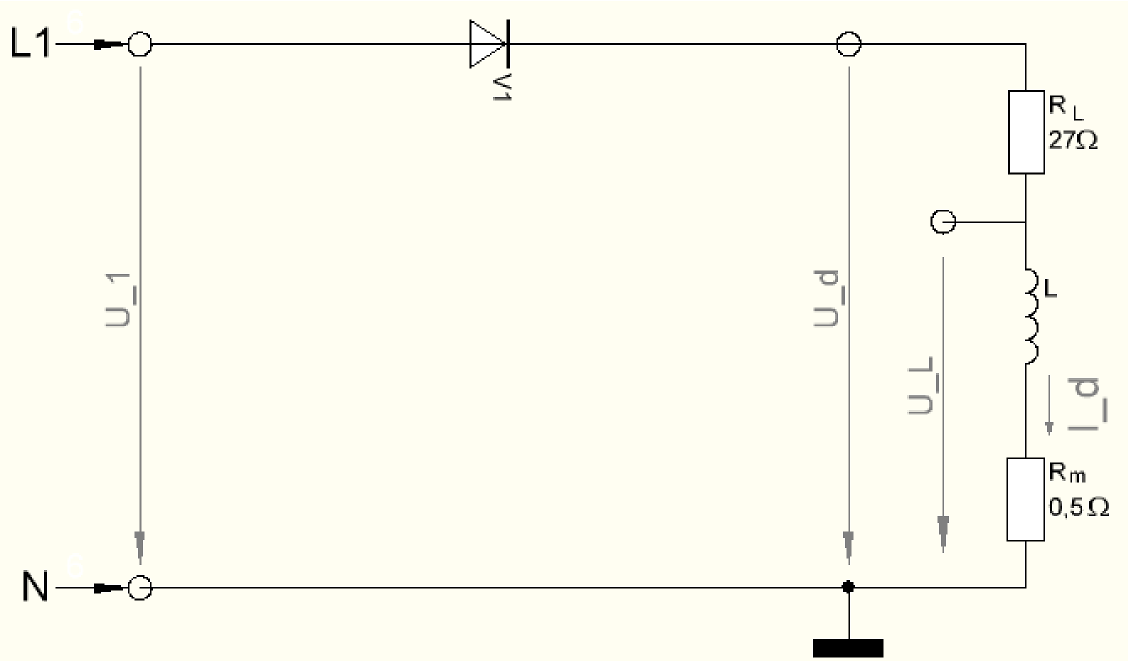
Question:	Compare U_S and U_d. What is the differences between the voltages?
Answer:	U_S and U_d have the same signal wave, $\hat{U}_d$ however is 0,7 V lower than
	$\hat{U}_S$. This is exactly the threshold value of the diode.
	This voltage difference of 0,7 V would not be so obvious in a 230 V
	System. Peak value in our test is approx. at 17 V.
	Thus voltage drop is 4%. In a 230 V system the peak value is approx.
	325 V, so voltage drop is about 0,2 %.

2.1.2 Test 2

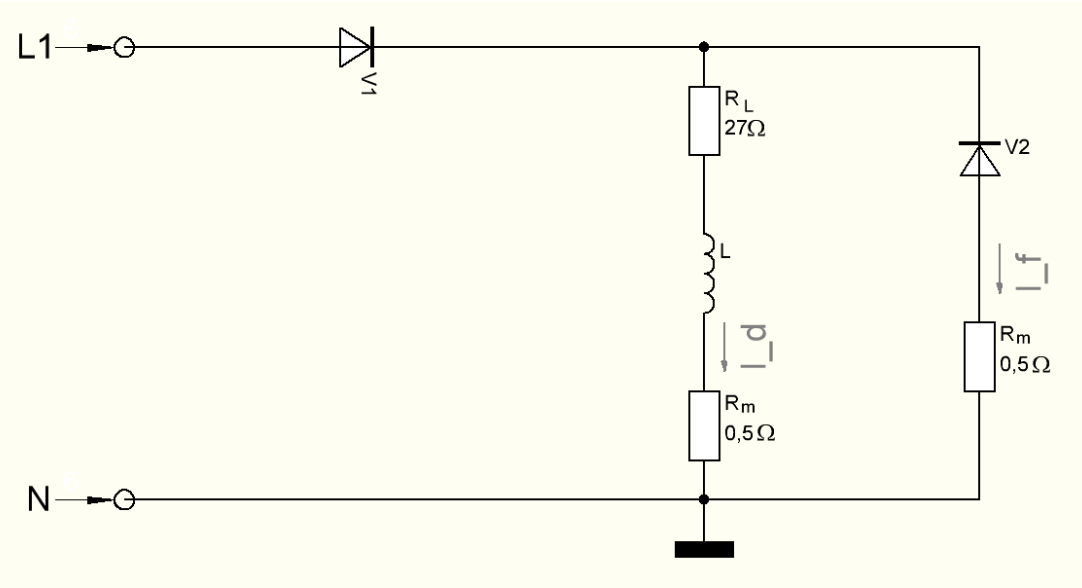
Currents and voltages in uncontrolled single-pulse center tapped circuits M1U at **ohmic-inductive load**.

Test Configuration & Test Procedure

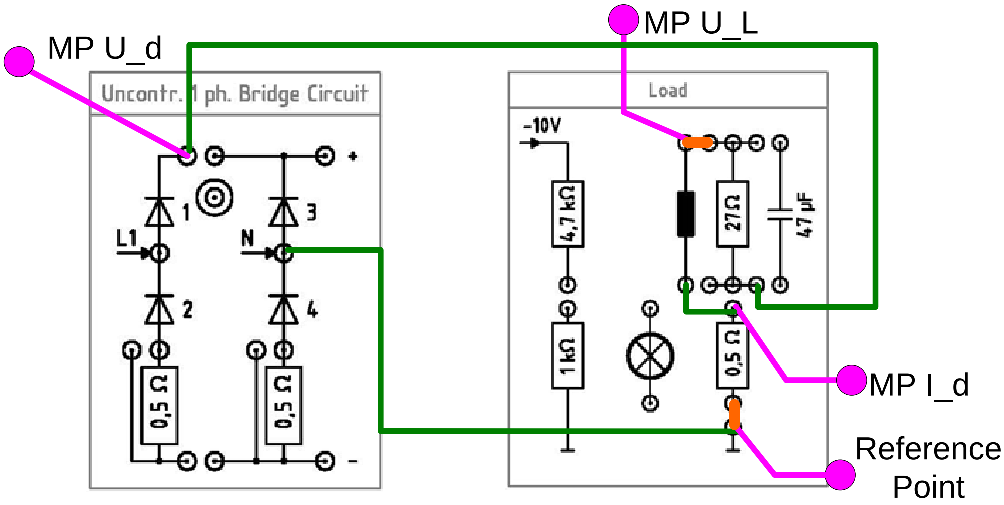
- Build up the circuit in pic. 2.1.2.0 and 2.1.2.1.



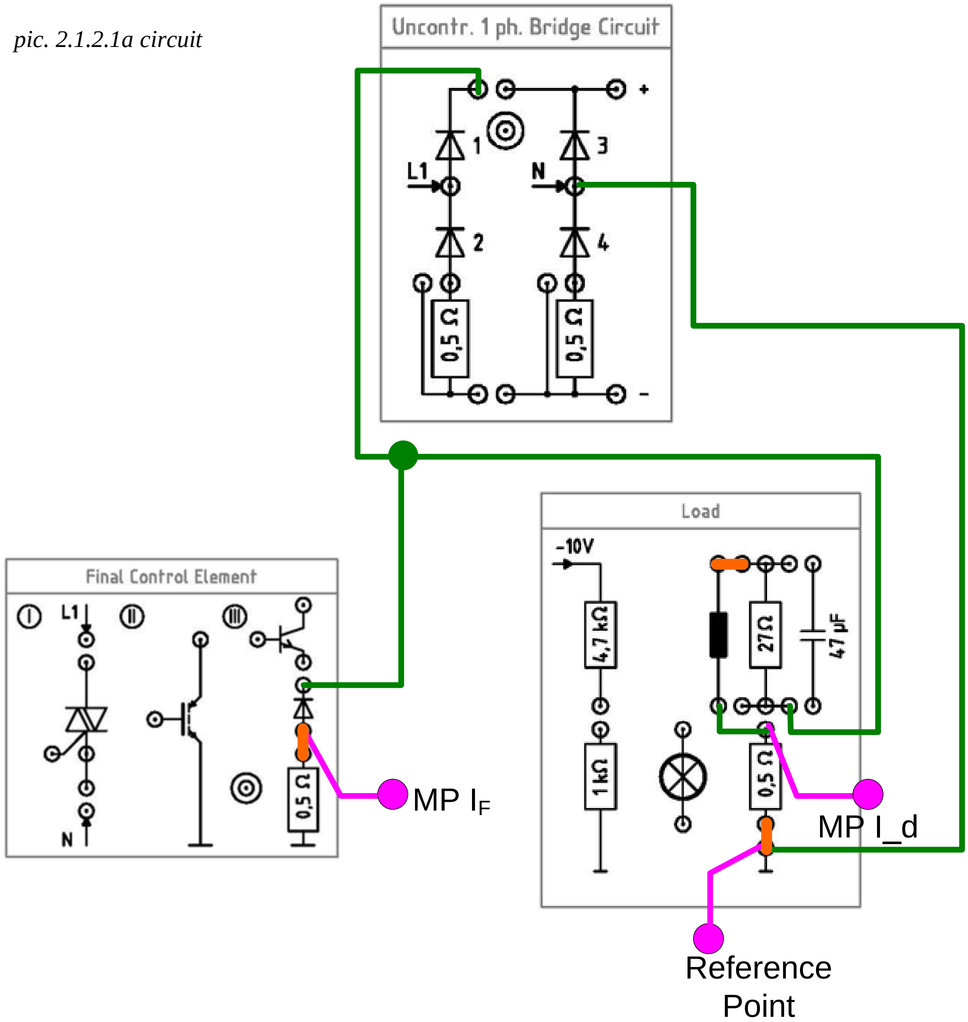
pic. 2.1.2.0a circuit



pic. 2.1.2.0b circuit



pic. 2.1.2.1a circuit

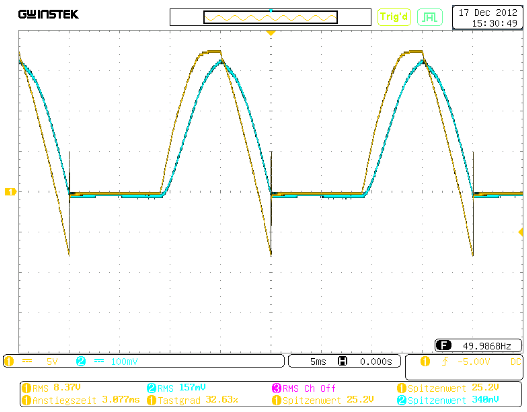


pic. 2.1.2.1b circuit

- First connect the load as described in 2.1.2.0a and 2.1.2.1a (series connection of inductive and ohmic resistor) to the output of the rectifier circuit.

- Measure with the oscilloscope following parameters:
  - Output Voltage U_d,
  - Output Current I_d (voltage drop across R_m)

- Draw the curve into pic. 2.1.2.2.



pic. 2.1.2.2

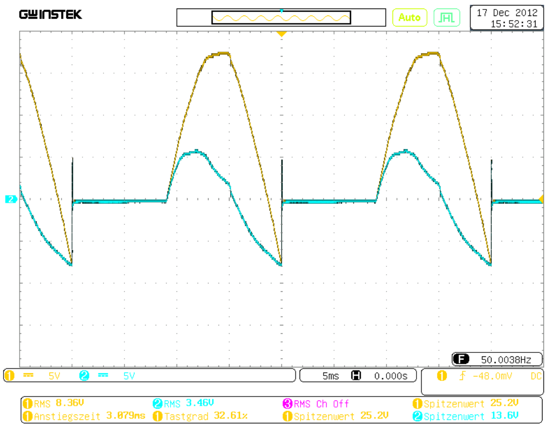
Oscilloscope Settings:

Output Voltage U_d:		5	V / div.
Output Current I_d:		0,2	A / div.
	=	0,1	V / div.
Time t:		5	ms / div.

Current Conversion with Rm = 0,5 Ohm

- Measure following parameters with the oscilloscope:
  - Output Voltage U_d,
  - Coil Voltage U_L

- Draw the curve into pic. 2.1.2.3.



pic. 2.1.2.3

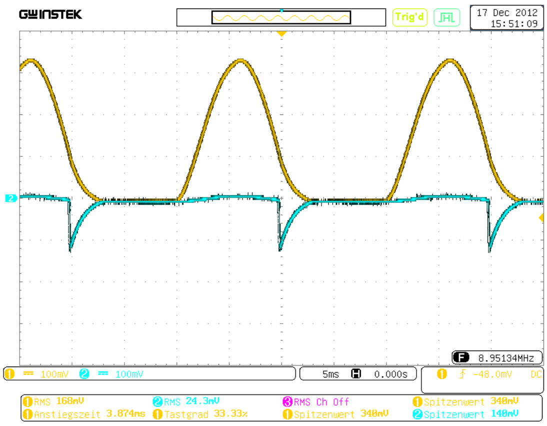
Oscilloscope Settings:

Output Voltage U_d:	5	V / div.
Coil Voltage U_L:	5	V / div.
Time t:	5	ms / div.

- Switch the free-wheeling branch at the output of the rectifier circuit in parallel to the load as shown in pic. 2.1.2.0b and 2.1.2.1b.

- Measure following parameters with the oscilloscope:
  - Load Current I_d,
  - Free-Wheeling Current I_F

- Draw the curve into pic. 2.1.2.4.



pic. 2.1.2.4

Oscilloscope Settings:

Load Current I_d:	0.2 A / div. = 0,1 V/div.
Free-Wheeling Current I_F:	0,2 A / div. = 0,1 V/div.
Time t:	5 ms / div.

Current Conversion with Rm = 0,5 Ohm

Note: ***The area, in which the output voltage is negative, is called negative voltage-time-area. If this should be suppressed, this could be done with a free-wheeling diode.***

Question 1:	Pic. 2.8 shows shifted phases between voltage and current. How big is it and why does it occur?
Answer:	The phase shifting between output voltage U_d and output current I_d
	in this example is approx. 25% (measured between the negative zero-crossing of two signals). The phase shifting
	occurs due to the inductive part of the mixed voltage.
	.

Question 2:	Pic. 2.9 shows partially negative output voltage U_d. How do you explain, that there are negative and positive voltage portions at the output of the rectifier circuit?
Answer:	As inductance delays the current flow due to the load, at the cathode
	side of the diode occurs slightly negative potential.
	Cathode potential is 0,7 V „more negative“ than the anode potential.
	(= $U_{L1\,N}$), the diode remains conducting and gives potential of the
	negative half-wave to the rectifier side.
	NOTE: If output voltage U_d and coil voltage U_L are measured
	simultaneously, the circuit has to be modified, so both signals
	have a common reference point, or output voltage and coil voltage
	have to be measured one after the other.

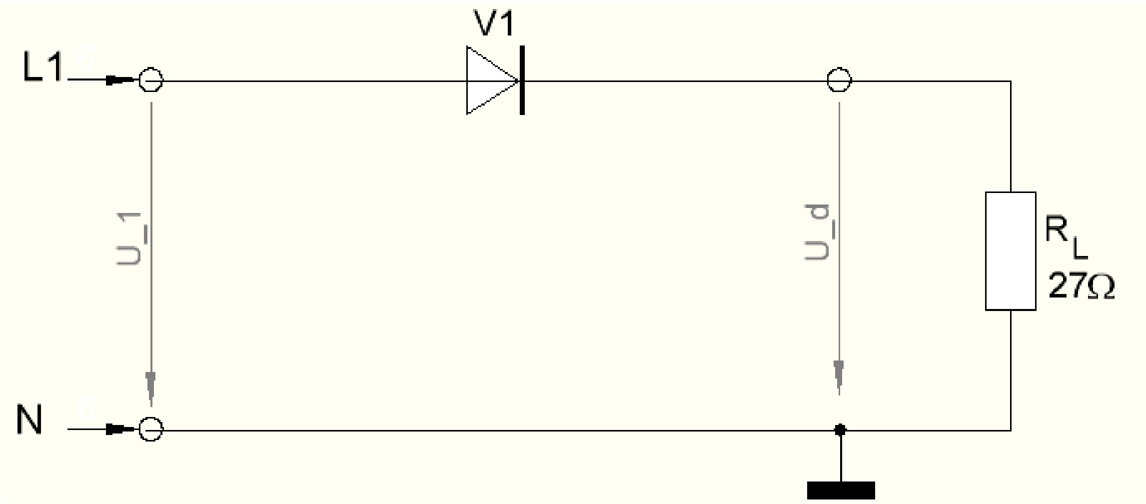
Question 3:	What effect does the free-wheeling diode have at the current due to ohmic-inductive load?
Answer:	Current flow is prolonged due to the use of free-wheeling diodes.
	Without free-wheeling diodes, the current flows (due to inductance)
	only as long the output voltage U_d is 0,7 V „more negative“ than
	mains voltage U_S. With free-wheeling diode, the current flows
	as long the output voltage is U_d more than -0,7 V.

2.1.3 Test 3

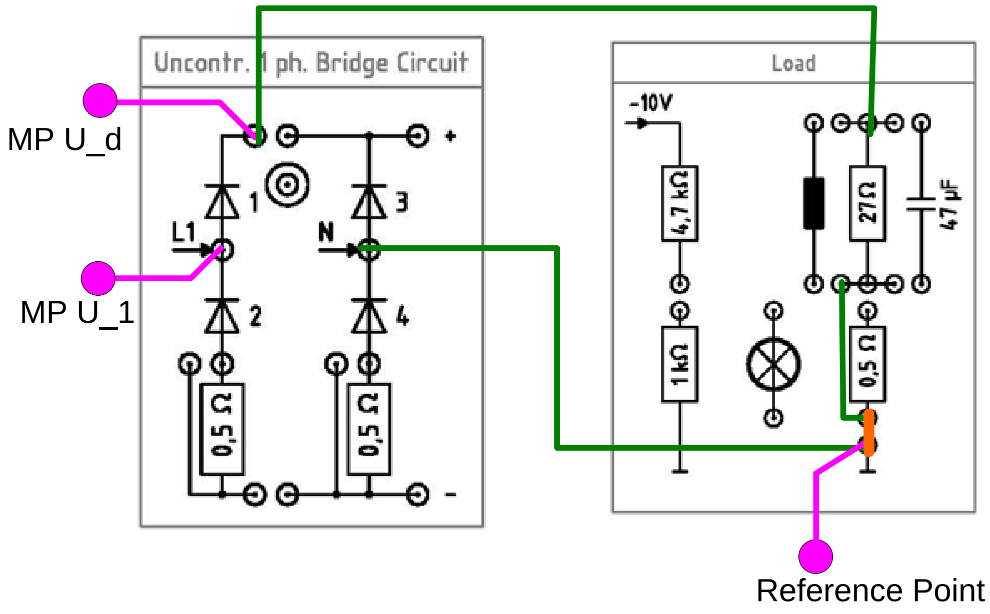
Arithmetic average and root mean square at uncontrolled rectifiers.

Test Configuration & Test Procedure

- Build up the circuit in pic. 2.1.3.0 and 2.1.3.1.



pic. 2.1.3.0 circuit



pic. 2.1.3.1 circuit

- Measure following parameters (see suitable measuring instruments in 1.3.1):
  - RMS of AC input voltage $U_{1\ eff}$,
  - RMS of AC output voltage $U_{d\ eff}$,
  - Arithmetic average of output voltage $U_{d\ ar}$

- Add the measured values to the chart 2.1.3.2.

Circuit	M1U
$U_{1\ eff}$ / V	13,3
$U_{d\ eff}$ / V	8,75
$U_{d\ ar}$ / V	5,25

chart 2.1.3.2

- Determine following values and add to chart 2.1.3.3.

M1U:

$$\frac{U_{1eff}}{U_{dar}} = \frac{13{,}3V}{5{,}25V} = 2{,}53 \qquad \frac{U_{deff}}{U_{dar}} = \frac{8{,}75V}{5{,}25V} = 1{,}67$$

Circuit	M1U
$U_{1\ eff}$ / $U_{d\ ar}$	2,53
$U_{d\ eff}$ / $U_{d\ ar}$	1,67

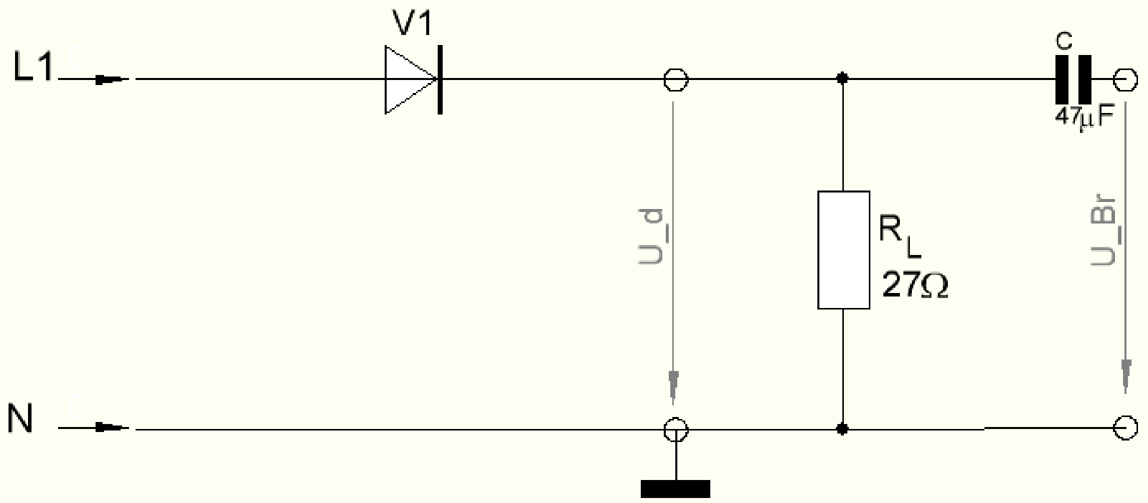
chart 2.1.3.3

2.1.4 Test 4

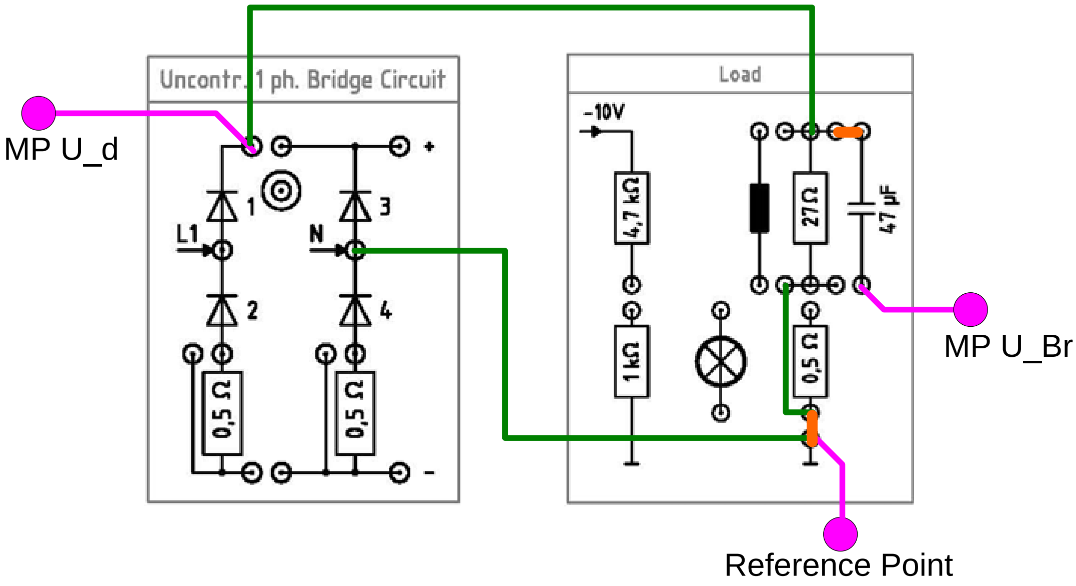
Pulse rate and ripple in uncontrolled rectifiers.

Test Configuration & Test Procedure

- Build up the circuit in pic. 2.1.4.0 and 2.1.4.1.



pic. 2.1.4.0 circuit



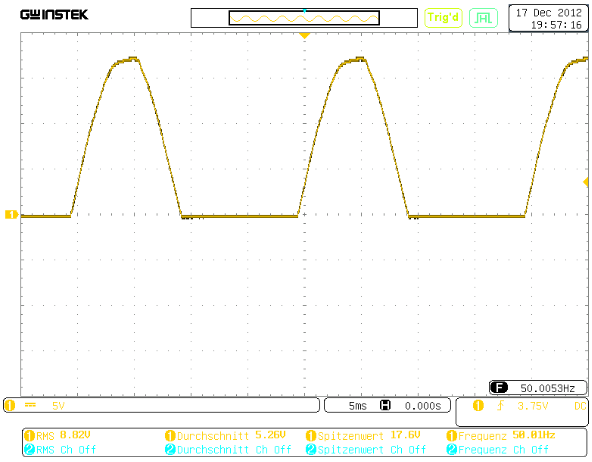
pic. 2.1.4.1 circuit

- Measure the output voltage (U_d) with the oscilloscope and draw the curve into pic. 2.1.4.1.

Note: ***Do not use the capacitor C_1 = 47 µF from the load block of the Power Electronic Panel for the measurement of the output voltage.***

Oscilloscope Settings:

Output Voltage U_d:	5	V / div.
Time t:	5	ms / div.



pic. 2.1.4.1 M1U circuit

- Measure following parameters (see 1.3.1 for suitable measuring instruments:
  - $U_{d\ ar}$ (arithmetic average of output voltage)
  - $U_{Br\ eff}$ (root mean square of ripple voltage)

Note: ***Use the capacitor C_1 = 47 µF from the load block of the Power Electronic Panel to decouple the DC portion.***

- Determine ripple w and pulse rate p.
- Add the measured values into chart 2.1.4.2.

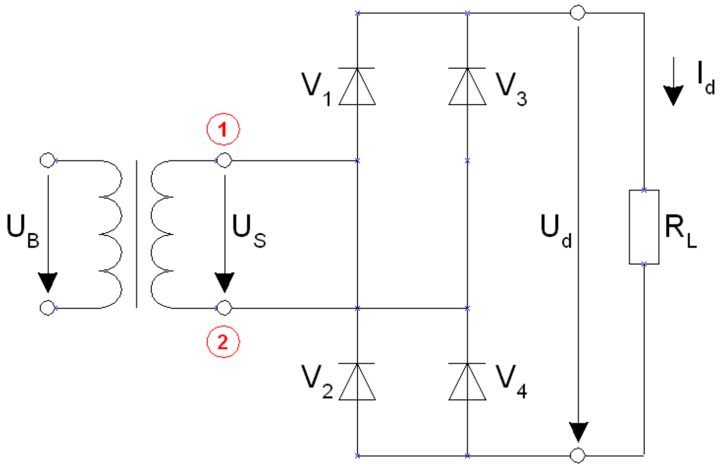
Circuit	M1U
$U_{d\ ar}$ / V	5,22
$U_{Br\ eff}$ / V	6,89
ripple w	1,32
Pulse rate p	1

chart 2.1.4.2

2.2 Uncontrolled Two-Pulse Bridge Circuit B2U

The most common rectifier circuit is the two-pulse bridge circuit B2U. This circuit is done with four identical diodes.

Circuit:



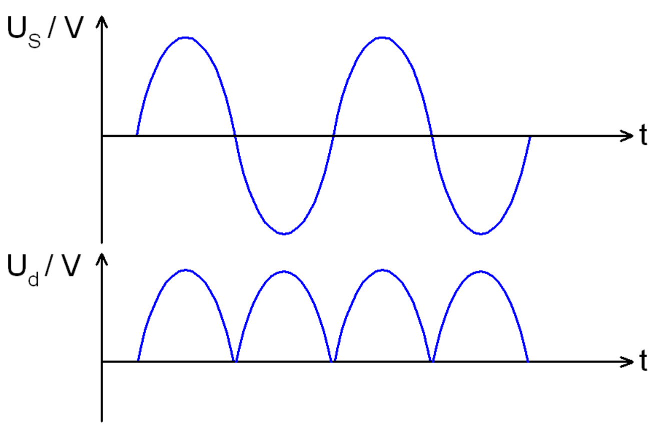
pic. 2.2.0 B2U circuit

Function:

Point 1 is with respect to point 2 positive during the positive half-wave. Current I_d through the diodes V_1 and V_4 pass the load resistance R_L.
This reverses during the negative half-wave. Point 2 is now positive with respect to point 1. This means that the current I_d now pass through V_3, R_L and V_2.

In this proceeding both half-waves (positive and negative) are used for the rectification. Output voltage U_d and current I_d have the same direction.

Signal Wave Form:



pic. 2.2.0.1 signal curve

Ripple / Ripple Voltage

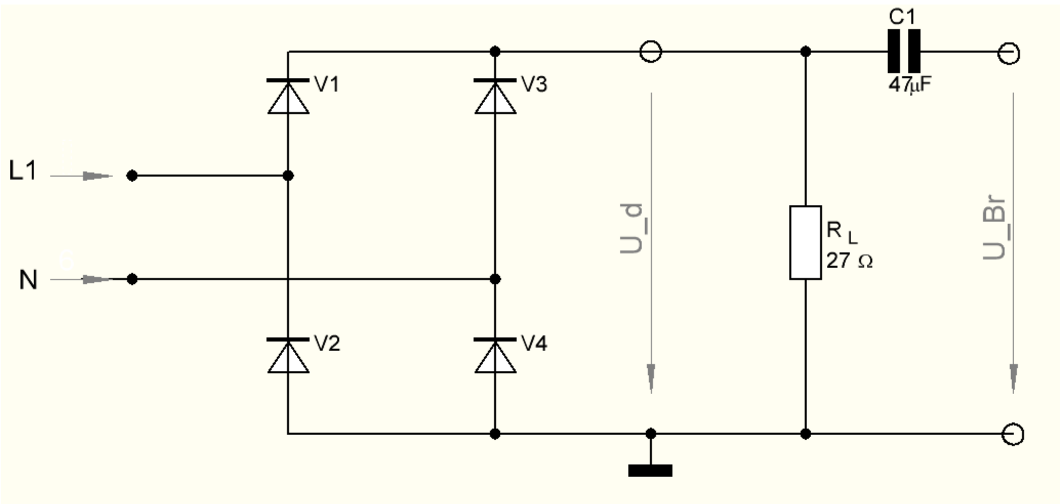
Ripple

The ripple w (stated in %) is significant for the quality of a rectifier circuit. The ripple shows the ratio of ripple portion (effective value of ripple voltage $U_{Br\,eff}$) and DC portion (arithmetic average $U_{d\,ar}$), it is calculated as follows:

$$w = \frac{U_{Br\,eff}}{U_{d\,ar}}$$

Root Mean Square Ripple Voltage

For determination of the ripple voltages' RMS, it is essential to separate the DC voltage from the rectifiers' output voltage U_d. The simplest way to do so is with a capacitor (C_1) at the output of the circuit.



pic. 2.2.0.2 Circuit for Ripple Voltage Measurement

Pulse Rate

The pulse rate p often is stated as additional quality criteria for rectifier circuits. This indicates the frequency of ripple voltage f_{Br}.

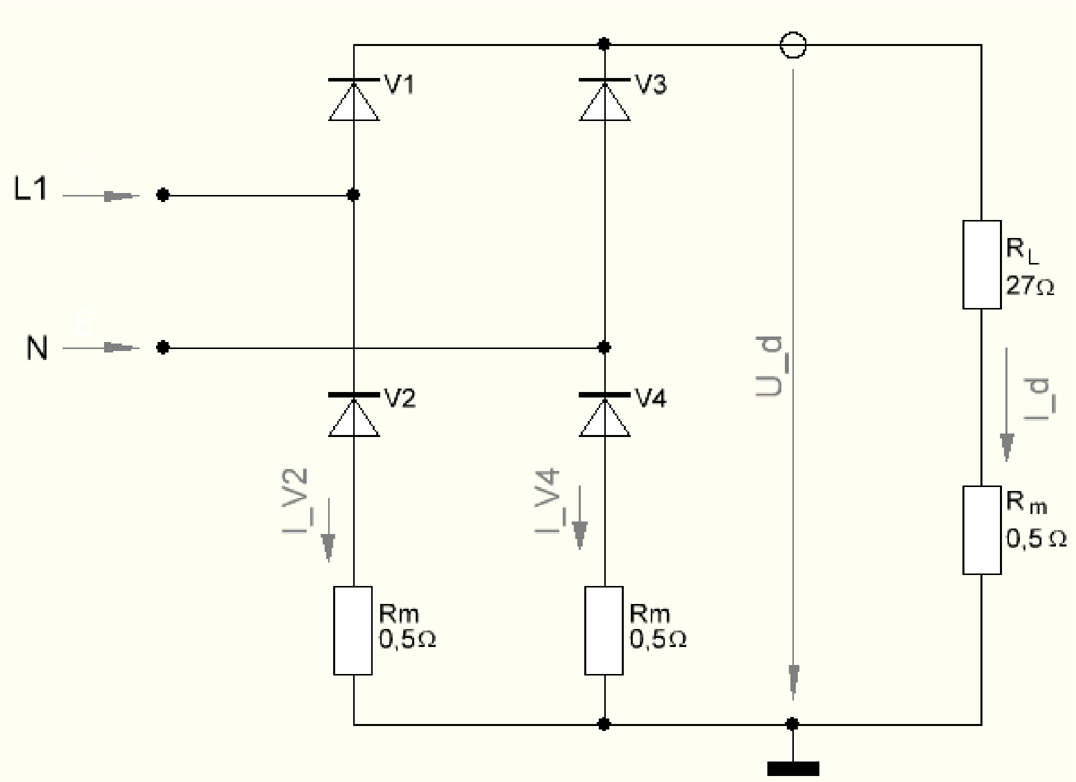
The pulse rate indicates the number of DC blocks occurring in one period of the applied AC voltage.

2.2.1 Test 1

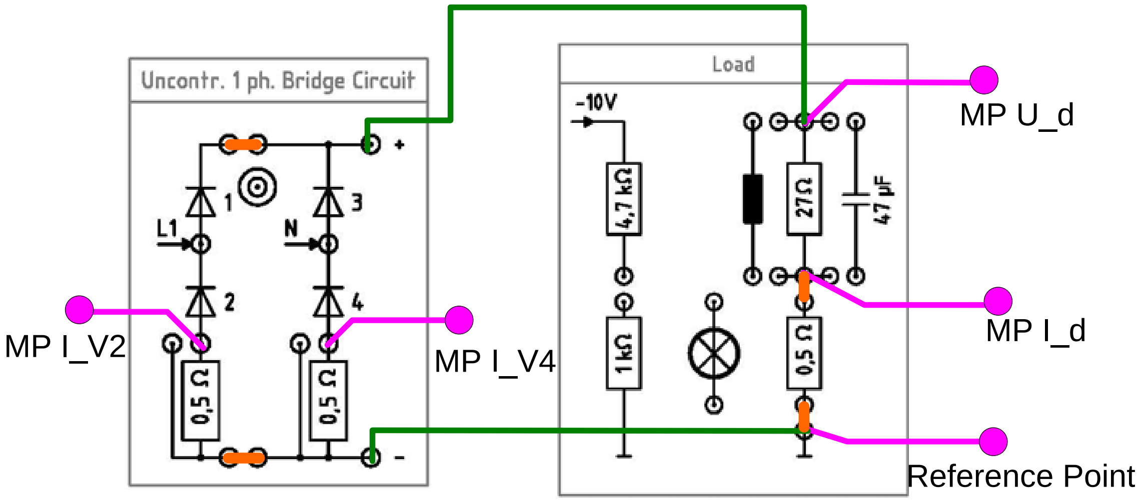
Currents and Voltages in uncontrolled two-pulse bridge circuits B2U at **ohmic load**.

Test Configuration & Test Procedure

- Build up the circuit in pic. 2.2.1.0 with the Power Electronic Panel pic. 2.2.1.1.



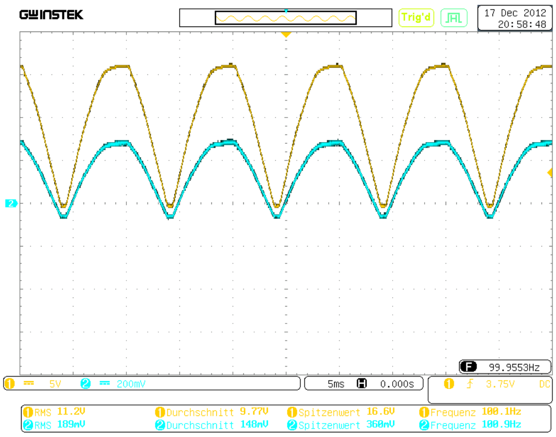
pic. 2.2.1.0 circuit



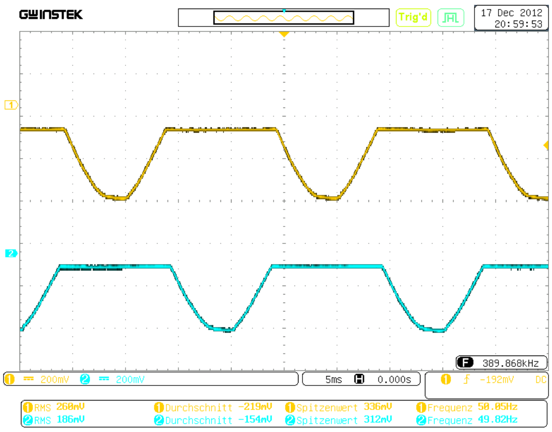
pic. 2.2.1.1 Circuit with the Power Electronic Panel

- Measure following parameters with the oscilloscope:
  - Output Voltage U_d,
  - Load Current I_d,
  - Diode Current I_{V2},
  - Diode Current I_{V4}

- Draw the curve into pic. 2.2.1.2 and 2.2.1.3.



pic. 2.2.1.2



pic. 2.2.1.3

Oscilloscope Settings:

Output Voltage U_d: 5 V / div.

Load Current I_d: 0,4 A / div. = 0,2 V / div.

Time t: 5 ms / div.

Current Conversion with Rm = 0,5 Ohm

Oscilloscope Settings:

Diode Current I_{V2}: 0,4 A / div. = 0,2 V / div.

Diode Current I_{V4}: 0,4 A / div. = 0,2 V / div.

Time t: 5 ms / div.

Current Conversion with Rm = 0,5 Ohm

Question :	What is the pulse rate (pulse rate = number of voltage pulses at the DC side per mains period) of the B2U circuit?
Answer:	The pulse rate of the B2U circuit is „2“. The first pulse is generated by
	the first positive half-wave. Diodes V_1 and V_4 are conducting.
	the second pulse is generated by the negative half-wave.
	V_3 and V_2 are conducting.

NOTE: *During the negative half-wave of mains voltage the diode V_3 blocks. During the positive half-wave diode V_4 blocks. Pic. 2.2.1.3 shows the correct oscillograph. If connecting cable between minus-terminal of the rectifier and load is too long, and the voltage drop measured over the complete cable with a measuring resistor, a minor voltage pulse occurs although blocking half-wave. As current flows on the connecting cable to earth also during the positive half-wave, there is voltage drop on (R_{m2}+cable), although current through R_{m2} only flows during the negative half-wave.*

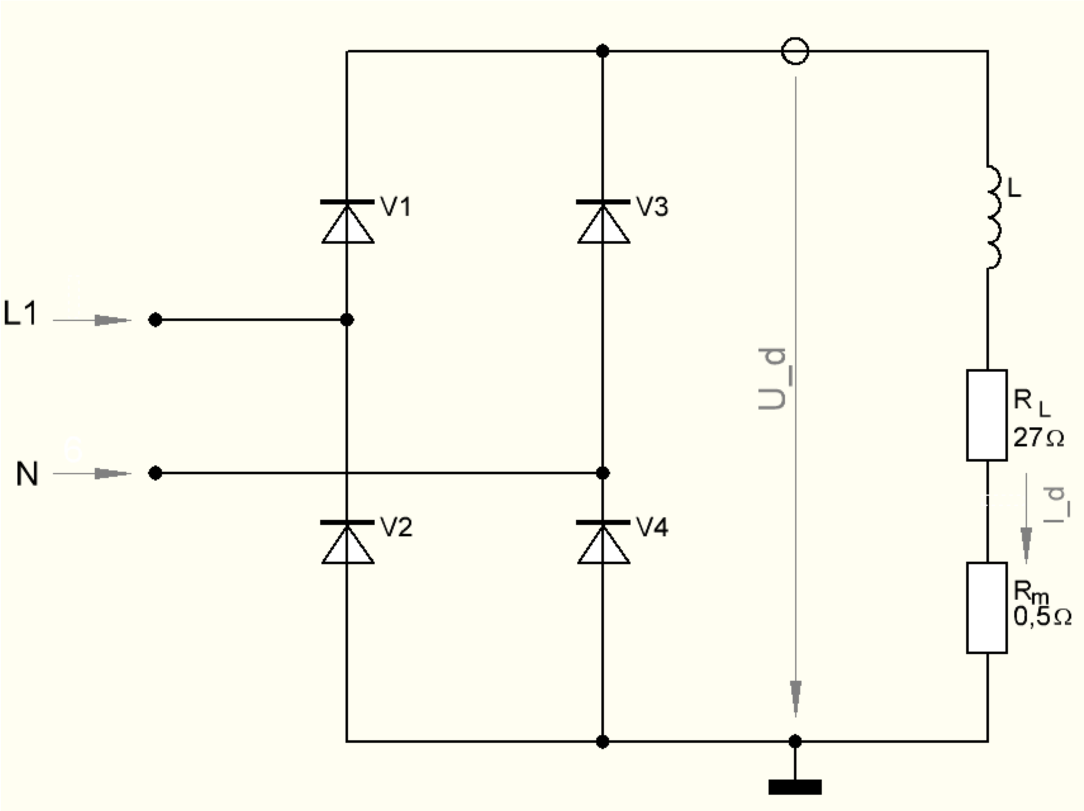
Remedy: *Shorter connecting cable or measurement directly between measuring resistor and minus-terminal.*

2.2.2 Test 2

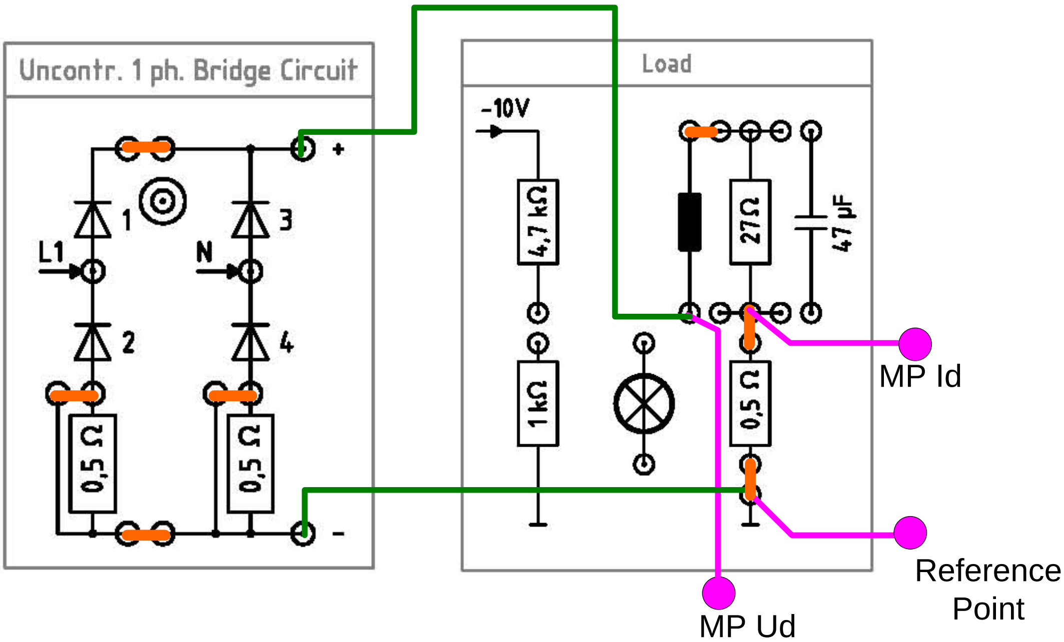
Currents and voltages in the uncontrolled two-pulse center tapped circuit B2U at **ohmic-inductive load.**

Test Configuration & Test Procedure

- Build up the circuit in pic. 2.2.2.0 / 2.2.2.1. Bridge the two 0,5 Ω measuring resistors with 2mm connecting plugs.



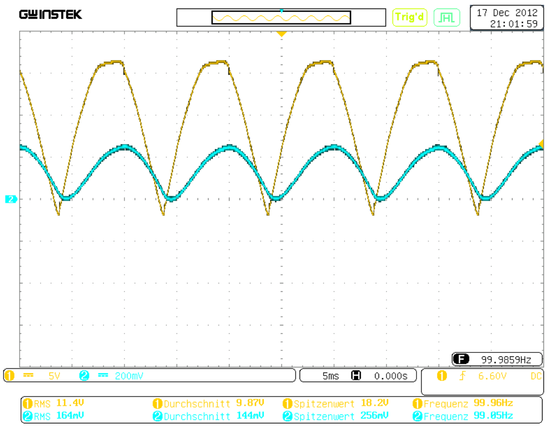
pic. 2.2.2.0 circuit



pic.2.2.2.1 circuit

- Measure following parameters with the oscilloscope:
  - Output Voltage U_d,
  - Load Current I_d

- Draw the curve into pic. 2.2.2.2.



pic. 2.2.2.2

Oscilloscope Settings:

Output Voltage U_d:		5	V / div.
Load Current I_d:		0,4	A / div.
	=	0,2	V / div.
Time t:		5	ms / div.

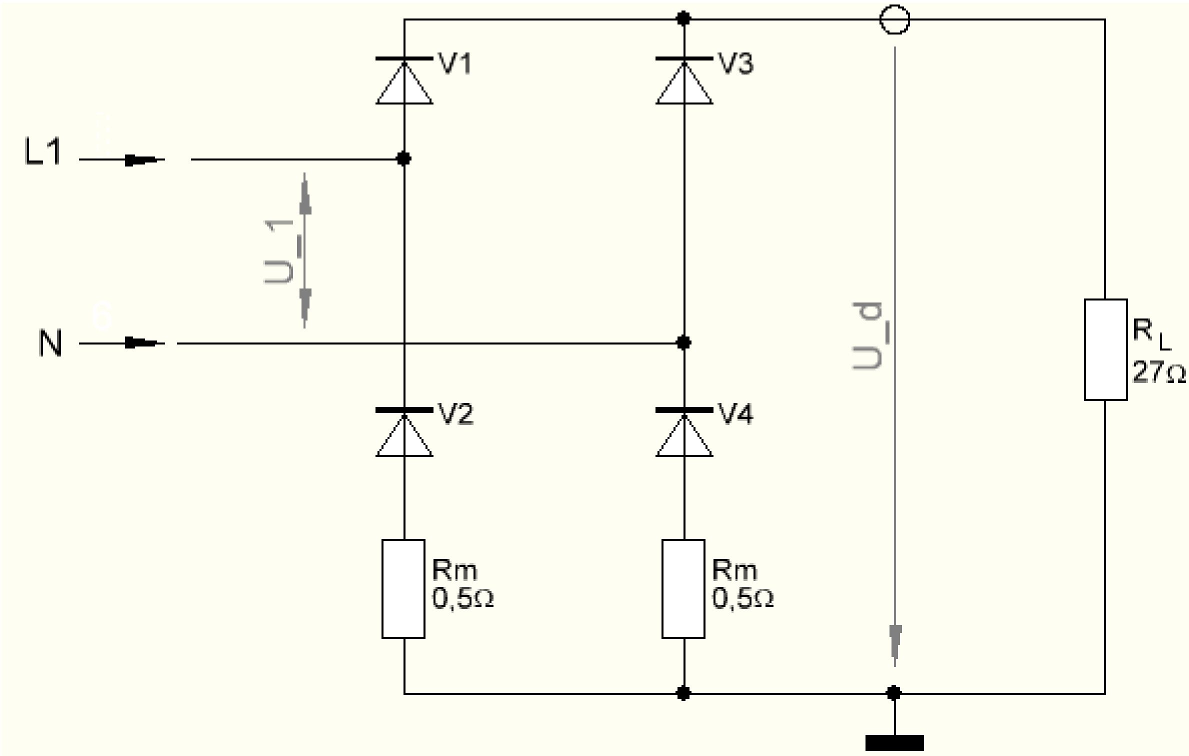
Current Conversion with Rm = 0,5 Ohm

2.2.3 Test 3

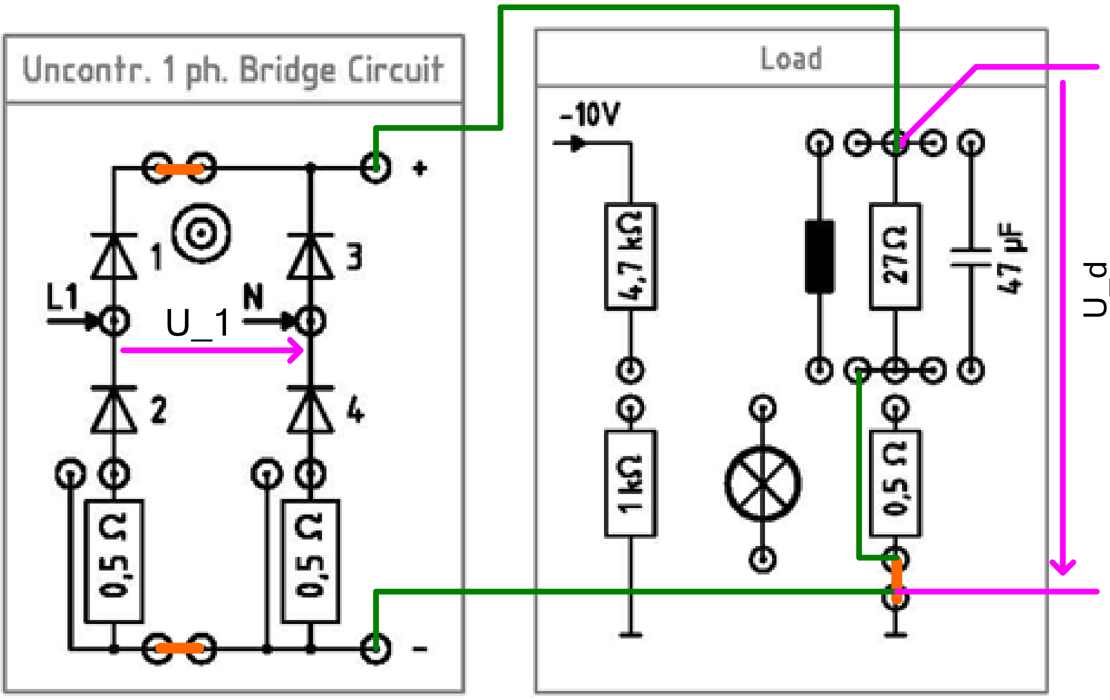
Arithmetic average and root mean square at uncontrolled rectifiers.
.

Test configuration & Test procedure

- Build up the circuit in pic. 2.2.3.0 / 2.2.3.1.



pic. 2.2.3.0 circuit



pic. 2.2.3.1 circuit

- Measure following parameters with a suitable measuring instrument (see 1.3.1):
  - Root mean square of the input AC voltage $U_{1\ eff}$,
  - Root mean square of output AC voltage $U_{d\ eff}$,
  - Arithmetic average of the output voltage $U_{d\ ar}$

- Add the measured into chart 2.2.3.2.

Circuit	B2U
$U_{1\ eff}$ / V	13,0
$U_{d\ eff}$ / V	11,0
$U_{d\ ar}$ / V	9,67

chart 2.2.3.2

- Determine following values and add to chart 2.2.3.3.

B2U:

$$\frac{U_{1eff}}{U_{dar}} = \frac{13{,}0V}{9{,}67V} = 1{,}34$$

$$\frac{U_{deff}}{U_{dar}} = \frac{9{,}0V}{9{,}67V} = 0{,}93$$

Circuit	B2U
$U_{1\ eff}$ / $U_{d\ ar}$	2,68
$U_{d\ eff}$ / $U_{d\ ar}$	1,86

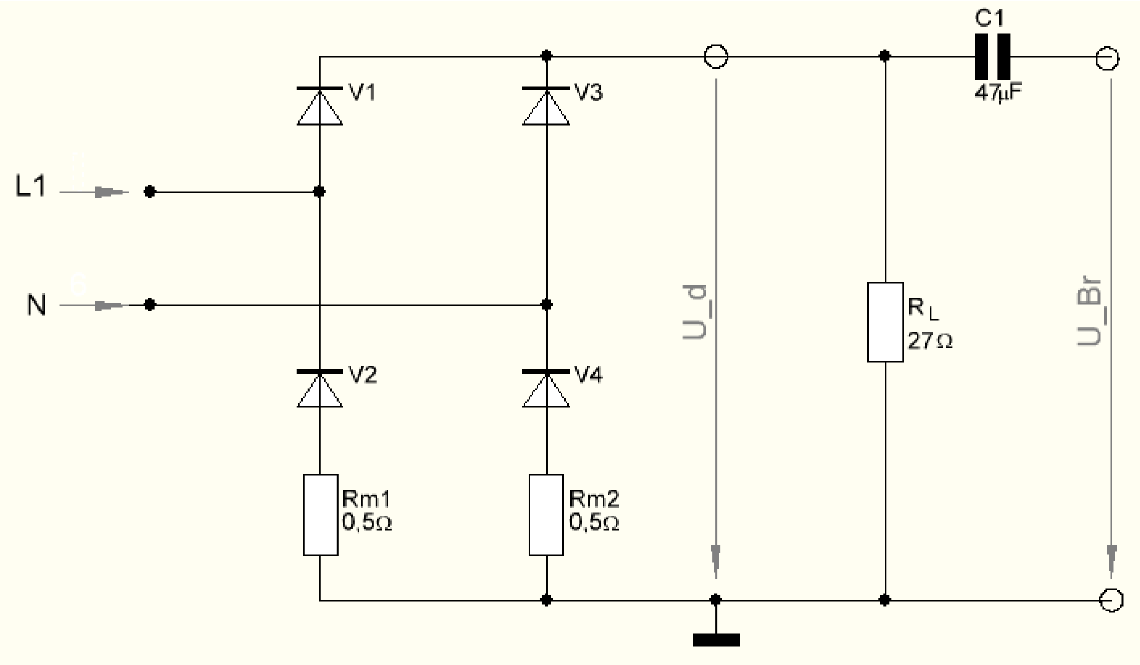
chart 2.2.3.3

2.2.4 Test 4

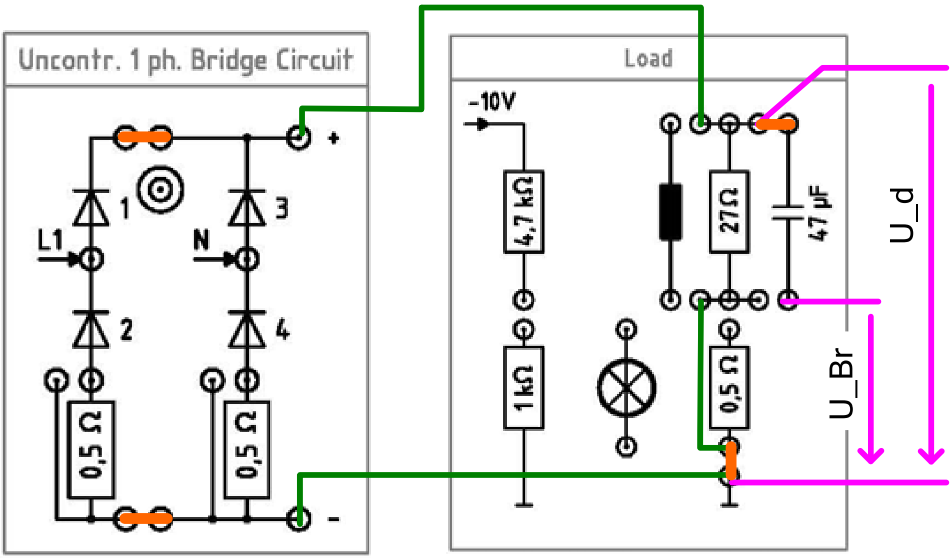
Pulse rate and ripple in uncontrolled rectifiers.

Test Configuration & Test Procedure

- Build up the circuit in pic. 2.2.4.0 / 2.2.4.1.



pic. 2.2.4.0 circuit



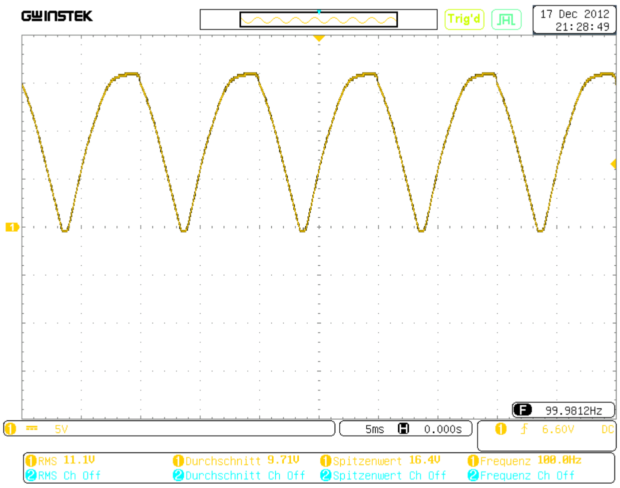
pic. 2.2.4.1 circuit

- Measure with the oscilloscope the output voltage (U_d) and draw the curve into pic. 2.2.4.2.

Note: ***Do not use capacitor C_1 = 47 µF from the load block of the Power Electronic Panel for the measurement of the output voltages.***

Oscilloscope Settings:

Output Voltage U_d:	5	V / div.
Time t:	5	ms / div.



pic. 2.2.4.2 B2U circuit

- Measure following parameters with a suitable measuring instrument (see 1.3.1):
  - $U_{d\ ar}$ (arithmetic average of output voltage)
  - $U_{Br\ eff}$ (root mean square of ripple voltage)

Note: ***Please use the capacitor C_1 = 47 µF at the load block of the Power Electronic Panel to decouple the DC portion.***

- Determine ripple w and pulse rate p.
- Add the measured values to chart 2.2.4.3.

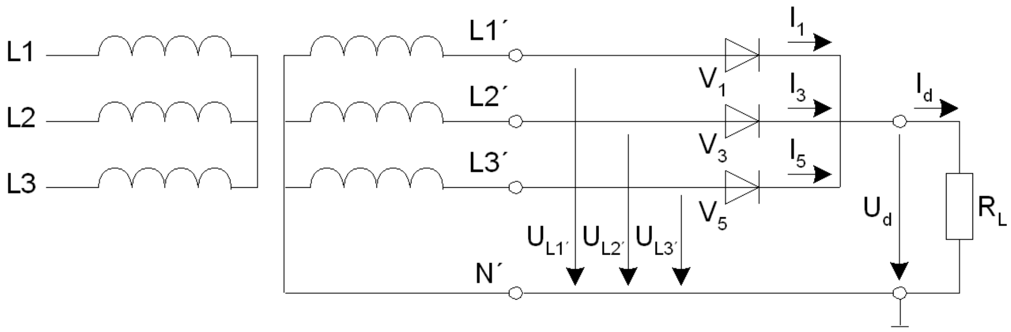
Circuit	B2U
$U_{d\ ar}$ / V	9,75
$U_{Br\ eff}$ / V	5,60
ripple w	0,57
Pulse rate p	2

chart 2.2.4.3

2.3 Uncontrolled Three-Pulse Center Tapped Circuit M3U

The uncontrolled three-pulse center tapped circuit M3U is a single-pulse center tapped circuit M1U with half-wave rectification. The N-conductor N' forms the common reference point for input voltages L1', L2', L3' and the output voltage U_d.

Circuit:



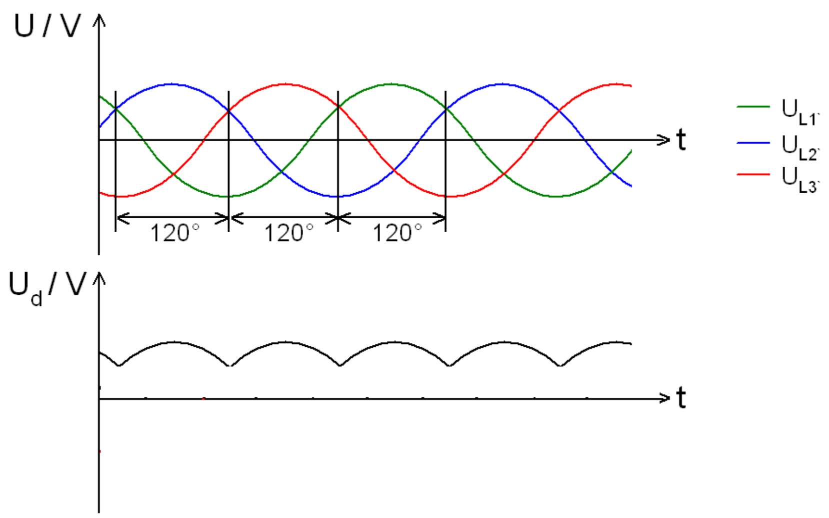
pic. 2.3.0.0 M3U circuit

In this circuit you can see, that the current only flows through the diode if the respective phase voltage is higher than U_d.

Function:

From the signal wave form of the M3U circuit it is evident, that the three phase voltages 120° do overlap shifted. Each of the three phase voltages dominate for an instant (also each with 120°). For example voltage $U_{L1'}$ in reference to its period is the highest voltage between 30° and 150°. The diode V_1 is not conducting directly with zero crossing of $U_{L1'}$, but after voltage flow is 0,7 Volt higher than voltage of $U_{L3'}$ (from 30° on). The diode V_1 then is conducting till 150°. Next conducting diode will be V_3 , as $U_{L2'}$, now between 150° and 270°, has the highest phase voltage. Between 270° and 30° $U_{L3'}$ has the highest phase voltage, diode V_5 now is conducting. Means each of the diodes V_1, V_3 and V_5 conduct a third of current I_d.

Signal Wave Form:



pic. 2.3.0.1 signal wave form of input – and output voltages

Commutation:

Communitation means the passing through of current from diode to diode (in our example at 30°, 150° and 270°). Current commutates from V_1 to V_3 to V_5 and then back to V_1.

Note:

In contrary to the M1U circuit, the current I_d cannot be zero at M3U three-pulse center tapped circuit.

Ripple / Ripple Voltage

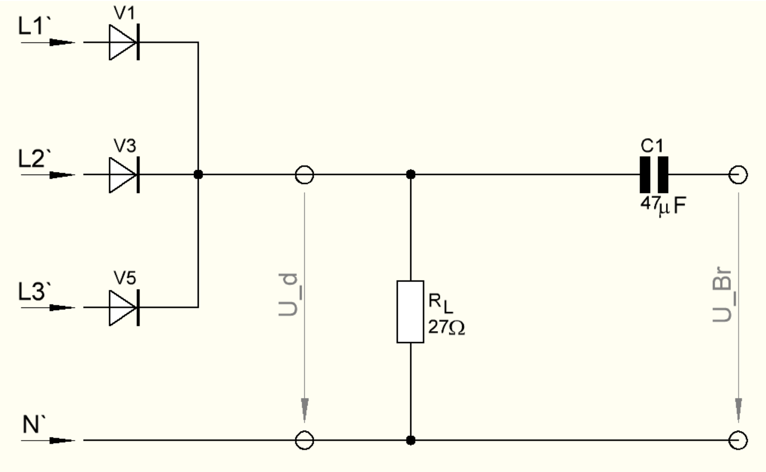
Ripple

The ripple w (stated in %) is significant for the quality of a rectifier circuit. The ripple shows the ratio of ripple portion (effective value of ripple voltage $U_{Br\ eff}$) and DC portion (arithmetic average $U_{d\ ar}$), it is calculated as follows:

$$w = \frac{U_{Br\,eff}}{U_{d\,ar}}$$

Root Mean Square Ripple Voltage

For determination of the ripple voltages' RMS, it is essential to separate the DC voltage from the rectifiers' output voltage U_d. The simplest way to do so is with a capacitor (C_1) at the output of the circuit.



pic. 2.3.0.2 circuit for ripple voltage measurement

Pulse Rate

The pulse rate p often is stated as additional quality criteria for rectifier circuits. This indicates the frequency of ripple voltage f_{Br}.

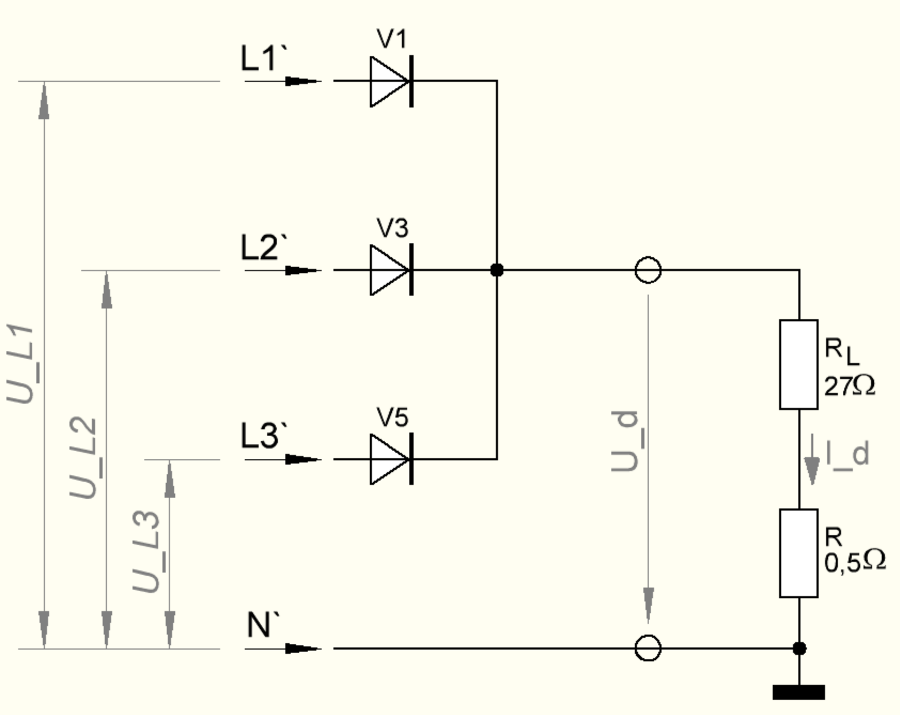
The pulse rate indicates the number of DC blocks occurring in one period of the applied AC voltage.

2.3.1 Test 1

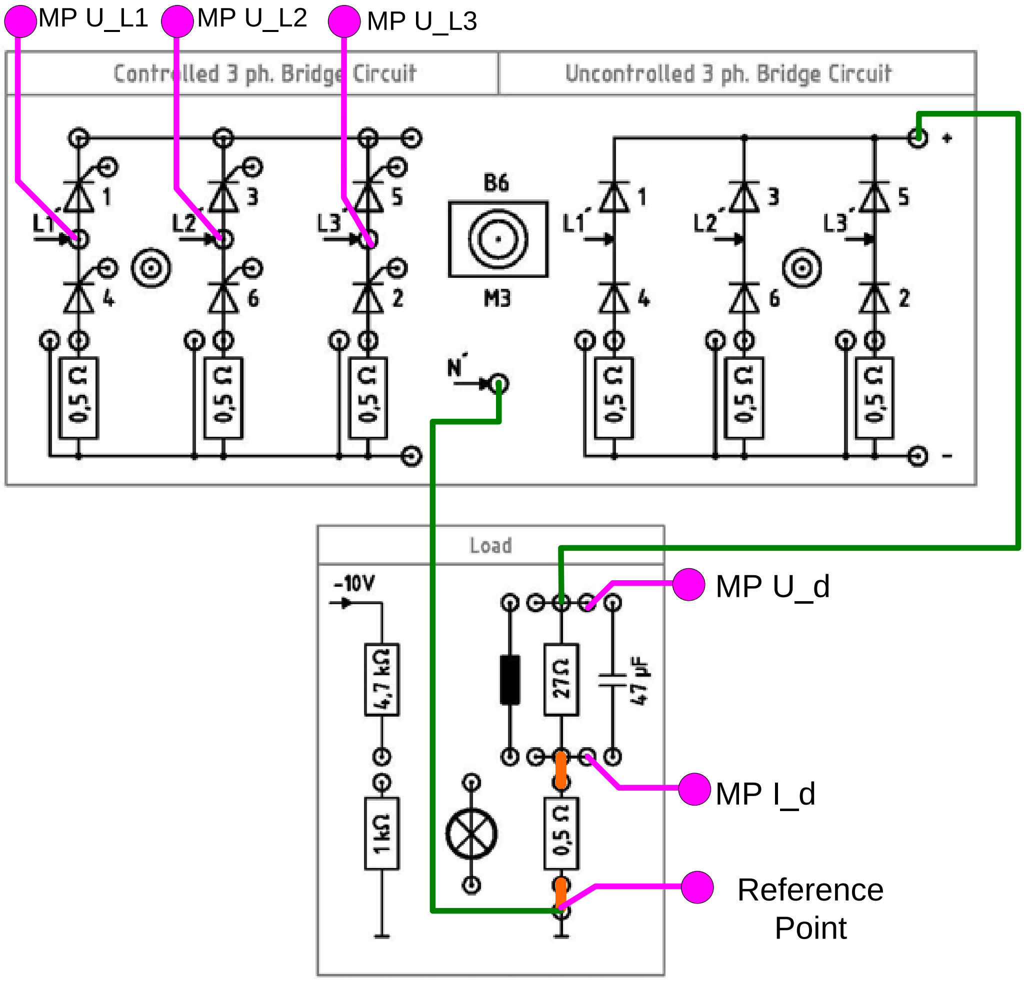
Currents and voltages in uncontrolled three-pulse center tapped circuit M3U at **ohmic load.**

Test Configuration & Test Procedure

- Build up the circuit in pic. 2.3.1.0 with the Power Electronic Panel pic. 2.3.1.1.



pic. 2.3.1.0 circuit



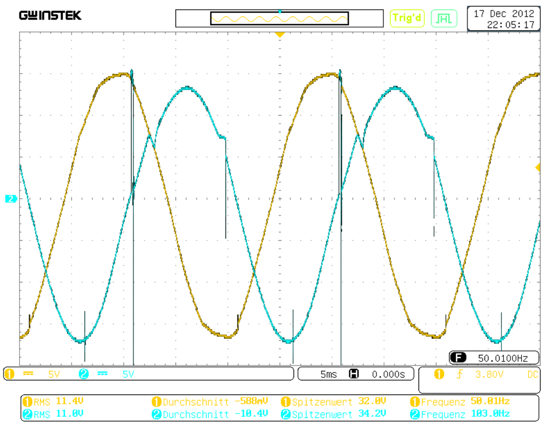
pic. 2.3.1.1 Circuit at the Power Electronic Panel

- Set the selector M3/B6 to position M3.

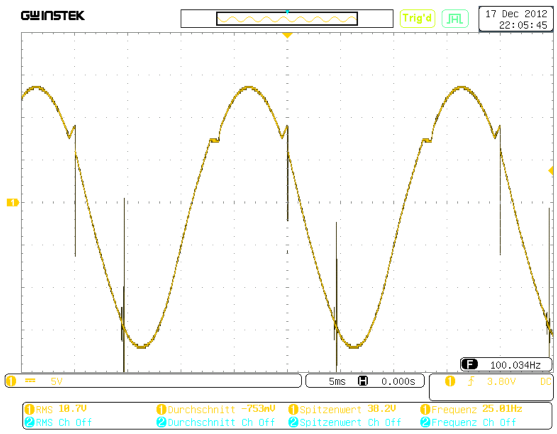
- Measure following parameters with the oscilloscope:
  - Phase Voltages $U_{L1'}$, $U_{L2'}$, $U_{L3'}$,
  - Output Voltage U_d,
  - Output Current I_d

Note: ***To trigger the oscilloscope following has to be done: Indicate phase voltage $U_{L1'}$ on the display and trigger internally via LINE (may vary with respect to the type).***

- Draw the curve into pic. 2.3.1.2, pic 2.3.1.3 and pic. 2.24.1.



pic. 2.3.1.2



pic. 2.3.1.3

Oscilloscope Settings:

Phase Voltage UL1': 5 V / div.

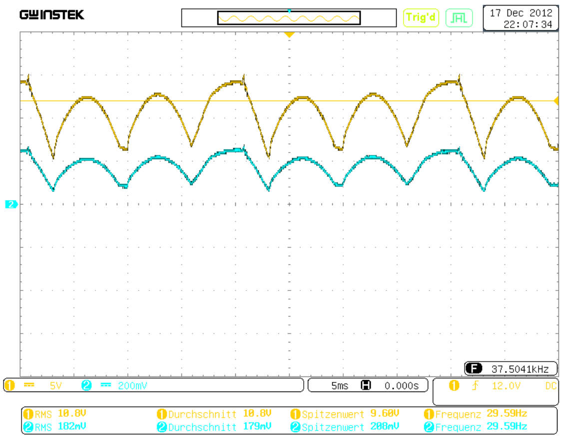
Phase Voltage UL2': 5 V / div.

Time t: 5 ms / div.

Oscilloscope Settings:

Phase Voltage UL3': 5 V / div.

Time t: 5 ms / div.



pic.2.3.1.4

Oscilloscope Settings:

Output Voltage U_d:		5	V / div.
Output Current I_d:		0,4	A / div.
	=	0,2	V / div.
Time t:		5	ms / div.

Current Conversion with Rm = 0,5 Ohm

Note: *Phase voltages hold distortions at its crossings. That is due to 12 V-operation. At the crossings current commutates from diode to diode. Therefore the secondary coil of a phase is charged respectively discharged, and voltage drops, respectively rises. At disconnecting the load the distortion clears away.*

Question 1:	What is the pulse rate of the M3U circuit?
Answer:	Pulse rate is „3“. Each half-wave of phase voltage generates a pulse.

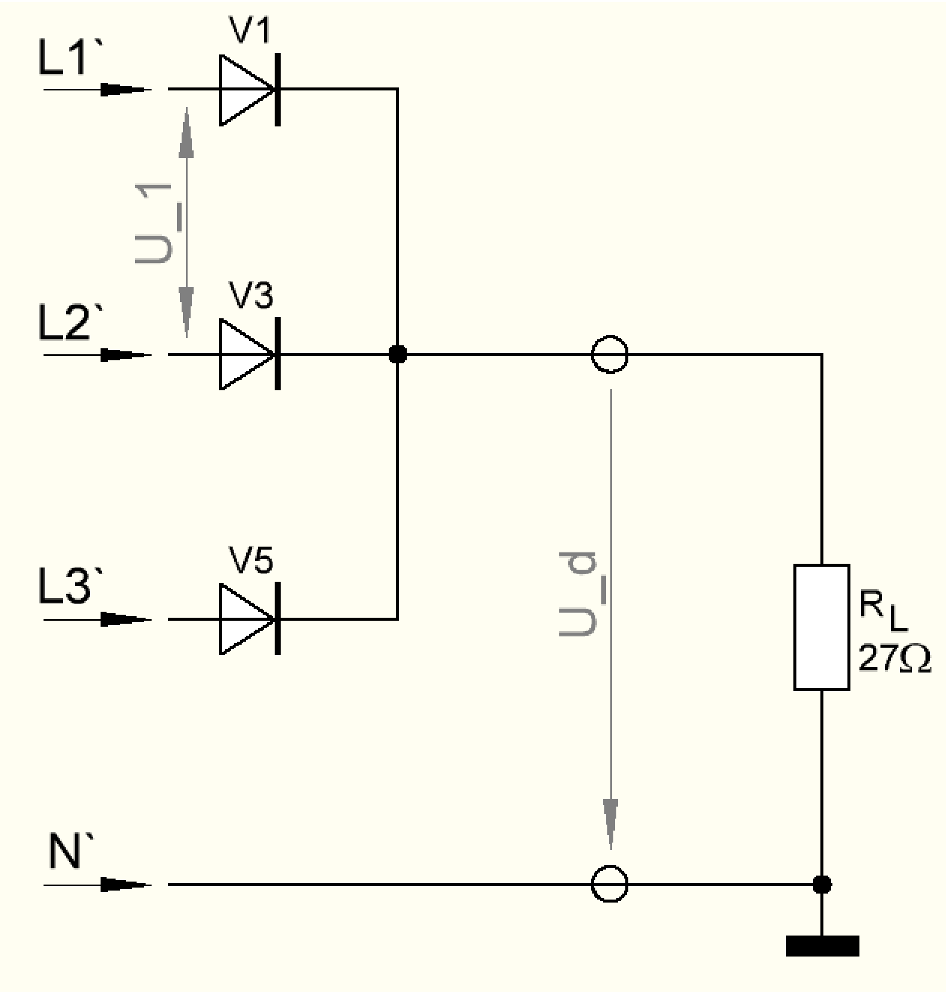
Question 2:	Which one of the two short terms M3UA or M3UK is true for the circuit in pic. 2.3.1.0? Explain your decision.
Answer:	Pic. 2.3.1.0 shows a M3UK circuit. „K“ indicates cathode.
	The diodes and their cathodes form a collective DC power supply.

2.3.2 Test 3

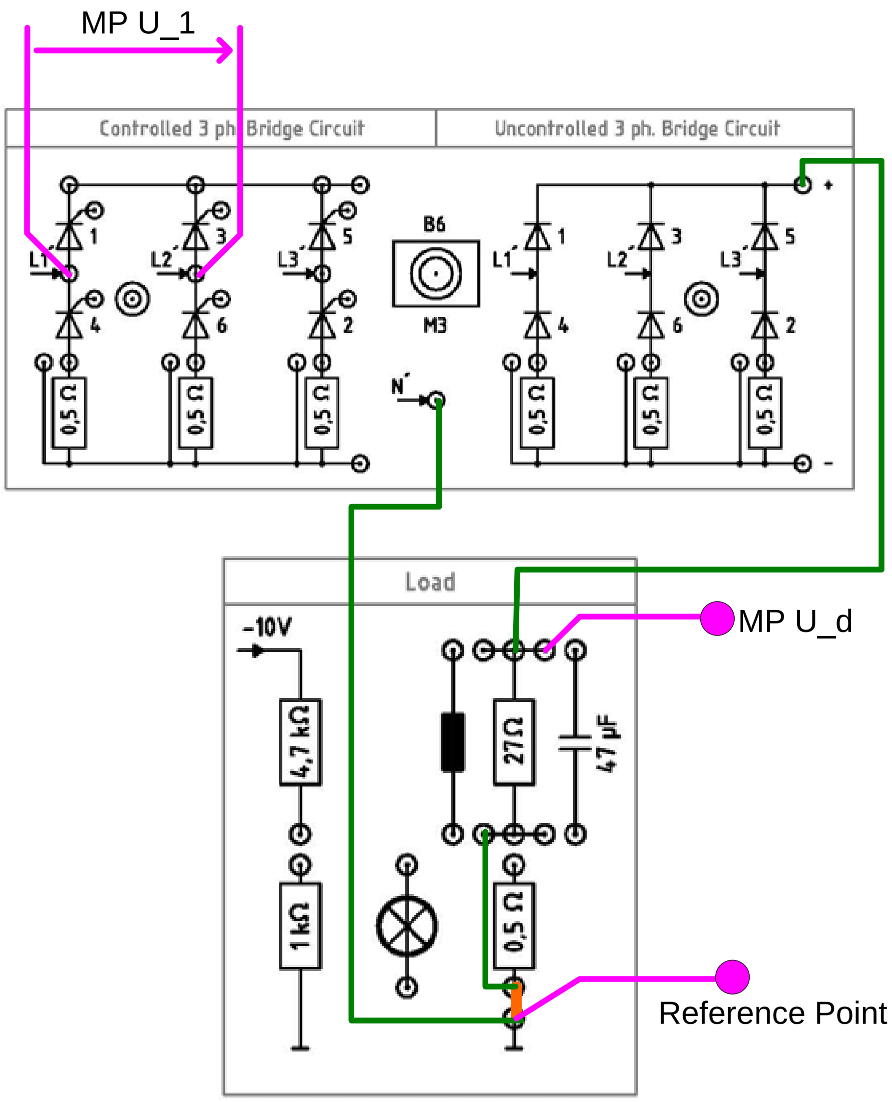
Arithmetic average and root mean square at uncontrolled rectifiers.

Test Configuration & Test Procedure

- Build up the circuit in pic. 2.3.2.0 / 2.3.2.1.
- Set the selector M3/B6 to position M3.



pic. 2.3.2.0 circuit



pic. 2.3.2.1 circuit

- Measure following parameters with a suitable measuring instrument (see 1.3.1):
  - Root mean square of input AC voltage $U_{1\ eff}$,
  - Root mean square of output AC voltage $U_{d\ eff}$,
  - Arithmetic average of output voltage $U_{d\ ar}$

Add the measured values to chart 2.3.2.2.

Circuit	M3U
$U_{1\ eff}$ / V	18,6
$U_{d\ eff}$ / V	10,7
$U_{d\ ar}$ / V	10,4

chart 2.3.2.2

- Determine following values and add to chart 2.3.2.3.

M3U:

$$\frac{U_{1eff}}{U_{dar}} = \frac{18{,}6V}{10{,}4V} = 1{,}79$$

$$\frac{U_{deff}}{U_{dar}} = \frac{10{,}7V}{10{,}4V} = 1{,}03$$

Circuit	M3U
$U_{1\ eff}$ / $U_{d\ ar}$	1,79
$U_{d\ eff}$ / $U_{d\ ar}$	1,03

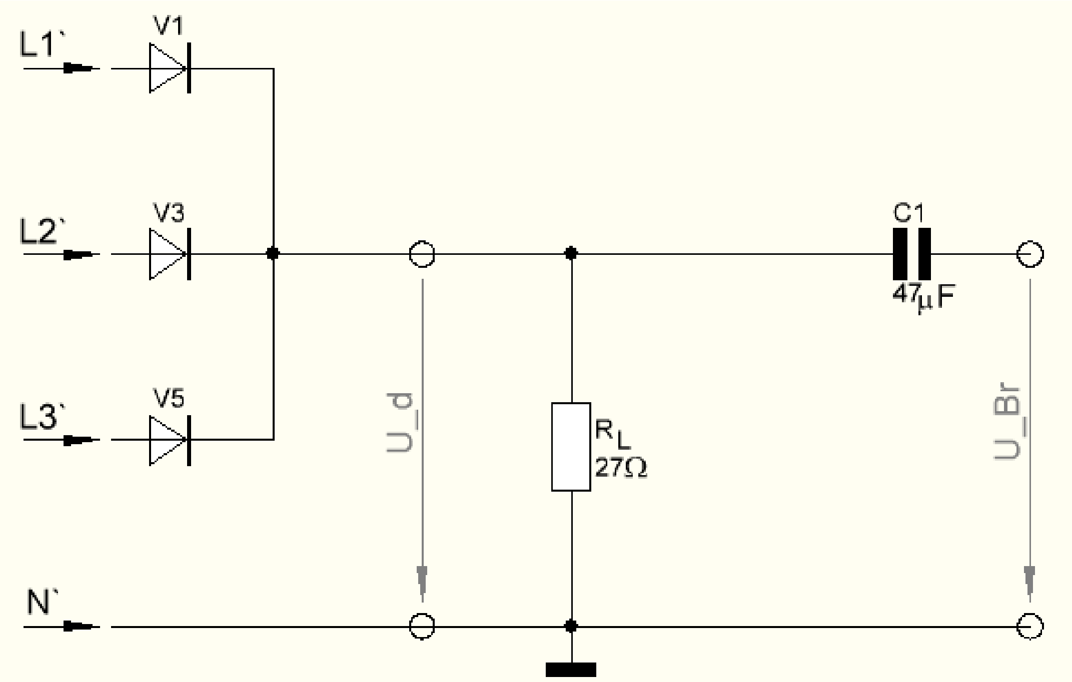
chart 2.3.2.3

2.3.3 Test 4

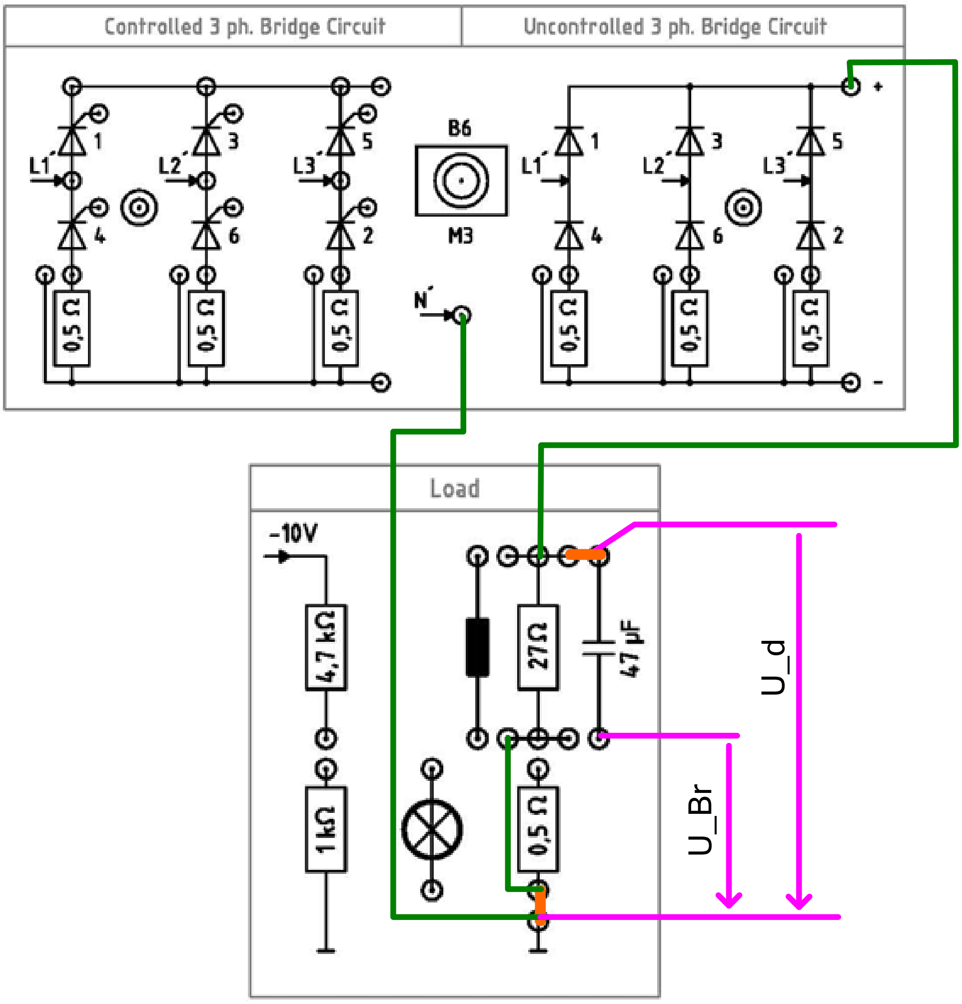
Pulse rate and ripple at uncontrolled rectifiers.

Test Configuration & Test Procedure

- Build up the circuit in pic. 2.3.3.0 / 2.3.3.1.
- Set the selector M3/B6 to position M3.



pic. 2.3.3.0 circuit



pic. 2.3.3.1 circuit

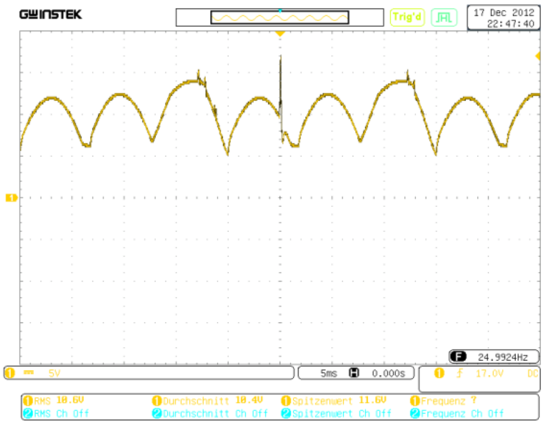
- Measure the output voltage (U_d) with the oscilloscope and draw the curve in pic. 2.3.3.2.

Note: ***Do not use capacitor C_1 = 47 µF from the load block of the Power Electronic Panel for the measurement of the output voltages.***

Oscilloscope Settings:

Output Voltage U_d: 5 V / div.

Time t: 5 ms / div.



pic. 2.3.3.2 M3U circuit

- Measure following parameters with a suitable measuring instrument (see page 1.3.1):
  - $U_{d\,ar}$ (arithmetic average of output voltage)
  - $U_{Br\,eff}$ (root mean square of ripple voltage)

Note: ***Please use the capacitor C_1 = 47 µF at the load block of the Power Electronic Panel to decouple the DC portion.***

- Determine ripple w and pulse rate p.
- Add the measured values to chart 2.3.3.3.

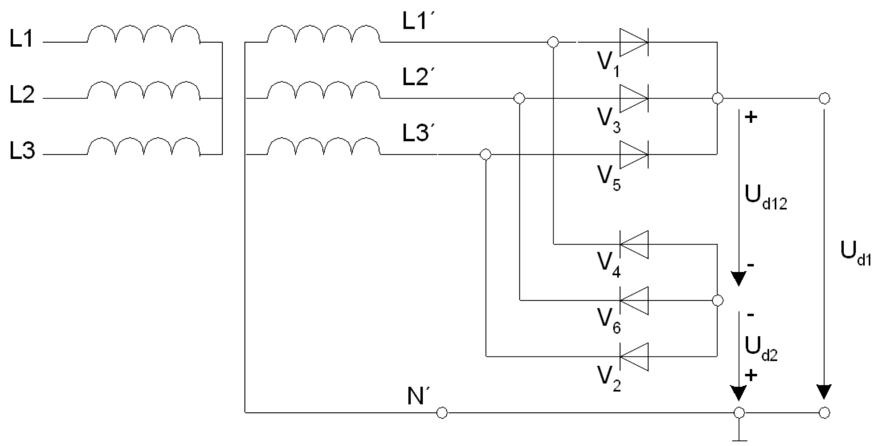
Circuit	M3U
$U_{d\,ar}$ / V	10,4
$U_{Br\,eff}$ / V	2,29
Ripple w	0,22
Pulse rate p	3

chart 2.3.3.3

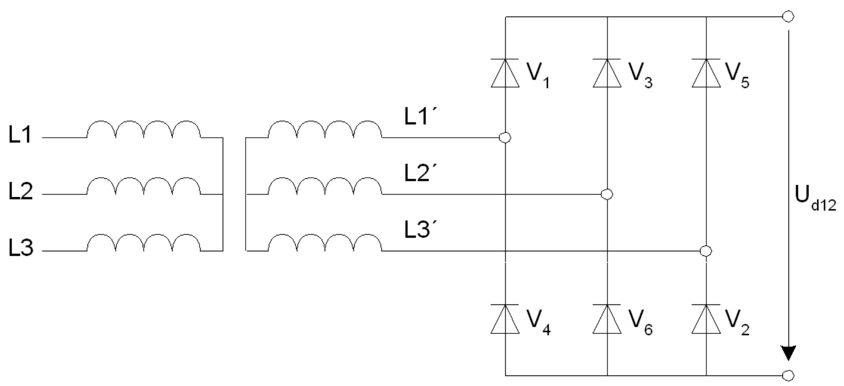
2.4 Uncontrolled Six-Pulse Bridge Circuit B6U

The uncontrolled B6U six-pulse bridge is used for rectification of 3phase alternating voltage. This circuit provides maximum idealized DC voltage, as the respective pair of diodes (V_1 + V_4, V_3 + V_6, V_5 + V_2) takes over flow of current at the commutation moment. Order of diode passage is given by the sequence of voltage rise. For easier comprehension the B6U circuit can be composed of two M3U circuits (see pic. 2.4.0.0).

Circuit:



pic. 2.4.0.0 B6U circuit composed of 2x M3U circuits



pic. 2.4.0.1 B6U circuit

Function:

Diodes V_1, V_3 and V_5 make a M3U circuit, which form a positive poled output voltage (U_{d1}) with respect to the transformer center. The diodes V_4, V_6 and V_2 are positioned reversed to the phase voltage, that means output voltage U_{d2} of the „second“ M3U circuit is of negativ polarity with respect to N’.

Total output voltage U_d is calculated as follows by interconnection of two M3U circuits (u = instant value, U = arithmetic average):

$$u_d = u_{d1} - u_{d2}$$

Ripple / Ripple Voltage

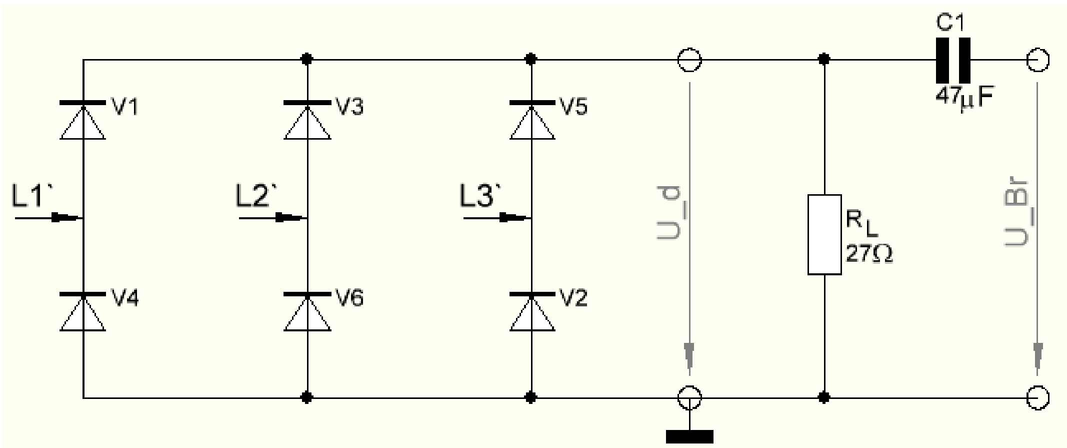
Ripple

The ripple w (stated in %) is significant for the quality of a rectifier circuit. The ripple shows the ratio of ripple portion (effective value of ripple voltage $U_{Br\,eff}$) and DC portion (arithmetic average $U_{d\,ar}$), it is calculated as follows:

$$w = \frac{U_{Br\,eff}}{U_{d\,ar}}$$

Root Mean Square Ripple Voltage

For determination of the ripple voltages' RMS, it is essential to separate the DC voltage from the rectifiers' output voltage U_d. The simplest way to do so is with a capacitor (C_1) at the output of the circuit.



pic. 2.4.0.2 Circuit for measurement of ripple voltage

Pulse Rate

The pulse rate p often is stated as additional quality criteria for rectifier circuits. This indicates the frequency of ripple voltage f_{Br}.

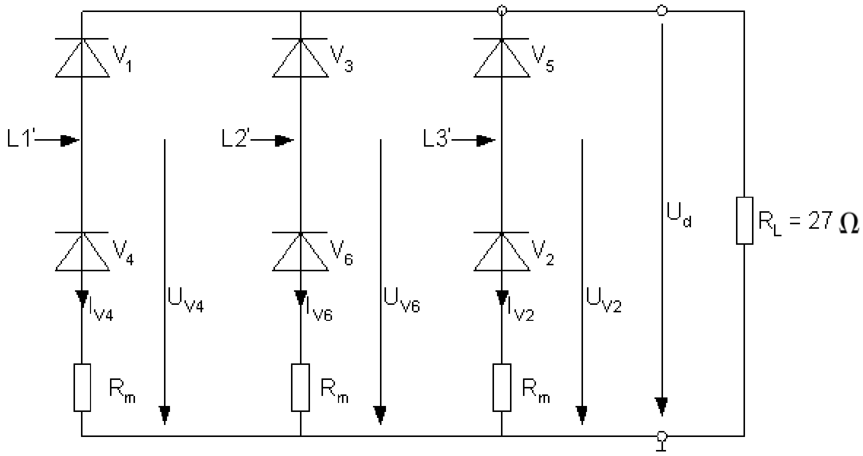
The pulse rate indicates the number of DC blocks occurring in one period of the applied AC voltage.

2.4.1 Test 1

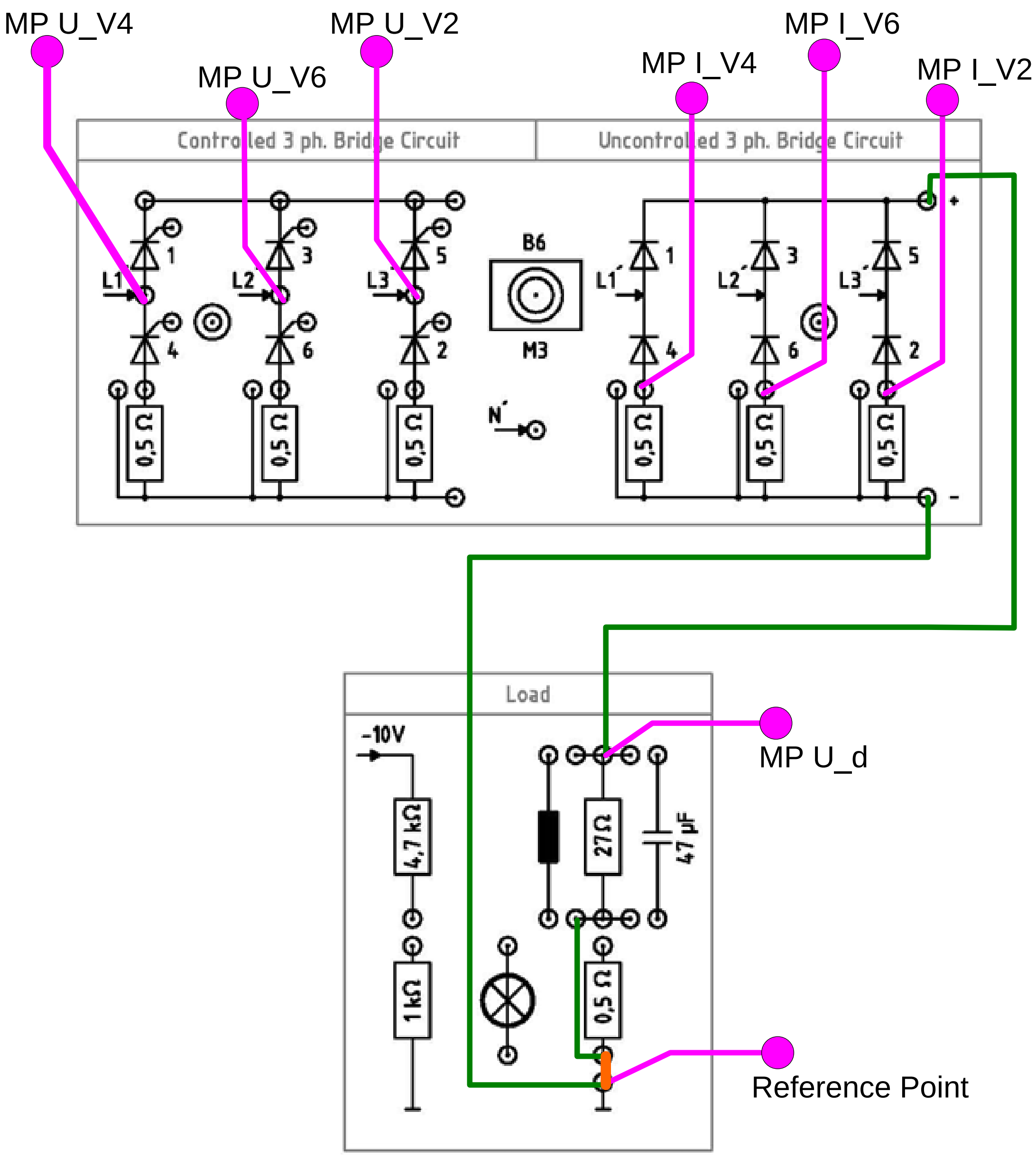
Currents and voltages in the uncontrolled six-pulse bridge circuit B6U.

Test Configuration & Test Procedure

Build up the circuit in pic. 2.4.1.0 / pic. 2.4.1.1.



pic. 2.4.1.0 circuit

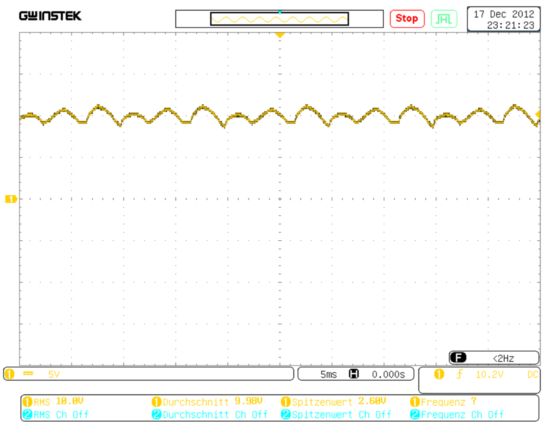


pic. 2.4.1.1 circuit

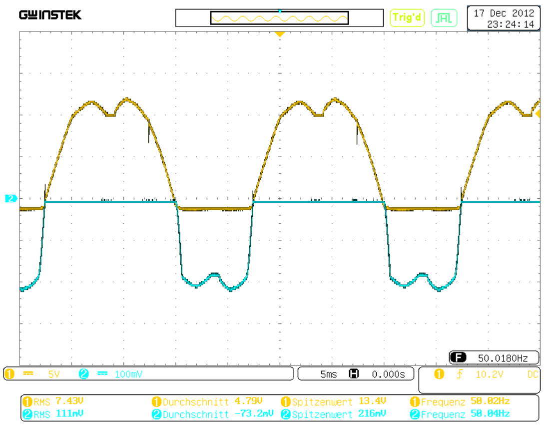
- Set the selector M3/M6 to position B6.

- Measure following parameters with the oscilloscope:
  - Output Voltage U_d,
  - Diode Voltages U_{V4}, U_{V6}, U_{V2},
  - Diode Currents I_{V4}, I_{V6}, I_{V2}

- Draw the curves into pic. 2.4.1.2 to pic. 2.4.1.5.



pic. 2.4.1.2



pic. 2.4.1.3

Oscilloscope Settings:

Output Voltage U_d: 5 V / div.

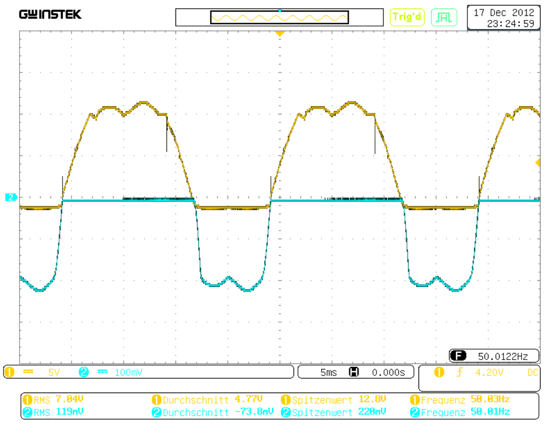
Time t: 5 ms / div.

Oscilloscope Settings:

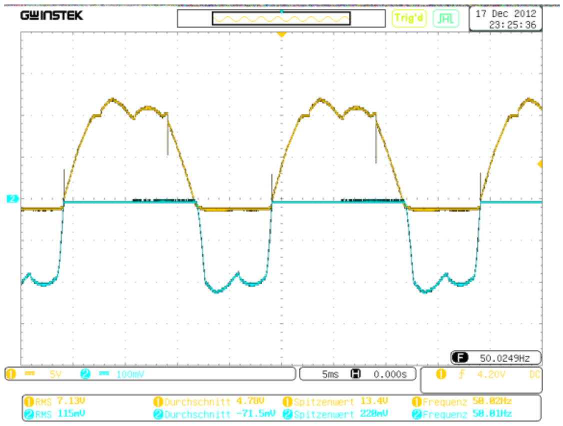
Diode Voltage U_{V4}: 5 V / div.
Diode Current I_{V4}: 0,2 A / div.
= 0,1 V / div.

Time t: 5 ms / div.

Current Conversion with Rm = 0,5 Ohm



pic. 2.4.1.4



pic. 2.4.1.5

Oscilloscope Settings:

Diode Voltage U_{V6}: 5 V / div.
Diode Current I_{V6}: 0,2 A / div.
= 0,1 V / div.
Time t: 5 ms / div.

Current Conversion with Rm = 0,5 Ohm

Oscilloscope Settings:

Diode Voltage U_{V2}: 5 V / div.
Diode Current I_{V2}: 0,2 A / div.
= 0,1 V / div.
Time t: 5 ms / div.

Current Conversion with Rm = 0,5 Ohm

Question 1:	If the diode V_2 of the lower bridge-half is conducting, which diodes of the upper bridge-half are possibly conducting?
Answer:	L1’ is more positive than L3’, thus current flows through V_1 and V_2.
	If L2’ is more positive than L3’, current will flow through V_3 and V_2.

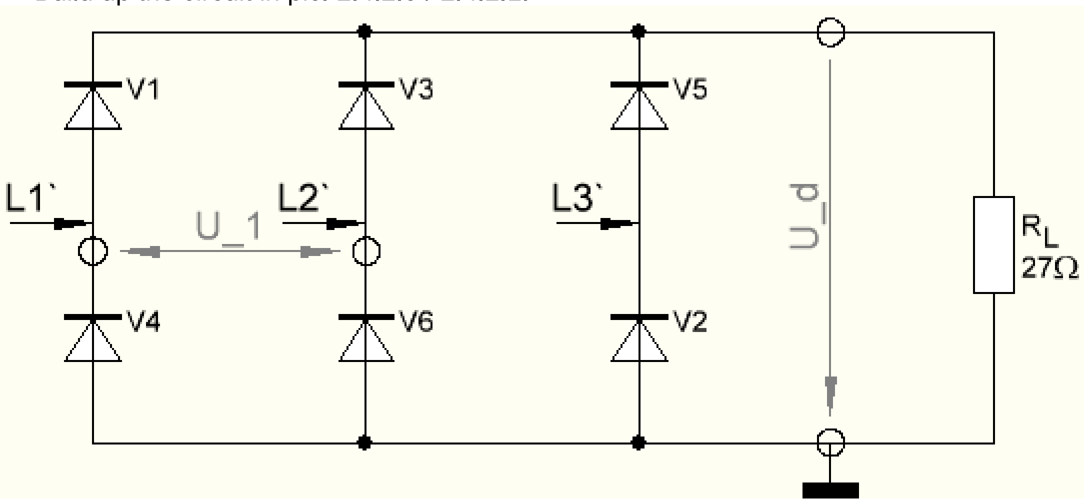
Question 2:	In chapter 2.4 we have learned, that the instant value of the rectifier output voltage u_d is calculated u_{d1} - u_{d2}. Why is root mean square U_d not U_{d1} - U_{d2}?
Answer:	The phases U_{d1} and U_{d2} are offset by 60°.
	Therefore only instant values u_{d1} and u_{d2} are used for the
	instant values of u_d.

2.4.2 Test 3

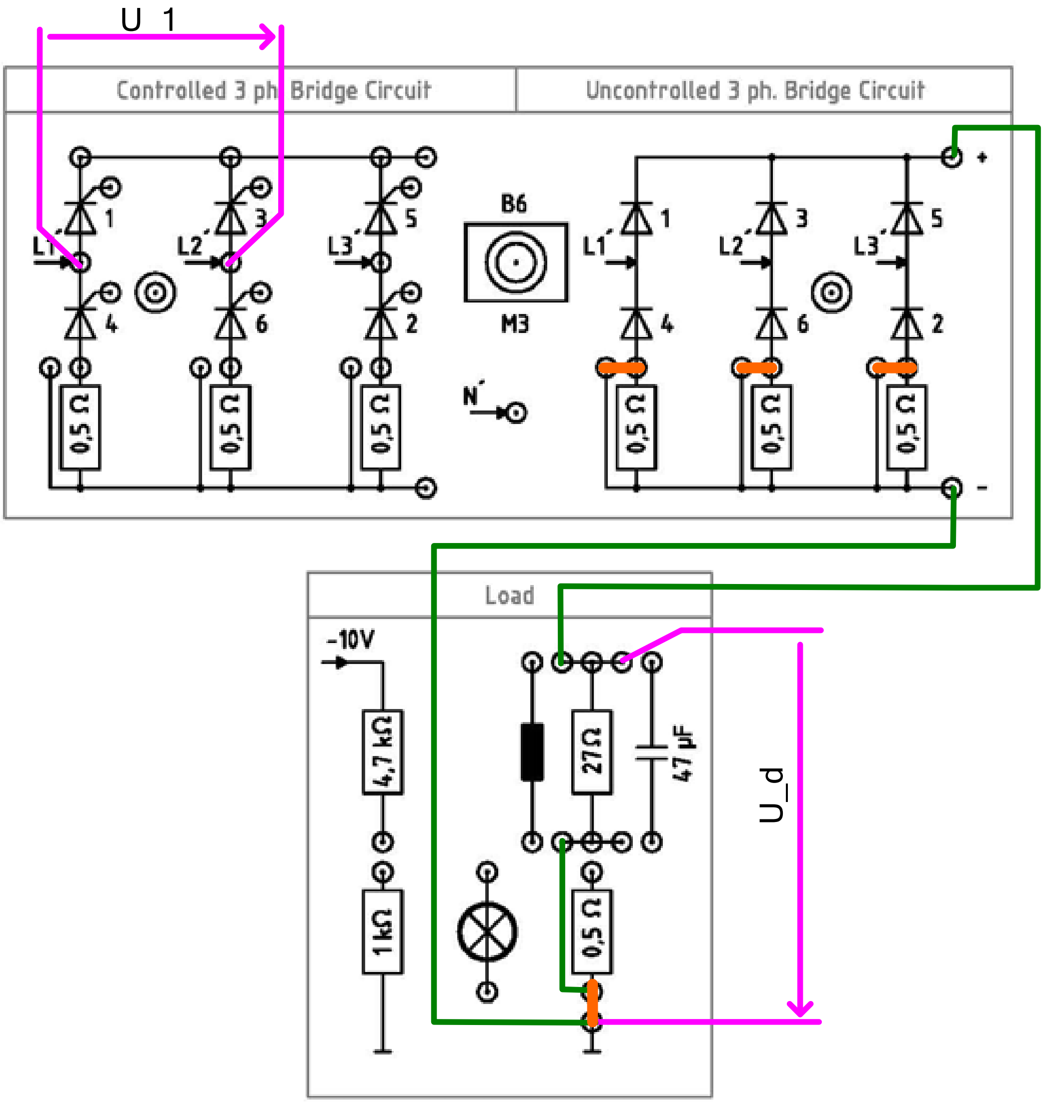
Arithmetic average and root mean square at uncontrolled rectifiers.

Test Configuration & Test Procedure

- Build up the circuit in pic. 2.4.2.0 / 2.4.2.1.



pic. 2.4.2.0 circuit



pic. 2.4.2.1 circuit

- Set the selector M3/M6 to position B6.

- Measure following parameters with a suitable measuring instrument (see 1.3.1):
  - Root mean square of input AC voltage $U_{1\,eff}$,
  - Root mean square of output AC voltage $U_{d\,eff}$,
  - Arithmetic average of output voltage $U_{d\,ar}$

- Add the measured values in chart 2.4.2.2.

Circuit	B6U
$U_{1\,eff}$ / V	9,25
$U_{d\,eff}$ / V	10,2
$U_{d\,ar}$ / V	10,2

chart 2.4.2.2

- Determine following values and add to chart 2.4.2.3.

B6U:

$$\frac{U_{1eff}}{U_{dar}} = \frac{9{,}25V}{10{,}2V} = 0{,}91$$

$$\frac{U_{deff}}{U_{dar}} = \frac{10{,}2V}{10{,}2V} = 1{,}00$$

Circuit	B6U
$U_{1\,eff}$ / $U_{d\,ar}$	0,91
$U_{d\,eff}$ / $U_{d\,ar}$	1,00

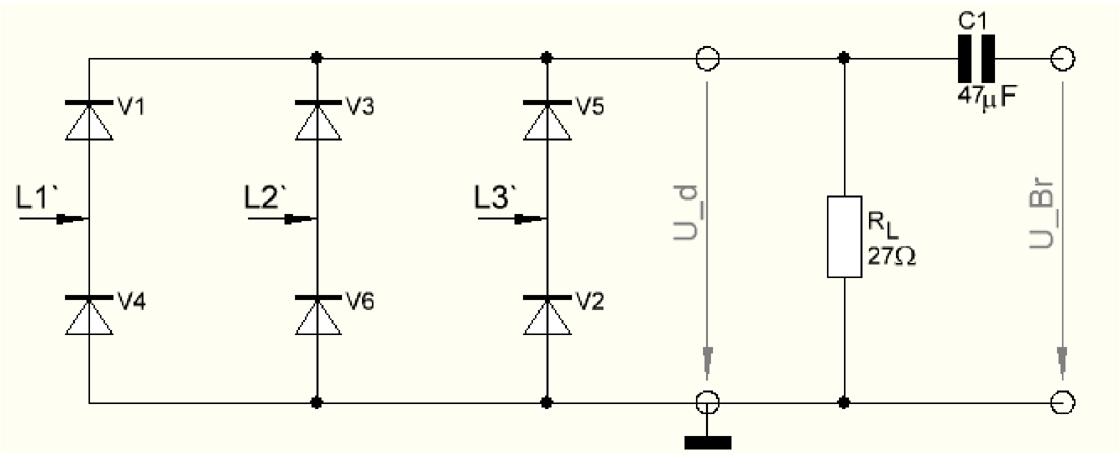
chart 2.4.2.3

2.4.3 Test 4

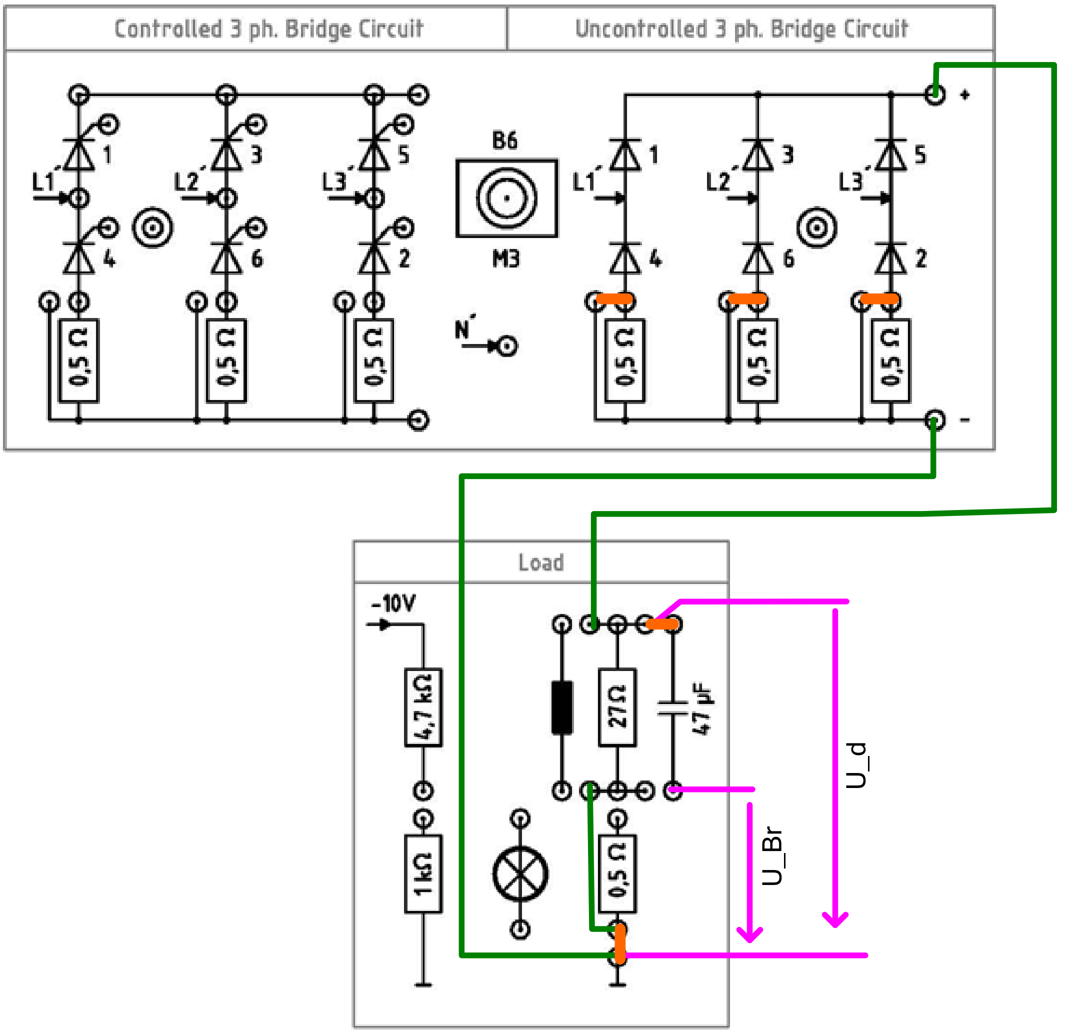
Pulse rate and ripple at uncontrolled rectifiers.

Test Configuration & Test Procedure

- Build up the circuit in pic. 2.4.3.0 / 2.4.3.1.
- Set the selector M3/M6 to position B6.



pic. 2.4.3.0 circuit



pic. 2.4.3.1 circuit

- Measure the output voltage (U_d) and draw the curve into pic. 2.4.3.2.

Note: ***Do not use capacitor C_1 = 47 µF from the load block of the Power Electronic Panel for the measurement of the output voltage.***

Oscilloscope Settings:

Output Voltage U_d:	5	V / div.
Time t:	5	ms / div.

pic. 2.4.3.2 B6U circuit

- Measure following parameters with a suitable measuring instrument (see 1.3.1):
  - $U_{d\ ar}$ (arithmetic average of output voltage)
  - $U_{Br\ eff}$ (root mean square of ripple voltage)

Note: ***Please use the capacitor C_1 = 47 µF at the load block of the Power Electronic Panel to decouple the DC portion.***

- Determine ripple w and pulse rate p.
- Add the measured values in chart. 2.4.3.3.

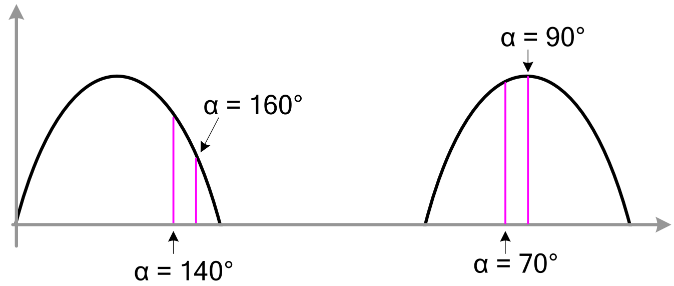
Circuit	B6U
$U_{d\ ar}$ / V	10,2
$U_{Br\ eff}$ / V	0,63
Ripple w	0,062
Pulse rate p	6

chart 2.4.3.3

3 Controlled Rectifier

If the output voltage of a rectifier should be altered, all or some of the diodes could be replaced by thyristors. This gives us a manipulable firing moment with variable output voltage. If the firing angle of α=0° is used, the circuit acts like an uncontrolled rectifier.

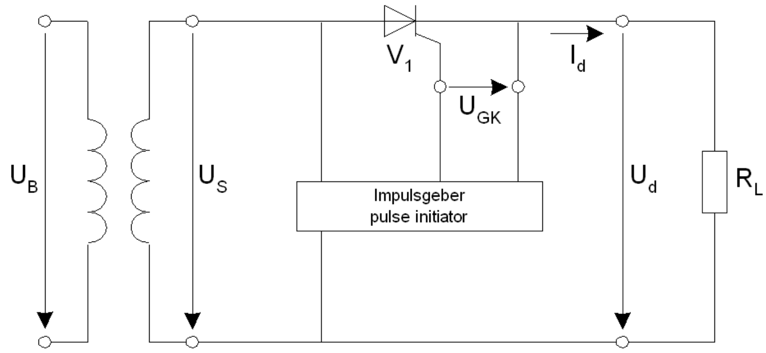
Controlled rectifiers allow the regulation of input voltage by phase-angle adjustment to a certain load R_L. Voltage increase is not linear as portions of the sinus mains voltage are transferred. If the triggering angle alternates from α = 140° by 20° to α = 160° energy increase is less than if alternated from α = 70° by 20° to α = 90°.



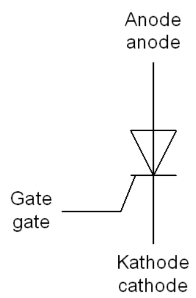
3.1 Controlled Single-Pulse Center Tapped Circuit M1C

The M1C single-pulse center tapped circuit is the simplest form of a rectifier circuit, and is exemplarily chosen to explain the function of a controlled rectifier.

Circuit:



pic. 3.1.0.0 M1C controlled single-pulse center tapped circuit

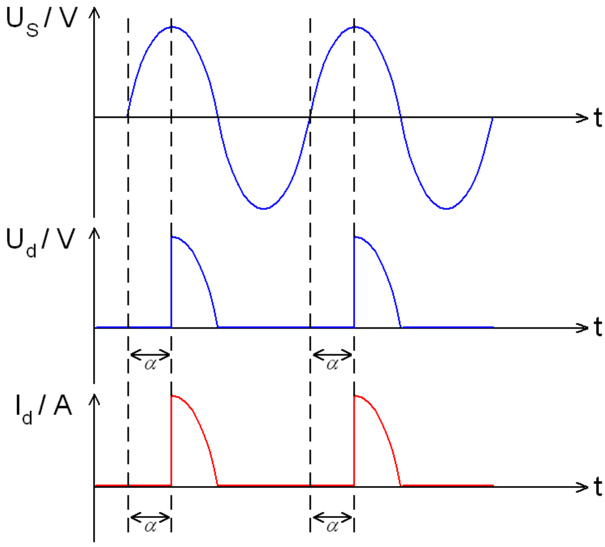


pic. 3.1.0.1 thyristor

Function:

The input AC voltage U_S is applied to the load R_L as DC voltage U_d via thyristor. Thereby the thyristor gets conducting, if voltage at the anode is higher than at the cathode and if a positive triggering signal U_{GK} is given at the gate.

Signal Wave Form:



pic. 3.1.0.2 signal wave form at α =90°

Triggering Angle:

The thyristor only switches-on during the positive half wave of AC voltage. Means that the triggering angle is somewhere between $\alpha = 0°$ and $\alpha = 180°$. If the triggering angle is $\alpha = 0°$ the output voltage U_d reaches its maximum ($0{,}45 \times U_S$). At a triggering angle of $\alpha = 180°$ output voltage is 0 V.

If the positive half-wave reverses into a negative one, switch-on of the thyristor is impossible. It is now in the so called reverse blocking state.

As the circuit above is an all ohmic load, the output voltage U_d and output current I_d are inphase (see signal wave form pic 3.1.0.2).

Operating Angle:

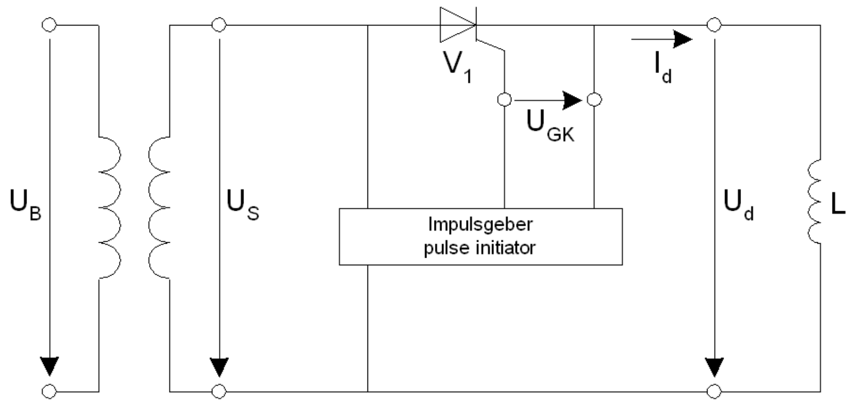
In this example, load current I_d flows between $\varphi = 90°$ and $\varphi = 180°$, thus operating angle Φ is 90°.

Following is true for the calculation of the operating angle:

$$\Phi = 180° - \alpha$$

3.1.1 Inductive Load

Circuit:

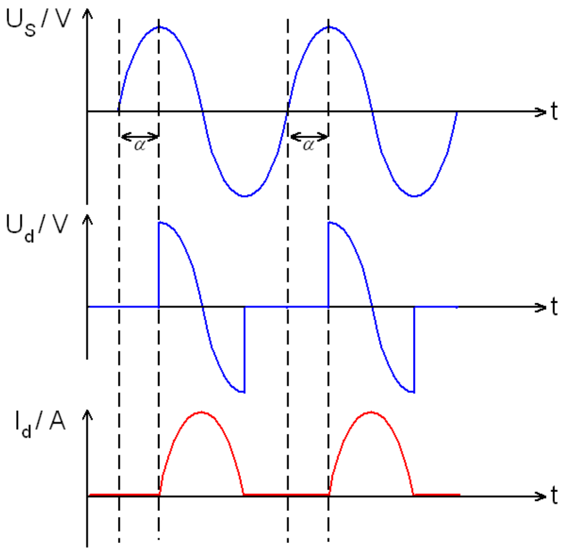


pic. 3.1.1.0 M1C with all inductive load

Pic. 3.1.1.0 shows a M1C rectifier circuit with all inductive load. See pic. 3.1.1.1 for the signal wave forms.

If the thyristor is „fired“ during the positive half-wave of the AC voltage U_S, current I_d increases, inductance L is fed in from mains. Voltage and current have the same polarity.
If the polarity of the DC voltage U_S reverses, current flow direction will not alter. The thyristor stays conducting. Inductive L however feeds energy into mains.
As pure inductance is regarded lossless, energy consumption and energy transfer has to be equal. Size of the positive half-wave of U_d is identical to size of the negative half-wave of U_d.

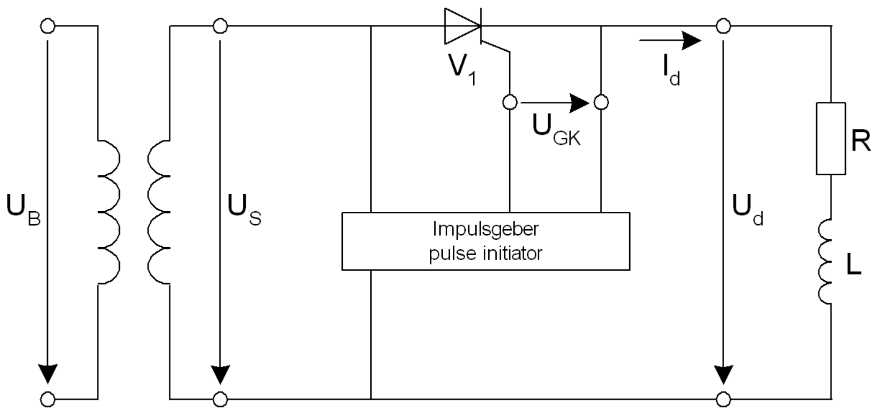
Signal Wave Form:



pic. 3.1.1.1 signal wave form of pure inductive load at α =90°

3.1.2 Inductive and Ohmic Load

Circuit:



pic. 3.1.2.0 M1C with inductive and ohmic load

Practically there is no application for all inductive loads as inductance never occurs without (ohmic) losses (see pic. 3.1.2). For this reason energy transfer to mains is less than energy consumption from mains. Size of the negative half-wave of U_d therefore is smaller than size of the positive half-wave of U_d (see pic. 3.1.2.1).

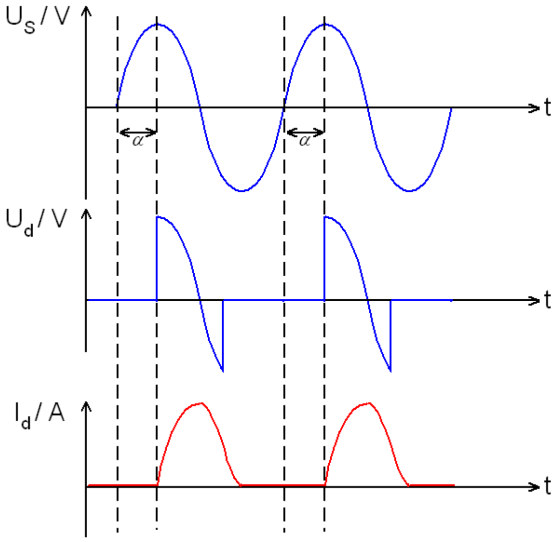
Voltage U_d is dependent on the triggering angle α.

.

$$U_{d\alpha} = U_{d0} \cdot \left(\frac{1 + \cos\alpha}{2} \right)$$

for M1C circuit it is: $U_{d0} = 0{,}45 \cdot U$

Signal Wave Form:



pic. 3.1.2.1 signal wave form inductive and ohmic load at α =90°

Notes to the measurements following:

- The adjuster for the triggering angle α_W within the phase gate control should be non-effective. Means it has to be positioned on the right hand sided arrester.

- For measurements in this area the phase gate control needs voltage of +U. Therefore set the potentiometer between 0 V and +10 V. Connect the potentiometer output to the control input +U of the phase gate control I.

- Instead of the gate trigger voltage, the number of the pulse initiator is stated on the thyristor. That means e. g. I_1 is the pulse initiator 1 of the phase gate control I. The upper connector has to be connected to the gate. The lower connector has to be connected to the cathode.

- For all oscillosgraphs the oscilloscope has to be internally triggered at LINE. If mains voltage U_S and output voltage U_d do not have a common reference point, they have to be measured separately one after the other.

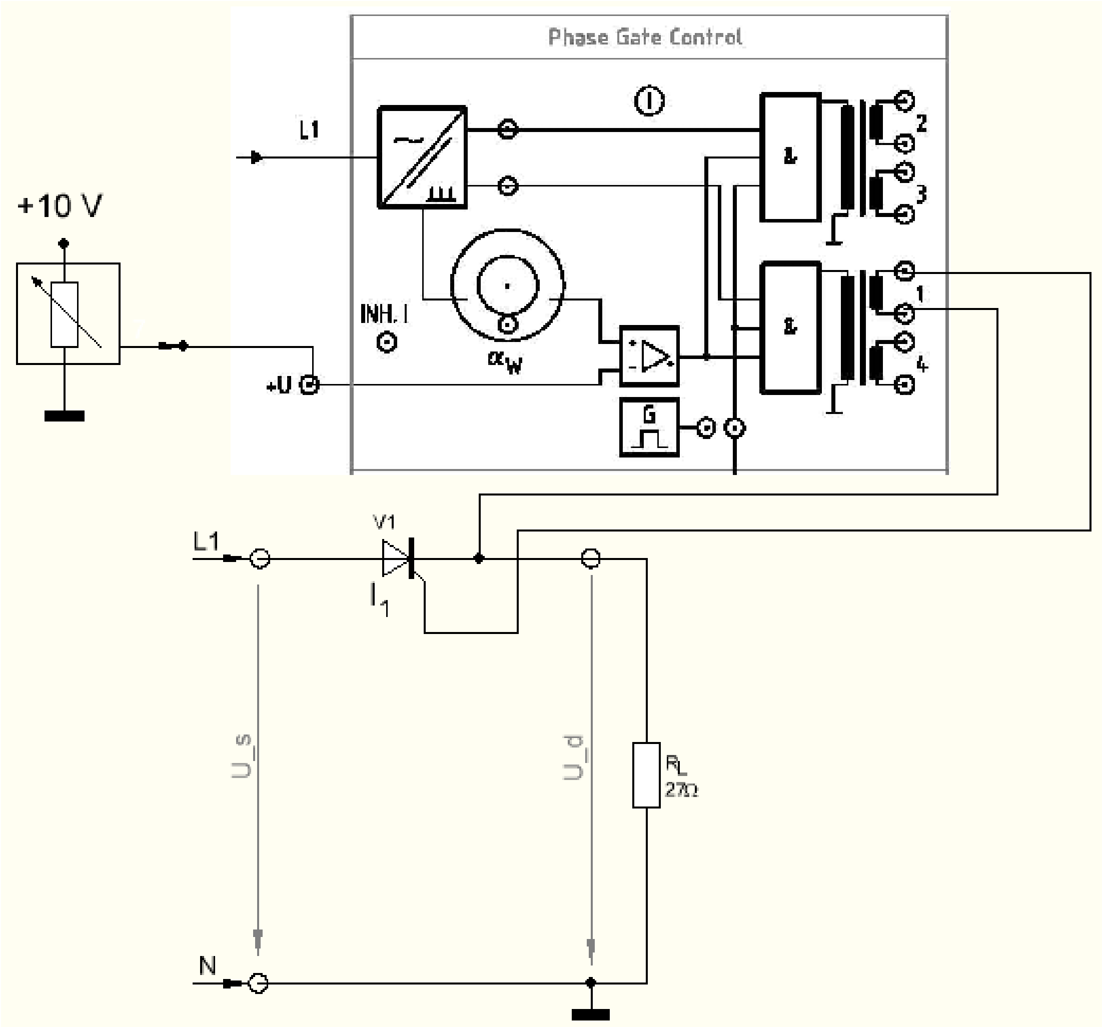
3.1.3 Test 1

Currents and voltages in the controlled single-pulse center tapped circuit M1C.

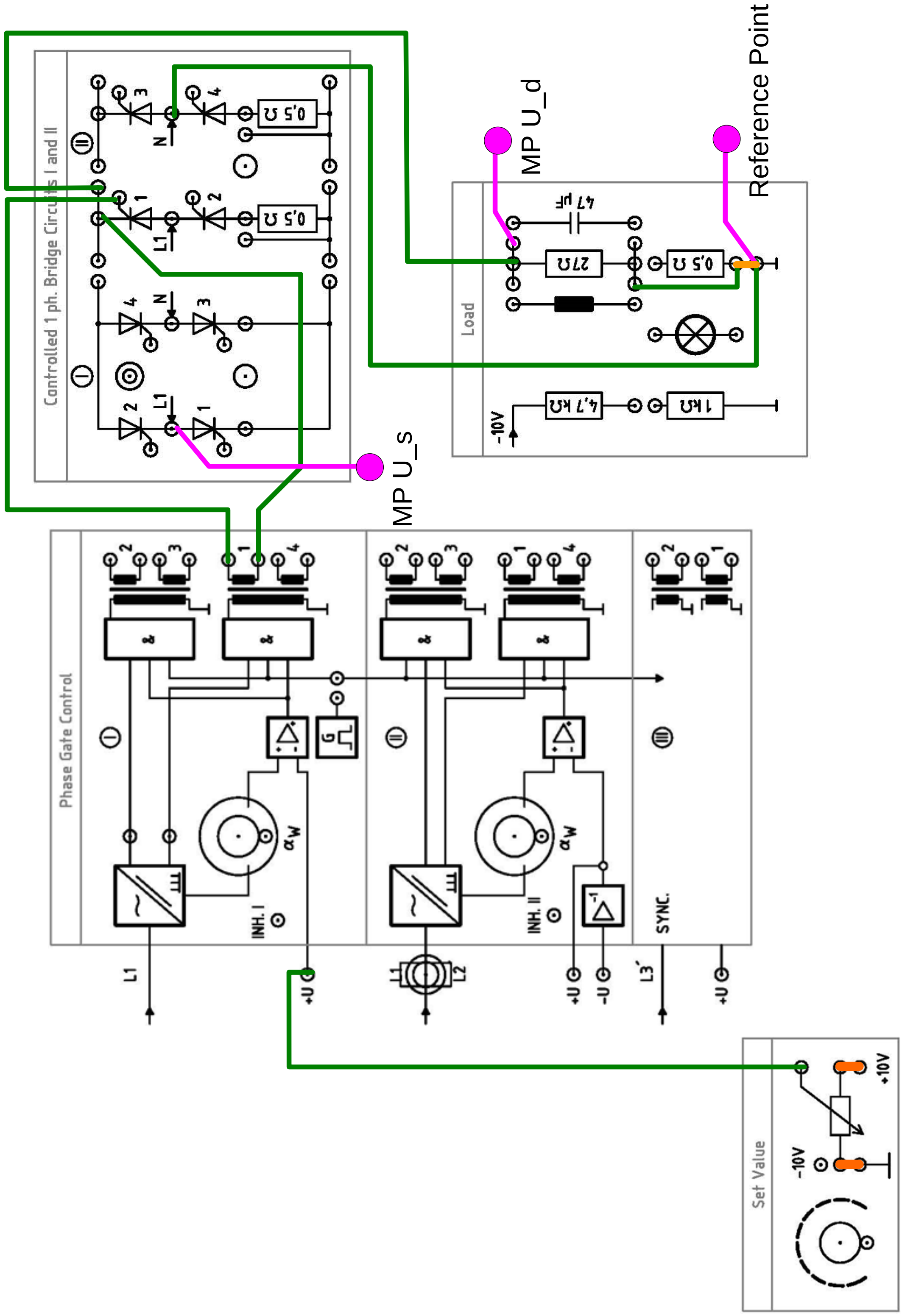
Test Configuration & Test Procedure

- Build up the circuit in pic. 3.1.3.0 and the Power Electronic Panel at pic. 3.1.3.1 auf.

Note: ***Please use thyristor 1 of the 1-phase bridge circuit I.***

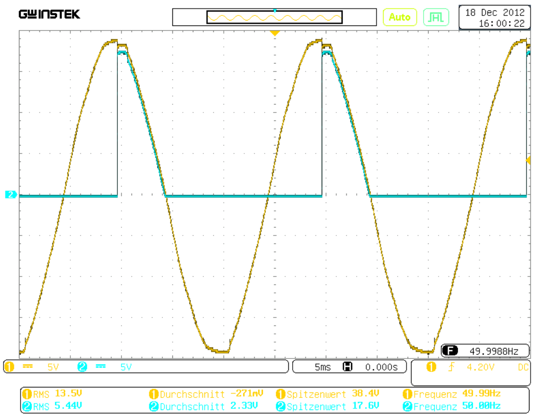


pic. 3.1.3.0 circuit



pic. 3.1.3.1 Circuit at the Power Electronic Panel

- Set the triggering angle to α = 90 °.
- For load connect an all-ohmic resistor.
- Measure following parameters with the oscilloscope:
  - Mains voltage U_S,
  - Output voltage U_d
- Draw the curve in pic. 3.1.3.2.

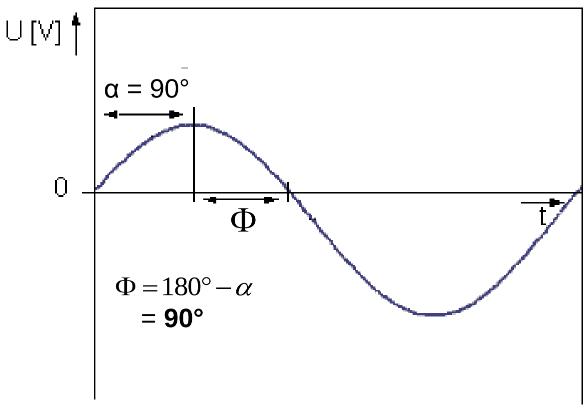


pic. 3.1.3.2

Oscilloscope Settings:

Mains Voltage U_S:	5 V / div.
Output Voltage U_d:	5 V / div.
Time t:	5 ms / div.

Question:	What is the duration of current flow and how big is the operating angle at ohmic load with a triggering angle of 90°?
Answer:	In the picture bellow you can see, that no current flows in the angle of 90° to 180°. Thus the operating angle is 90°. That makes an operating period of 5 ms.



3.1.4 Test 2

Influence of an inductive component in the load on the behaviour of the M1C circuit.

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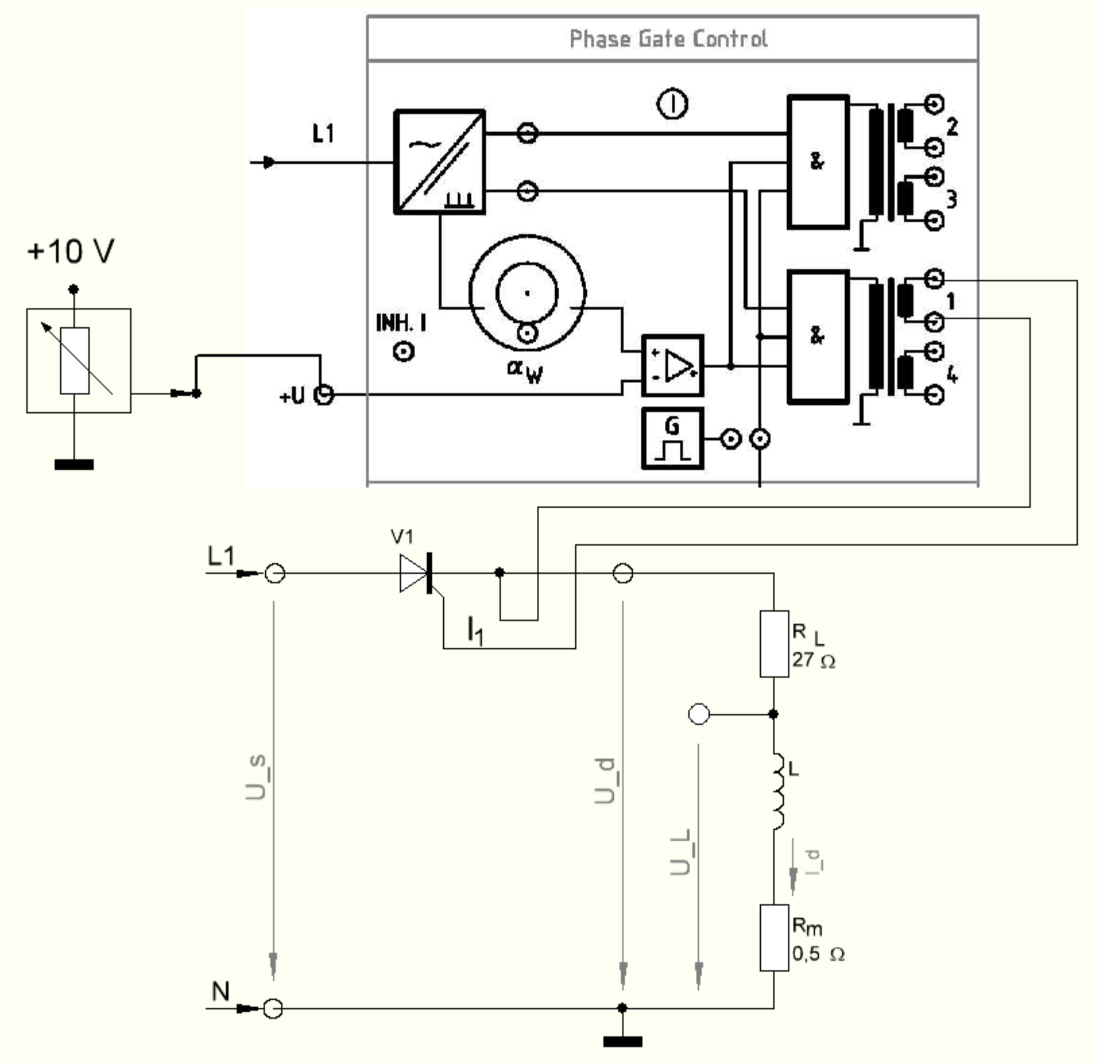
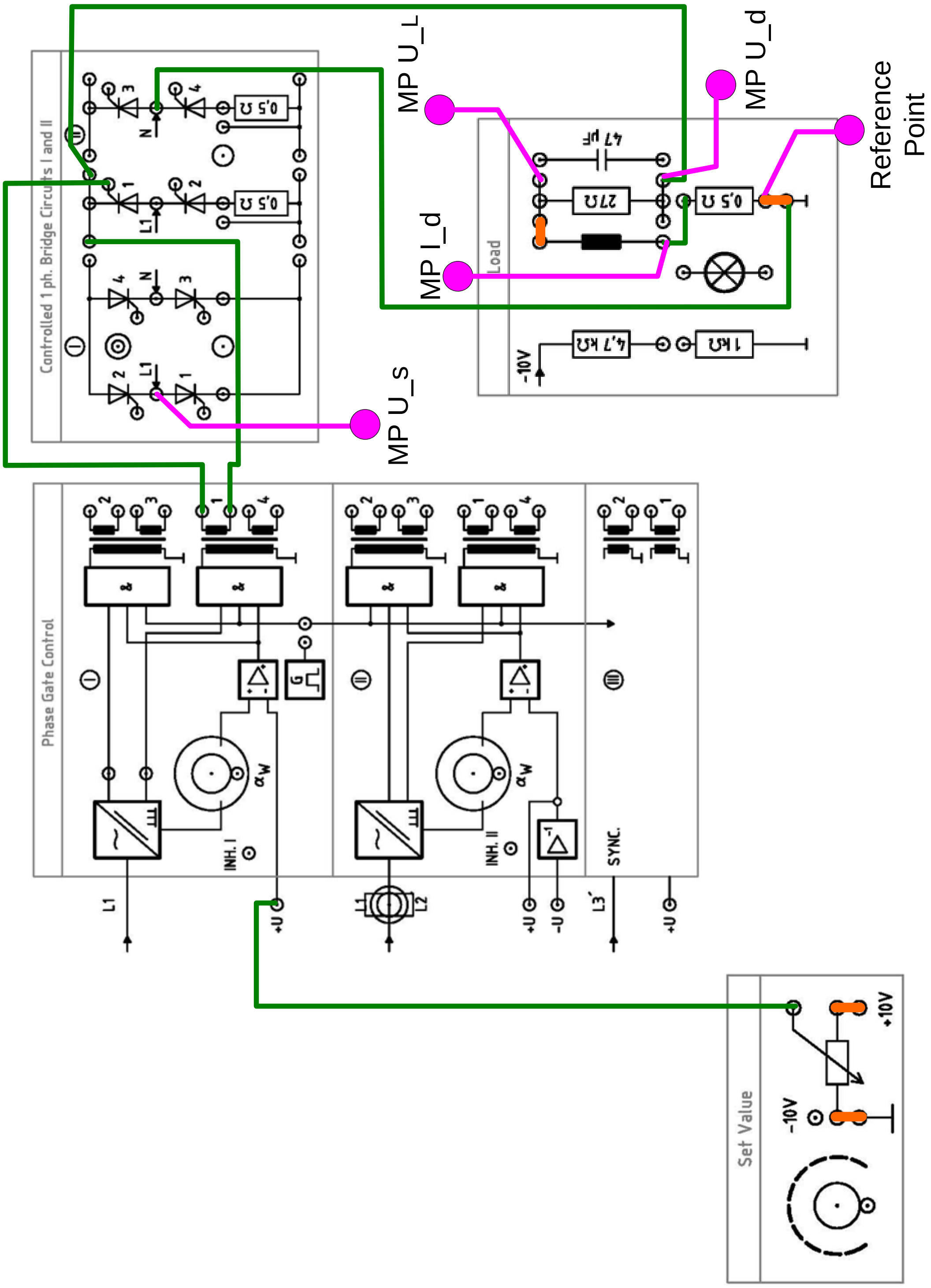
Test Configuration & Test Procedure

Build up the circuit in pic. 3.1.4.0 and pic. 3.1.4.1.



pic. 3.1.4.0circuit

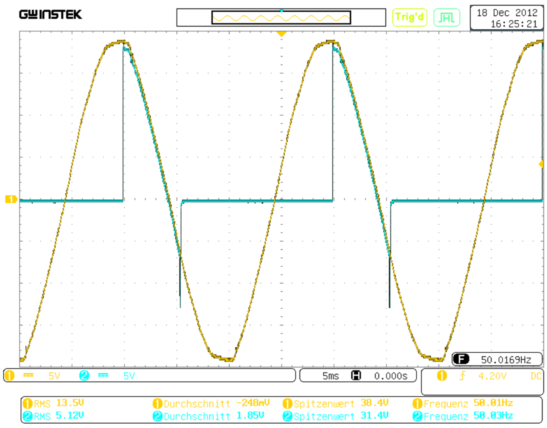


pic. 3.1.4.1 circuit

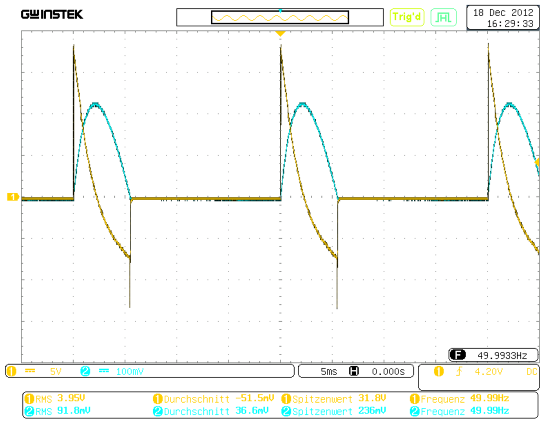
- For load connect inductance, load resistance and measuring resistance in series.

- Measure following parameters with the oscilloscope for a triggering angle of 90°:
  - Mains Voltage U_S,
  - Output Voltage U_d,
  - Coil Voltage U_L,
  - Load Current I_d

- Draw the curves into pic. 3.1.4.2 and pic. 3.1.4.3.



pic. 3.1.4.2



pic. 3.1.4.3

Oscilloscope Settings:

Mains Voltage U_S: 5 V / div.
Output Voltage $U_{d'}$: 5 V / div.

Time t: 5 ms / div.

Oscilloscope Settings:

Coil Voltage U_L: 5 V / div.
Load Current I_d: 0,2 A / div.
= 0,1 V / div.
Time t: 5 ms / div.

Current Conversion with Rm = 0,5 Ohm

Question 1:	What is the maximum theoretical operating angle at mixed load?
Answer:	Assumed the circuit is conducting exactly at 0°, and also assumed the load would be ideal inductive, operating angle could be 180° + 90° (270°).

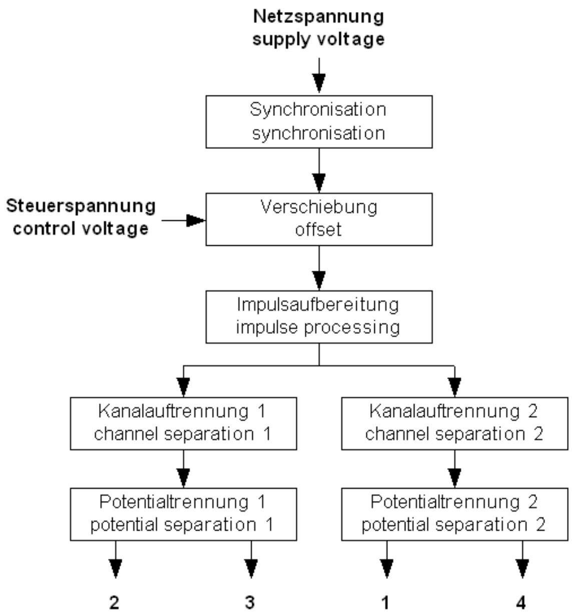
Question 2:	How would you explain the short-termed occurance of negative voltage at the output side of the M1C circuit, when ohmic-inductive load is connected?
Answer:	As long current flows, the thyristor is conducting. Current is delayed
	by the inductive portion of the load, so the thyristor remains linear
	conducting after zero-crossing of mains voltage.
	Therefore it passes complete negative mains voltage to rectifier site
	until dropping below holding current.

Question 3:	What kind of voltage is applied to the coil? All AC voltage, all DC voltage or mixed voltage?
Answer:	The coil voltage is an all AC voltage. The stored energy is equal to the
	transferred energy.
	This can be controlled at the oscilloscope by switching between AC
	and DC. At an all AC voltage the wave form has the same position.

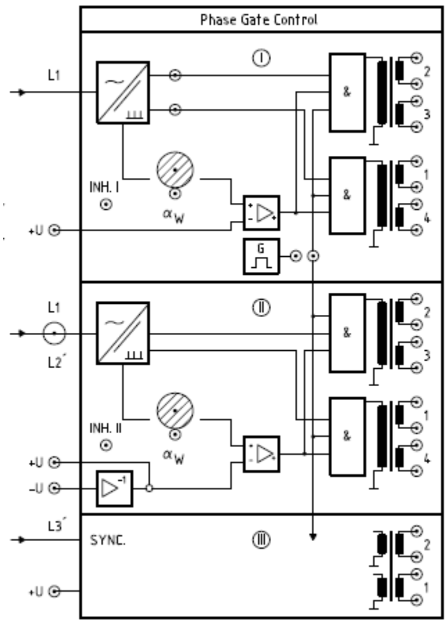
Question 4:	Compare I_d and U_L (pic. 3.1.4.5) a.) In what instant does the coil voltage changes its sign? b.) How long is U_L negative? c.) In which section does the coil store energy? When does it transfer energy?
Answer:	a.)
	Coil voltage changes its sign the instant the current flow changes from
	rising to falling.
	b.)
	U_L is negative in the falling period of the current.
	c.)
	If U_L and I_d have same polarity, the coil stores energy.
	If polarity of U_L and I_d are different, the coil transfers energy.

3.2 Phase Gate Control

To trigger a B2C two-pulse bridge it is essential to generate four galvanically isolated triggering signals, whereof two have to act synchronously at a time. Second pair of triggering signals has to be 180° offset.
It is important that the triggering signals are „fixed“ to mains voltage and the phasing is shiftable by a so called control voltage (U_e). Therefore a special triggering circuit is essential, it is shown below:



pic. 3.2.0.0 Block Diagram/ Triggering Circuit



pic. 3.2.0.1 Phase Gate Control at Panel

Function:

While zero crossing mains voltage, a saw tooth generator is started on synchronisation level (see block diagram). The generator sets its positive edge always in the zero crossing. Additionally information signals for the positive and negative half-wave are generated.
The downstream connected offset level then compares the saw tooth voltage to the control- or offset voltage U_e. If potential at the non-inverting input of the comparator (see pic. Phase Gate Control) is more positive than the signal of the inverting input, output switches to +U. If potential of the inverting input is higher, output switches to 0 Volt.
This circuit generates a square-wave signal, which has its positive edge always at the zero crossing of mains voltage. Therefore the square-wave signal is fixed synchronized to mains voltage. The negative edge is variably shiftable between zero crossings of a half-wave via control voltage U_e. Then a signal processing (pulse processing) is done, so the thyristors can be triggered.

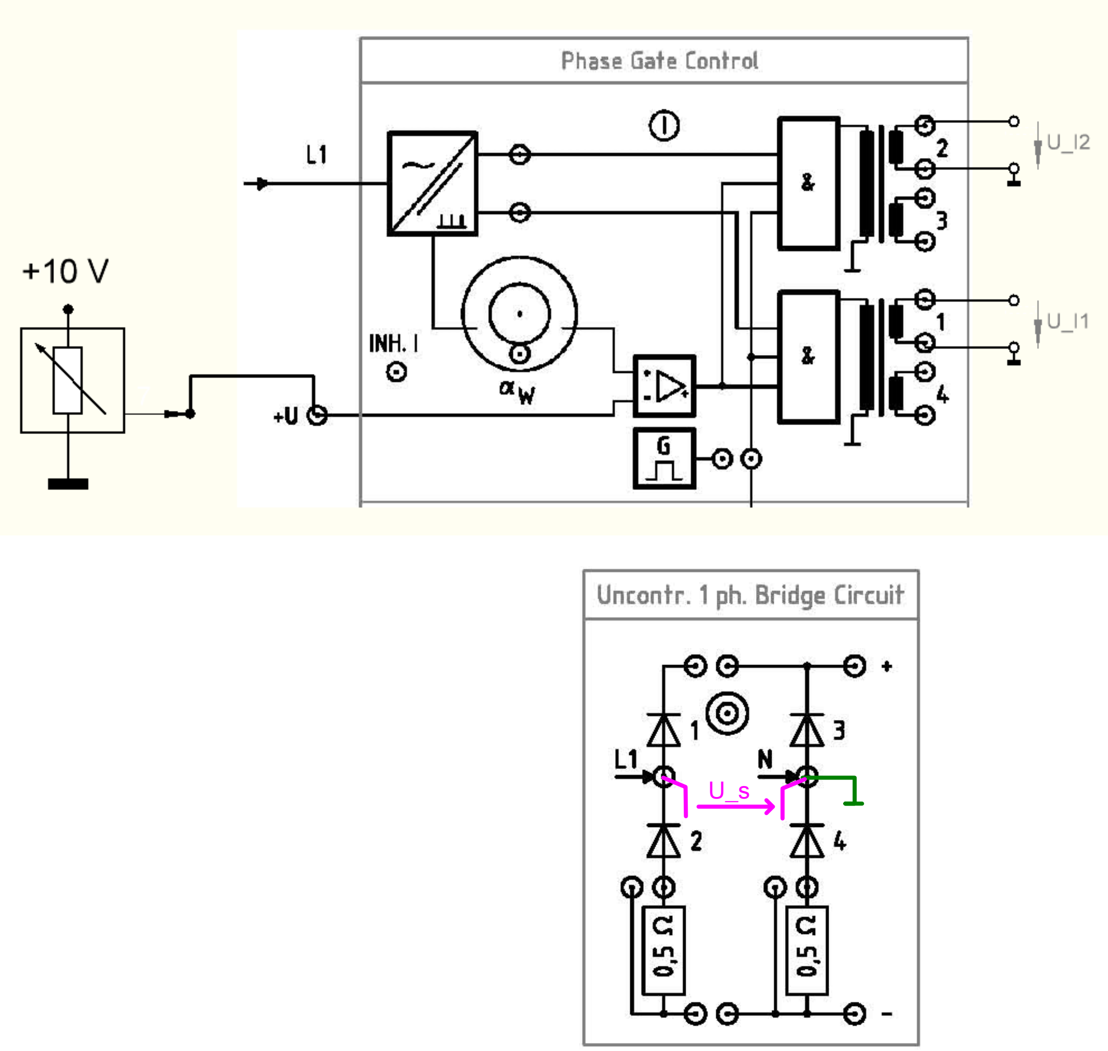
Channel separation links the positive and negative half-wave with the information signals, thus signals are only generated at the positive or rather at the negative half-wave.
In the downstream connected potential separation the triggering signals are separately and synchronously transferred to the thyristors via pulse initiator. By triggering the transmission inductance, the triggering voltage U_{GK} rises in addition.

3.2.1 Test 1

Signal wave forms in the Phase Gate Control of the Power Electronic Panels.

Test Configuration & Test Procedure

- Build up the circuit in pic. 3.2.1.

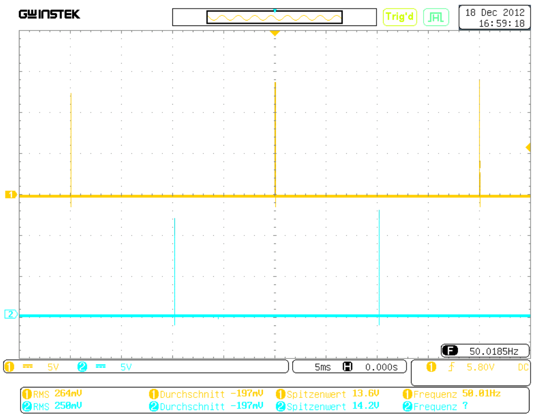


pic. 3.2.1.0 circuit

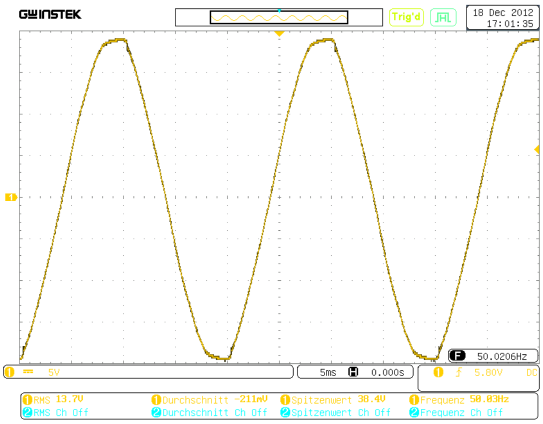
- Set the control voltage to +6 V at the potentiometer.
- Measure following parameters with the oscilloscope:
  - Triggering Voltages U_{I1}, U_{I2}
  - Mains Voltage U_S,

Note: ***The adjuster for the triggering angle α_W in the Phase Gate Control shall be non-effective. Therefore it has to be placed at the right hand sided arrester.***

- Draw the curve into pic. 3.2.1.1 and pic. 3.2.1.2.



pic. 3.2.1.1



pic. 3.2.1.2

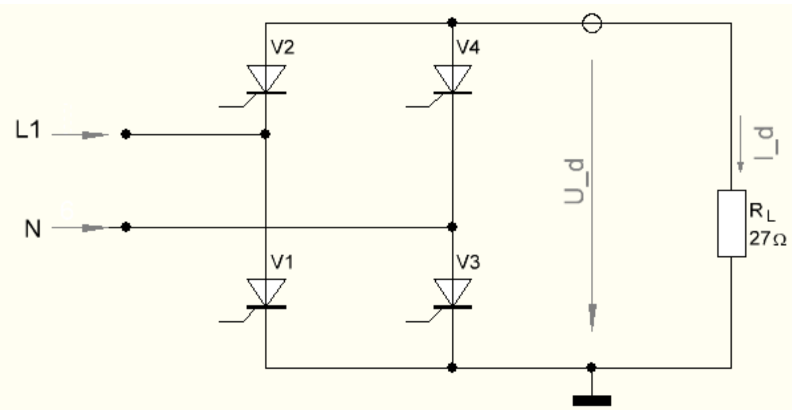
Oscilloscope Settings:

Triggering Voltage U_{I1}: 5 V / div.
Triggering Voltage U_{I2}: 5 V / div.
Time t: 5 ms / div.

Oscilloscope Settings:

Mains Voltage U_S: 5 V / div.
Time t: 5 ms / div.

Question:	If the Phase Gate Control I (pic. 3.2.1.3) should control the 1-phase bridge circuit II, what allocation to the thyristors is required?
Answer:	V_1: I_1
	V_2: I_2
	V_3: I_3
	V_4: I_4

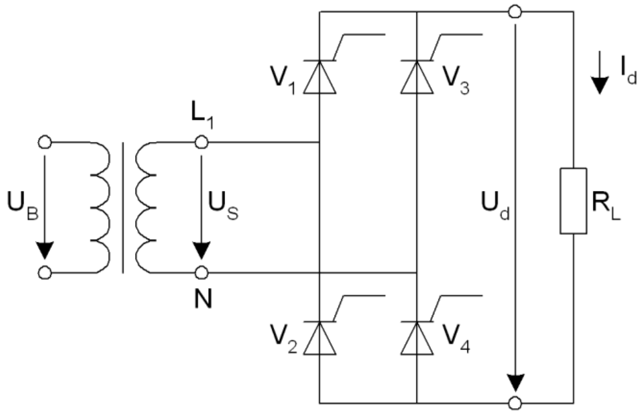


pic. 3.2.1.3

3.3 Controlled Two-Pulse Bridge Circuit B2C

To control the output voltage U_d with the phase gate control at a two-pulse bridge a configuration with 4 thyristors is required.

Circuit:

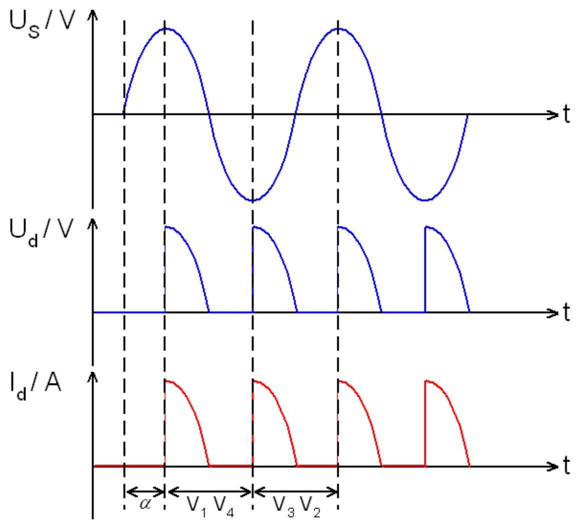


pic. 3.3.0.0 B2C circuit

Function:

Two of the four thyristors have to be conducting at a time. At the positive half-wave it is V_1 and V_4, at the negative one it is V_3 and V_2. The pulse initiator has to produce two 180° offset pairs of triggering signals.

Signal Wave Form:



pic. 3.3.0.1 signal wave form at ohmic load with α =90°

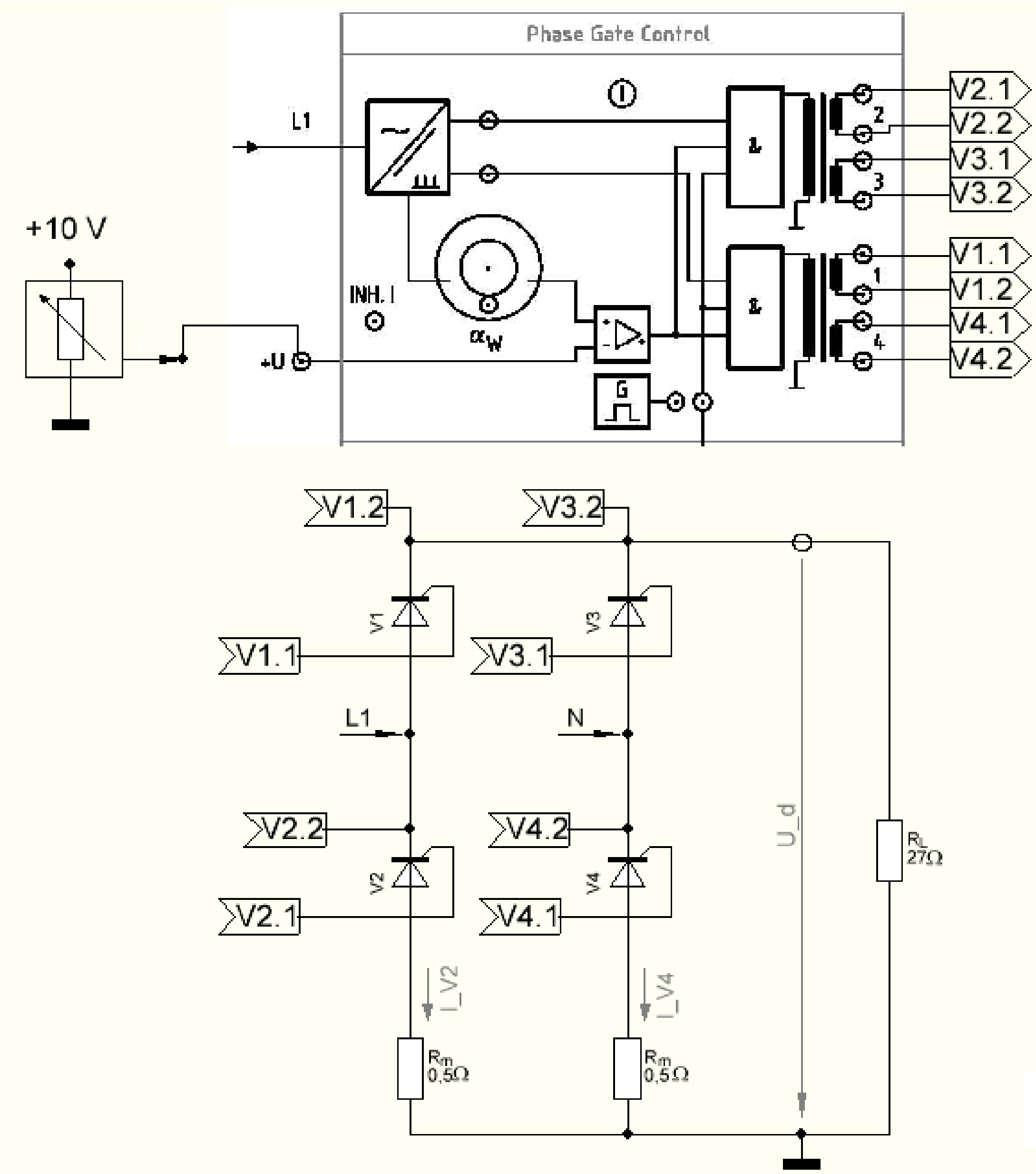
3.3.1 Test 1

Currents and voltages in the controlled two-pulse bridge circuit B2C.

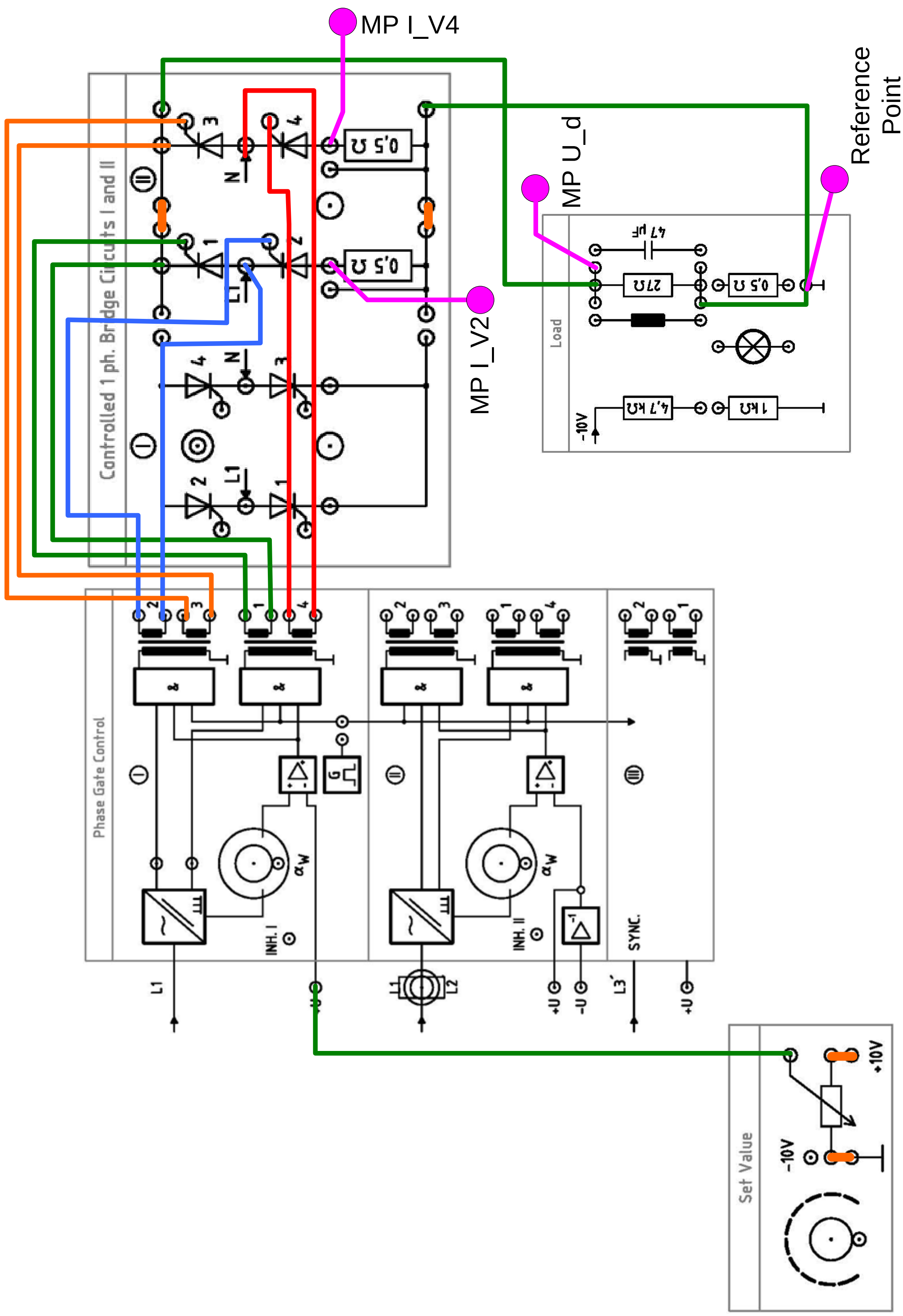
Test Configuration & Test Procedure

- Build up the circuit in pic. 3.3.1.0 / 3.3.1.1.

Note: ***Use the 1-phase Bridge Circuit I and Phase Gate Control I.***



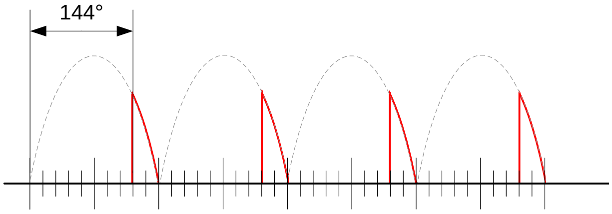
pic. 3.3.1.0 circuit



pic. 3.3.1.1 circuit

- Connect the 27 Ω resistor to ground potential.

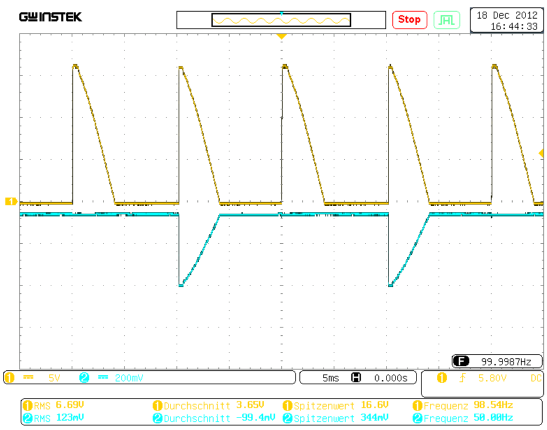
- Set the triggering value to α = 144°.



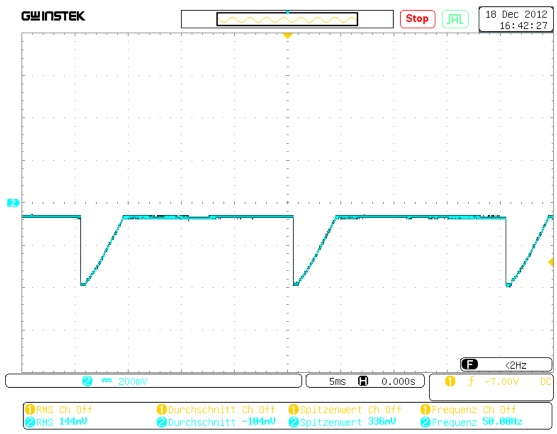
- Connect an ohmic resistor for load.

- Measure following parameters with the oscilloscope:
  Output Voltage U_d,
  Thyristor Currents I_{V2}, I_{V4}

- Draw the curve into pic. 3.3.1.2 and pic. 3.3.1.3.



pic. 3.3.1.2



pic. 3.3.1.3

Oscilloscope Settings:

Output Voltage U_d: 5 V / div.
Thyristor Current I_{V2}: 0,4 A / div.
= 0,2 V / div.
Time t: 5 ms / div.

Current Conversion with Rm = 0,5 Ohm

Oscilloscope Settings:

Thyristor Current I_{V4}: 0,4 A / div.
= 0,2 V / div.

Time t: 5 ms / div.

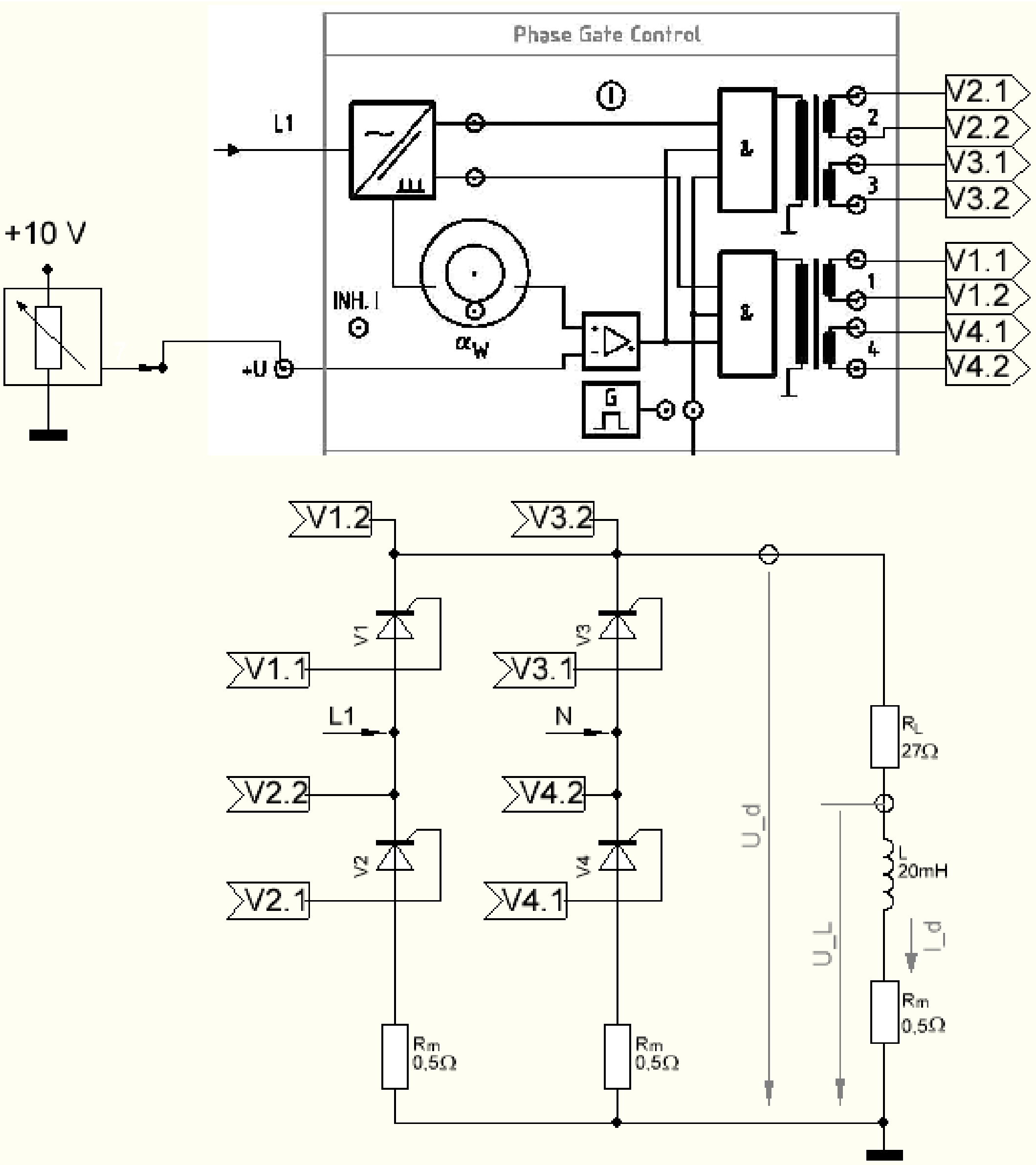
Current Conversion with Rm = 0,5 Ohm

3.3.2 Test 2

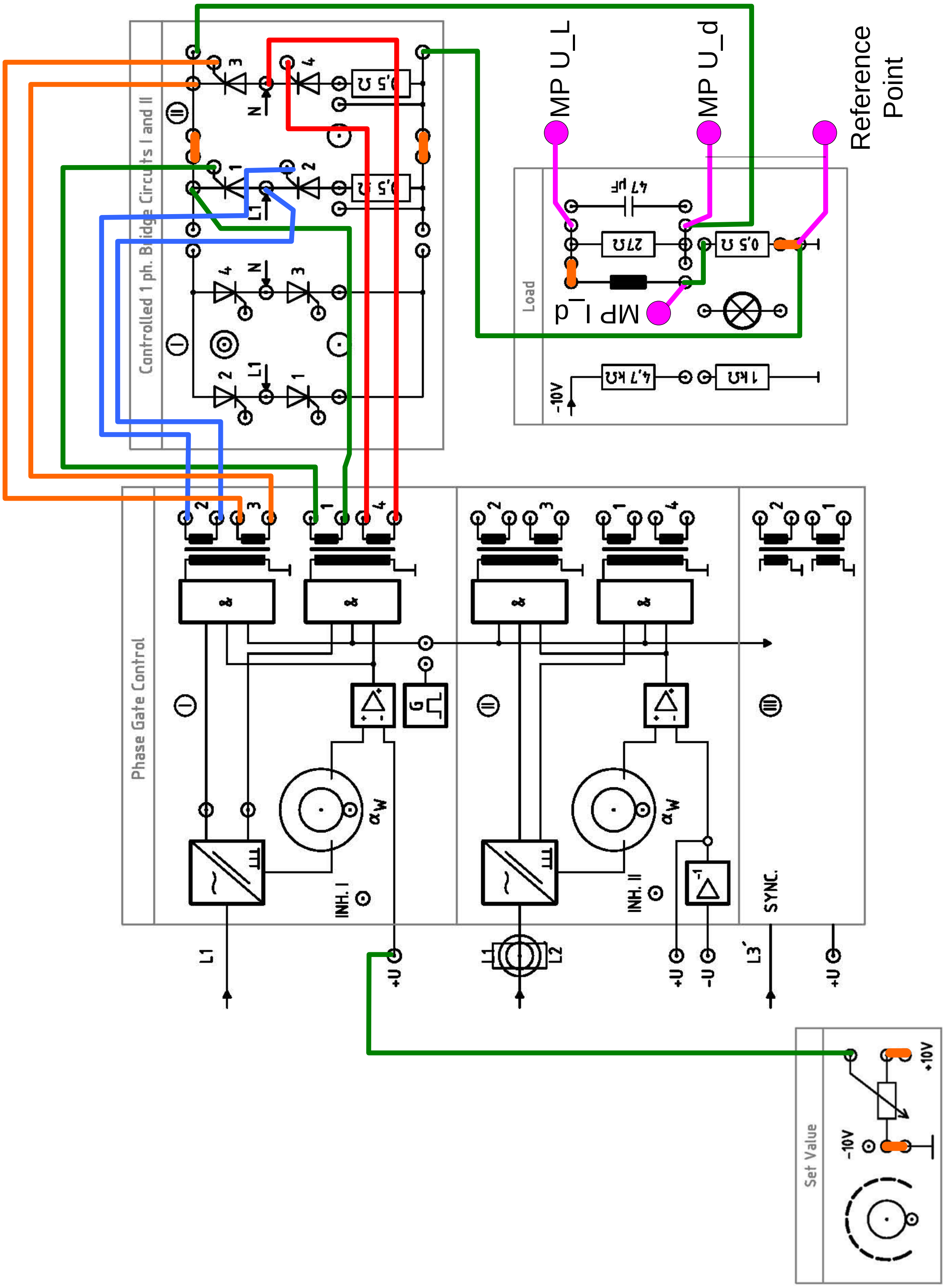
Influence of an inductive component in the load on the behaviour of the B2C circuit.

Test Configuration & Test Procedure

- Connect the load of resistance and inductance in series as pictured in 3.3.2.0 / 3.3.2.1.



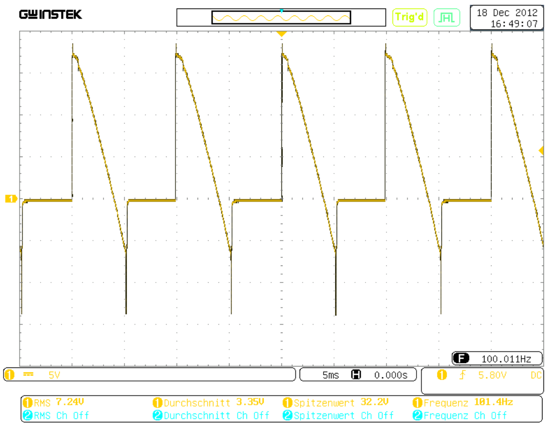
pic. 3.3.2.0 circuit



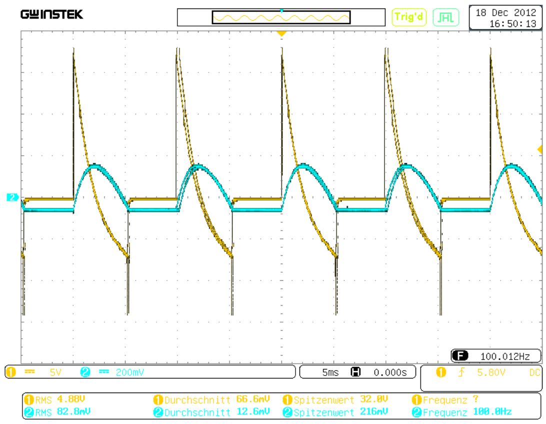
pic. 3.3.2.1 circuit

- Connect the 0,5 Ω resistor to ground potential.
-
- Measure following parameters with the oscilloscope:
  - Output Voltage U_d,
  - Output Current I_d,
  - Coil Voltage U_L

- Draw the curves into pic. 3.3.2.2 and pic. 3.3.2.3.



pic. 3.3.2.2



pic. 3.3.2.3

Oscilloscope Settings:

Output Voltage U_d: 5 V / div.
Time t: 5 ms / div.

Current Conversion with Rm = 0,5 Ohm

Oscilloscope Settings:

Coil Voltage U_L: 5 V / div.
Output Current I_d : 0,2 A / div.
= 0,1 V / div.
Time t: 5 ms / div.

Question 1:	What is the phase interrelation of the four triggering signals?
Answer:	The triggering signals of V_1 and V_4 are co-phasal, same as the triggering signals of V_2 and V_3. The groups V_1/V_4 and V_2/V_3 are 180° offset.

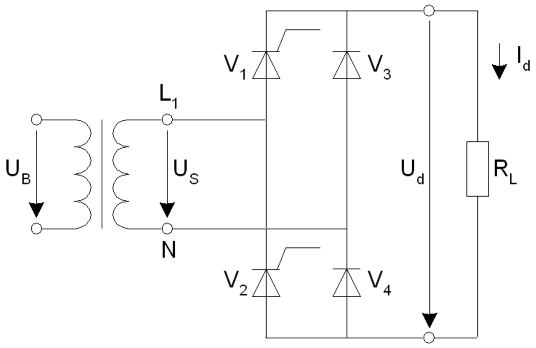
Question 2:	How do I know, that temporarily the coil acts as generator?
Answer:	If coil voltage and coil current have the same polarity, the coil will store energy. If voltage and current have different polarity, the coil will transfer energy. Thus it operates as generator.

3.4 Half Controlled Two-Pulse Bridge Circuit B2H

To control the output voltage of a two-pulse bridge by Phase Gate Control, two of the diodes have to be substituted by controllable semiconductor devices, in our example thyristors. There are two possibilities to control the positive and negative half-wave of the circuit.

Twin pair half-controlled bridge circuit B2HZ

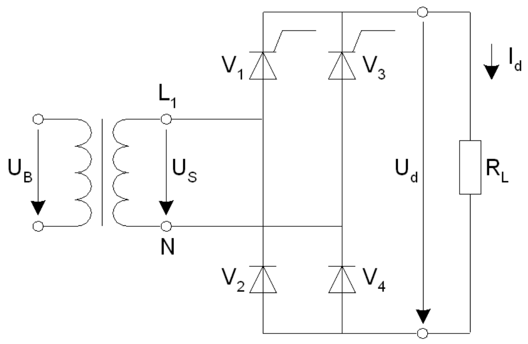
The semiconductors V_1 and V_2 respectively V_3 and V_4 form a so called twin pair. If both controllable semiconductors are positioned in one twin pair, the circuit is called „twin pair half-controlled bridge B2HZ". In the second twin pair there are the non-controllable semiconductors.



pic. 3.4.0.0 B2HZ twin pair half-controlled circuit

Circuit:

Single-pole bridge circuit



controlled two-pulse B2HK

pic. 3.4.0.1 B2HK single-pole controlled circuit

In each twin pair a controllable semiconductor device is built-in. The circuit therefore is called "single-pole controlled two-pulse bridge B2HK". The letter "K" stands for the cathodes of the two controllable semiconductors, which form a pole of DC voltage.

Circuit:

At the above mentioned half-controlled bridges the positive as well as the negative half-waves are controllable. At all ohmic load the form of the output voltage U_d behaves like the one at the controlled B2C bridge. If load with inductance is added, the two diodes of the B2HZ circuit, respectively one diode at a time and the conducting thyristor at the B2HK circuit, act like a free-wheeling path for negative voltage -/ time area. For this reason no negative voltage at the rectifiers' side is possible at the half-controlled bridge circuit.

Notes to the measurements following:

- The adjuster for the triggering angle α_W within the phase gate control should be non-effective. Means it has to be positioned on the right hand sided arrester.
- For measurements in this area the phase gate control needs voltage of +U. Therefore set the potentiometer between 0 V and +10 V. Connect the potentiometer output to the control input +U of the phase gate control I.
- Instead of the gate trigger voltage the number of the pulse initiator is stated on the thyristor. That means e. g. I_1 is the pulse initiator 1 of the phase gate control I. The upper connector of a pulse has to be connected to the gate. The lower connector has to be connected to the cathode.
- For all oscillosgraphs the oscilloscope has to be internally triggered at LINE. If mains voltage U_S and output voltage U_d do not have a common bench mark, they have to be measured separately one after the other.
- Representatively for half-controlled rectifiers the twin pair half-controlled bridge B2HZ is examined.

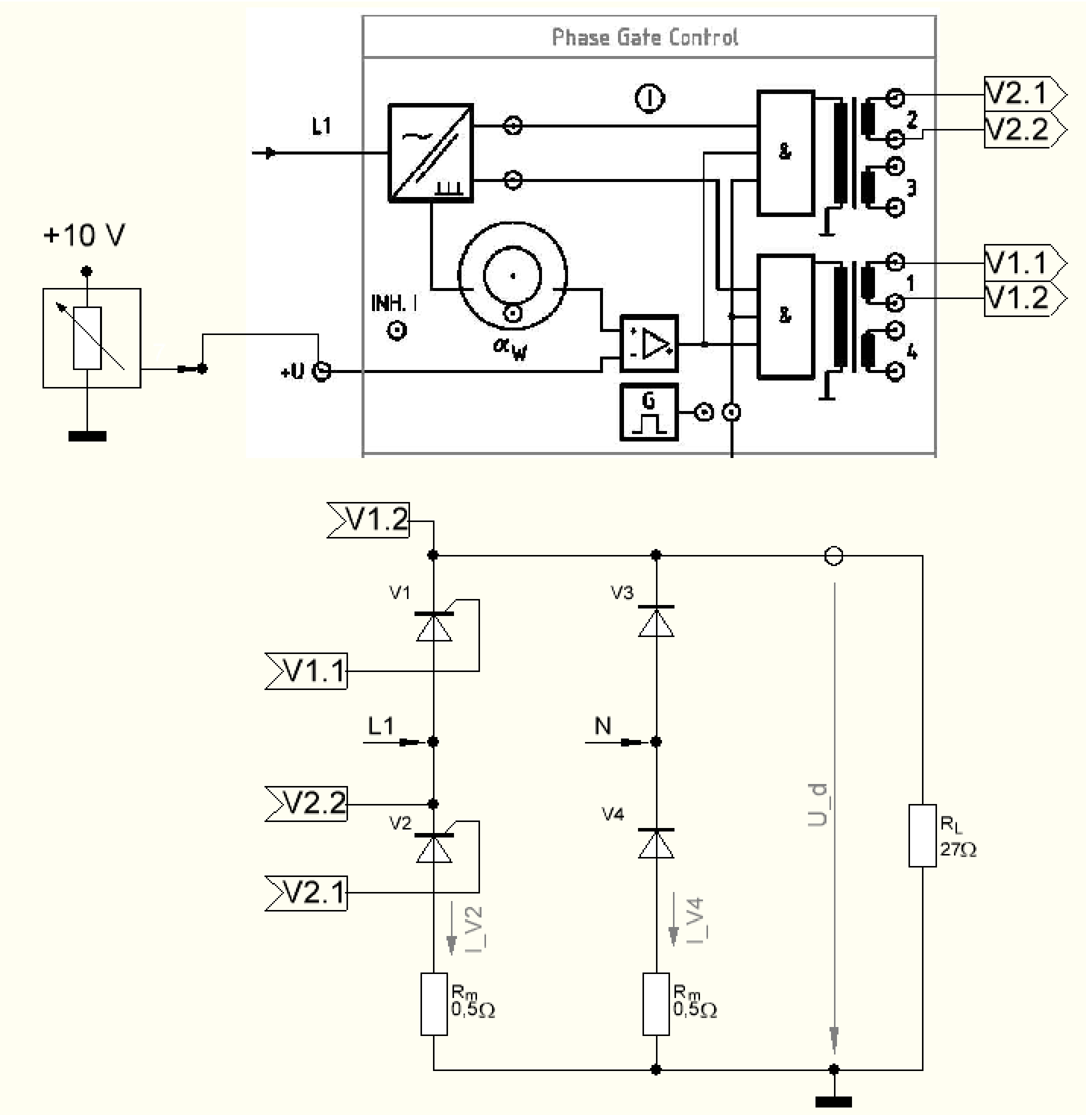
3.4.1 Test 1

Currents and voltage in the twin pair half-controlled bridge B2HZ.

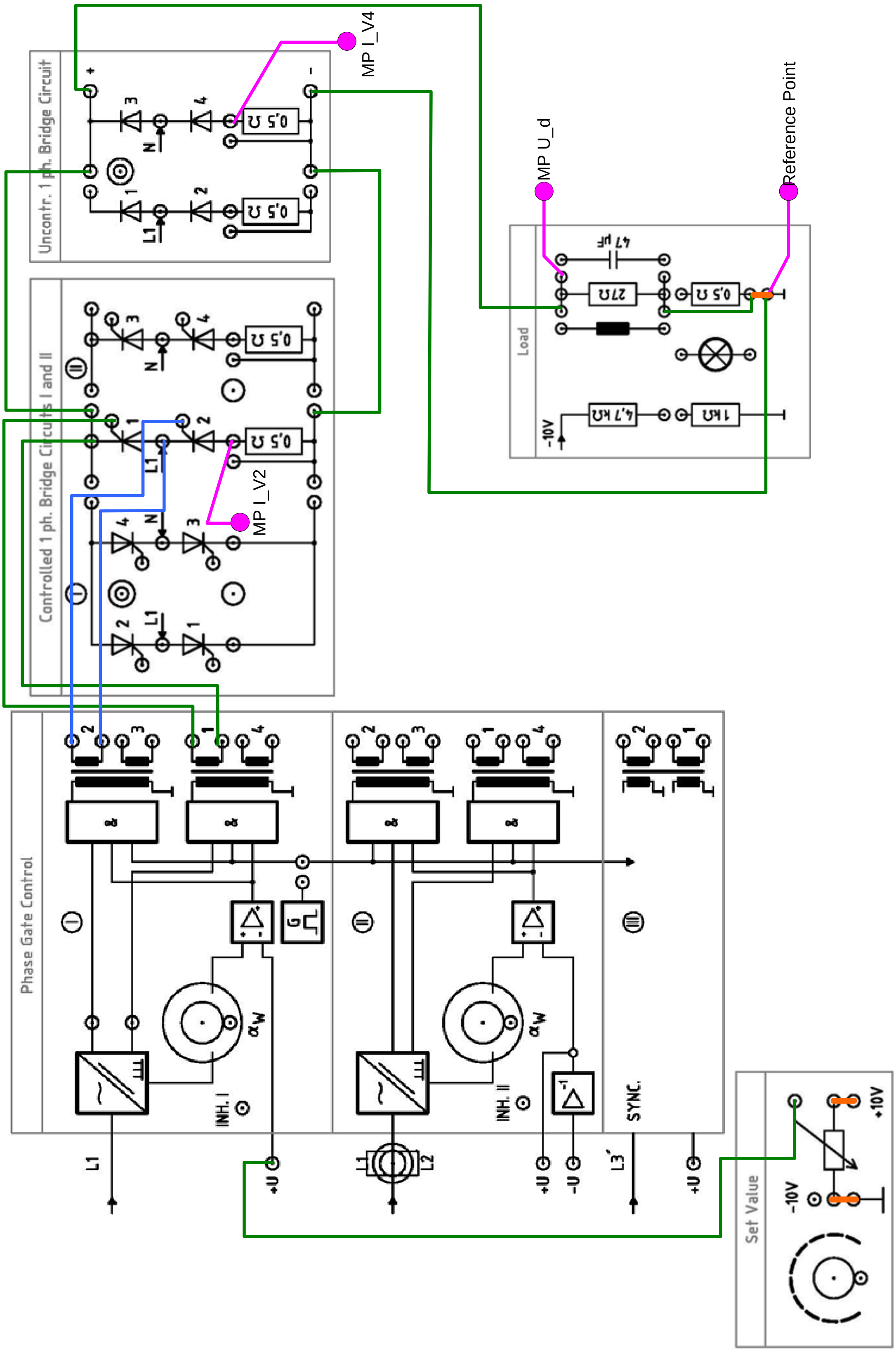
Test Configuration & Test Procedure

- Build up the circuit in pic. 3.4.1.0 / 3.4.1.1 with the Power Electronic Panel.

Note: ***The adjuster for the triggering angle α_W in the Phase Gate Control shall be non-effective. Therefore it has to be placed at the right hand sided arrester.***

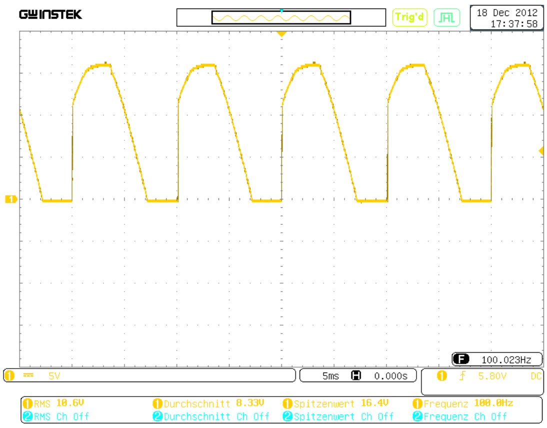


pic. 3.4.1.0 circuit

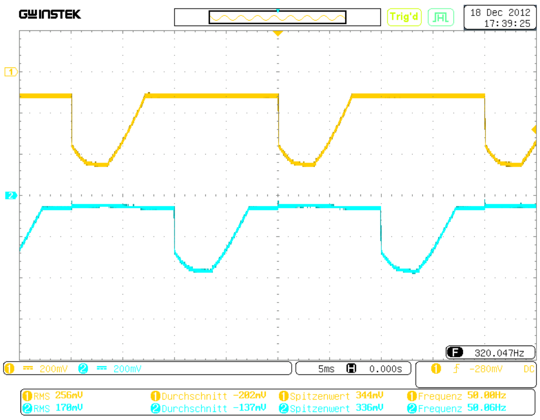


pic. 3.4.1.1 Circuit at the Power Electronic Panel

- First connect an all-ohmic resistor for load as pictured in 3.4.1.0 / 3.4.1.1.
- Set the triggering angle to α = 36°.
- Measure the following parameters with the oscilloscope:
  - Output Voltage U_d,
  - Thyristor Current I_{V2},
  - Diode Durrent I_{V4}
- Draw the curve into pic. 3.4.1.2 and pic. 3.4.1.3.



pic. 3.4.1.2



pic. 3.4.1.3

Oscilloscope Settings:

Output Voltage U_d: 5 V / div.

Ttime t: 5 ms / div.

Oscilloscope Settings:

Thyristor Current I_{V2}: 0,4 A / div.
= 0,2 V / div.
Diode Current I_{V4}: 0,4 A / div.
= 0,2 V / div.
Time t: 5 ms / div.

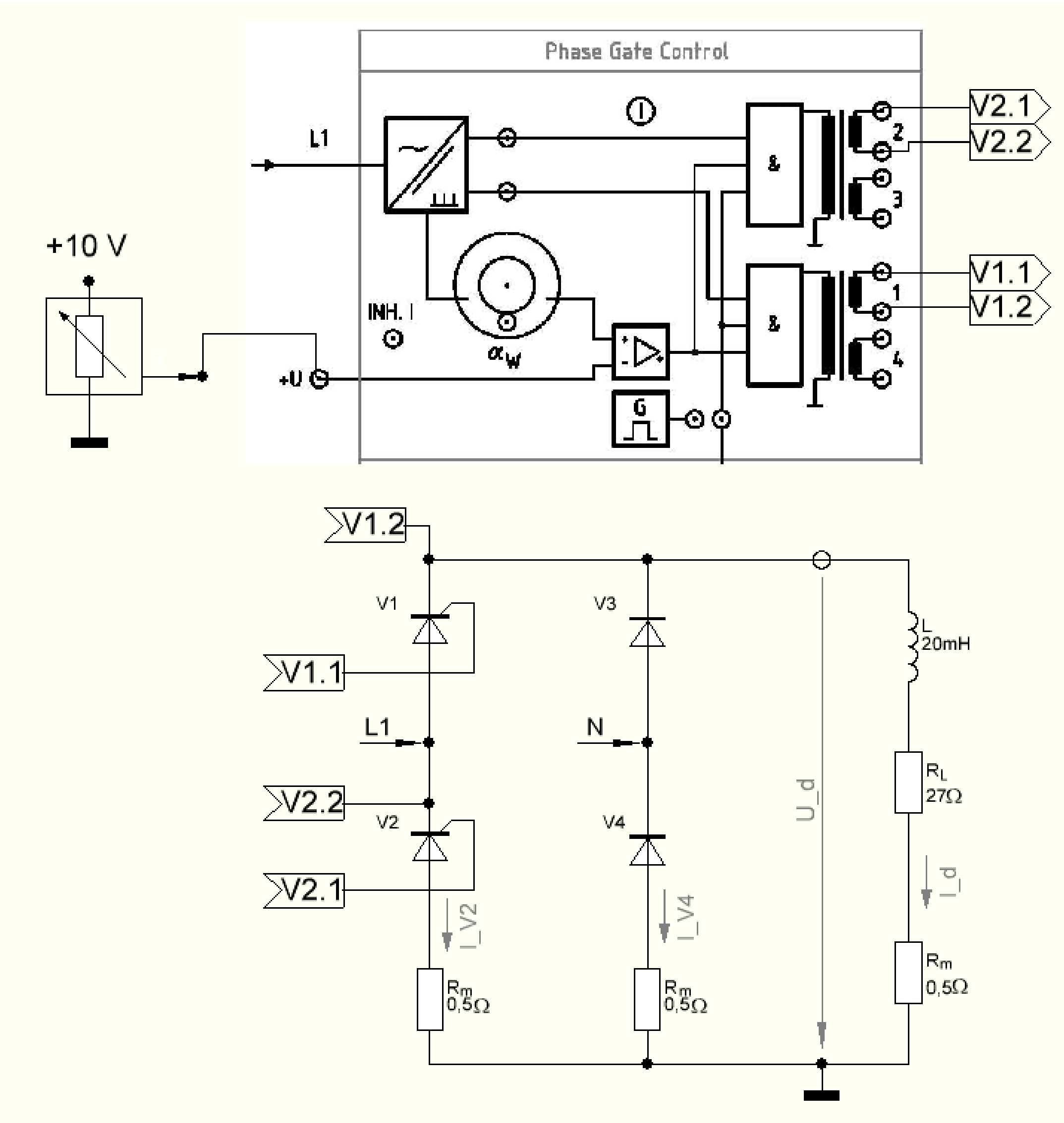
Current Conversion with Rm = 0,5 Ohm

3.4.2 Test 2

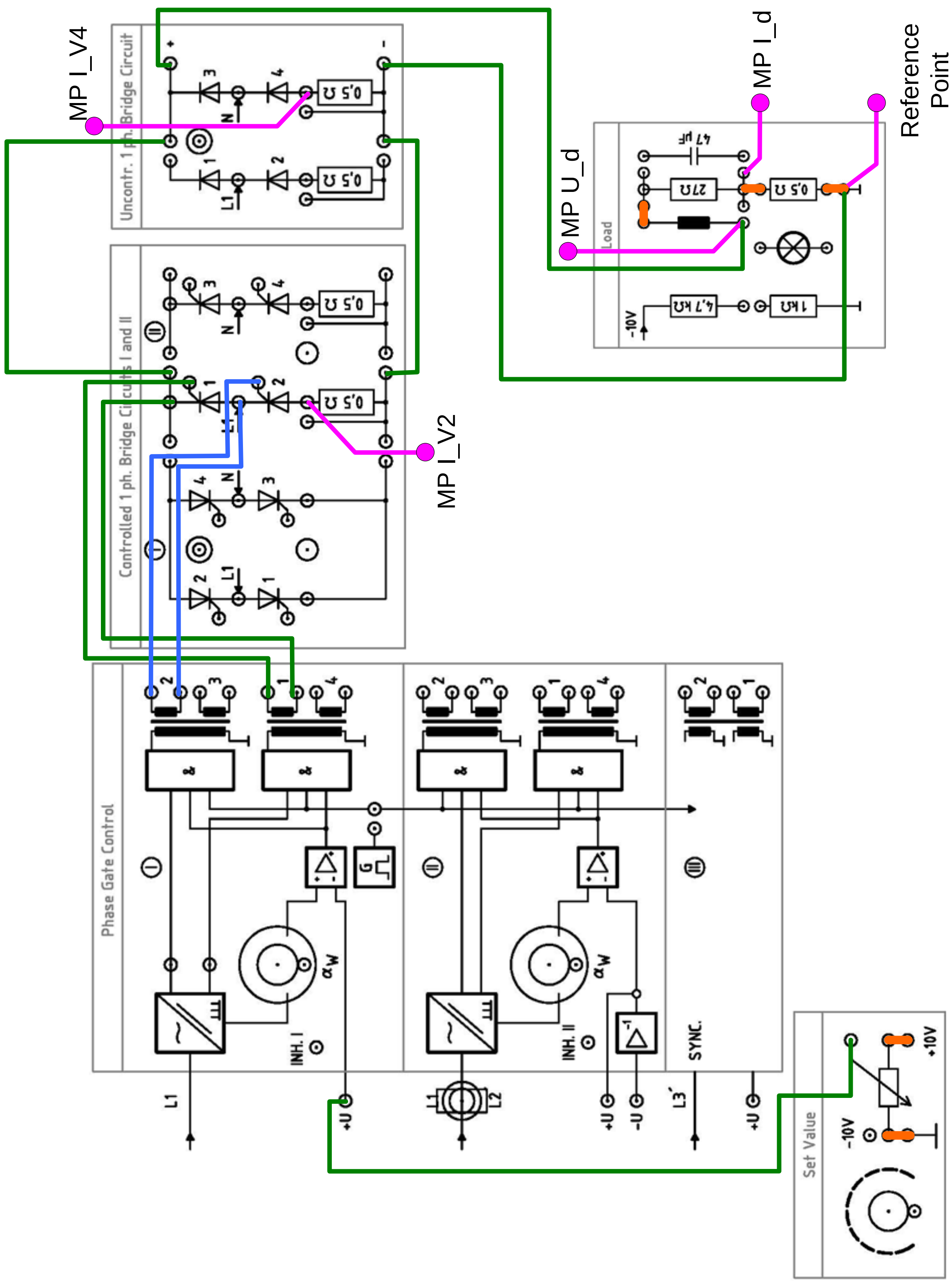
Influence of an inductive component in the load to the behavior of a twin pair of half controlled bridge circuit B2HZ.

Test Configuration & Test Procedure

- Connect the load of resistance and inductivity in series as pictured in 3.4.2.0 / 3.4.2.1.



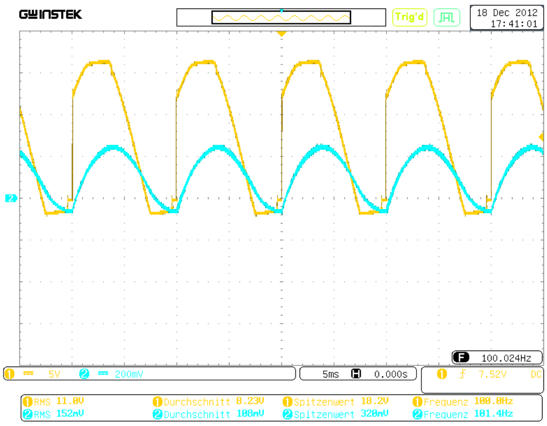
pic. 3.4.2.0 circuit



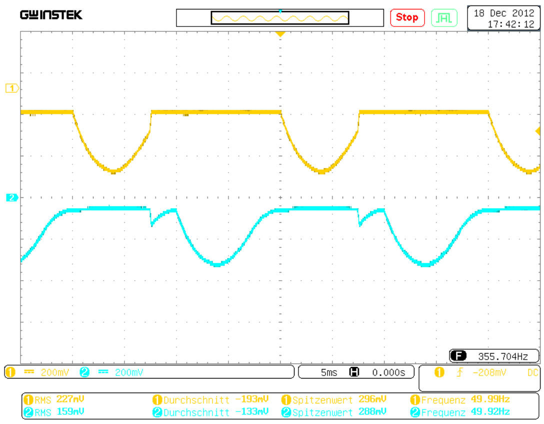
pic. 3.4.2.1 Circuit at the Power Electronic Panel

- Measure following parameters with the oscilloscope:
  - Output Voltage U_d,
  - Output Current I_d,
  - Thyristor Current I_{V2},
  - Diode Current I_{V4}

- Draw the curves into pic. 3.4.2.2 and pic. 3.4.2.3.



pic. 3.4.2.2



pic. 3.4.2.3

Oscilloscope setting:

Output voltage U_d:	5	V / div.
Output current I_d:	0,4	A / div.
=	0,2	V / div.
time t:	5	ms / div.

Current conversion with Rm = 0,5 Ohm

Oscilloscope setting:

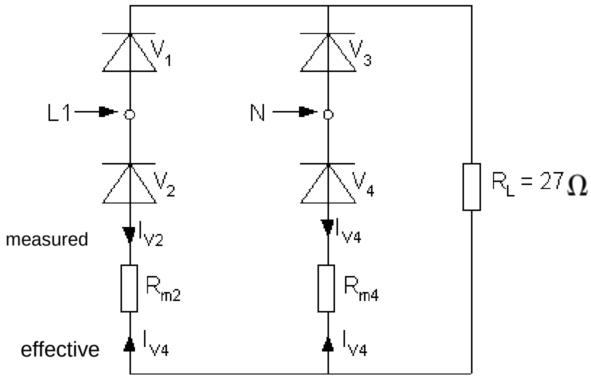
Thyristor current I_{V2}:	0,4	A / div.
=	0,2	V / div.
Diode current I_{V4}:	0,4	A / div.
=	0,2	V / div.
time t:	5	ms / div.

Current conversion with Rm = 0,5 Ohm

Question 1:	When does current flow through diode V_4?
Answer:	V_4 is conducting, while current flows from L1 through thyristor $V_1$to load. Current also flows through V_4, when output voltage is more than -1,4 V. Meanwhile diodes V_3 and V_4 operate as free-wheeling diodes.

Question 2:	What co-relation do the phase length of the two triggering signals I_1 and I_2 have?
Answer:	Triggering signals I_1 and I_2 have to be offset by 180°.

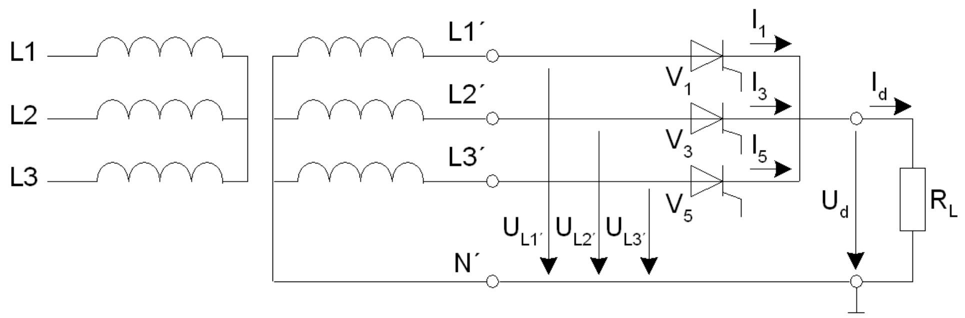
Question 3:	Why are negative currents measured at I_{V2} and I_{V4}?
Answer:	If I_{V2} and I_{V4} are measured together common reference point is the minus-terminal of the bridge. Currents are also measured related to This reference point. Actually current flows from this point to L1 respectively N. Thus these currents are measured as negative signals.



3.5 Controlled Three-Pulse Center Tapped Circuit M3C

The controlled three-pulse center tapped circuit M3C is, like the uncontrolled three-pulse center tapped circuit M3U, a half-wave rectifier.
The respective thyristor will get conducting, when the potential at the anode is higher than the potential at the positive pole of the output voltage U_d. To generate the triggering signals the pulse initiator has to give three pulses 120° offset per period. That pulses have to be variably shiftable to meet the requested control area.

Circuit:

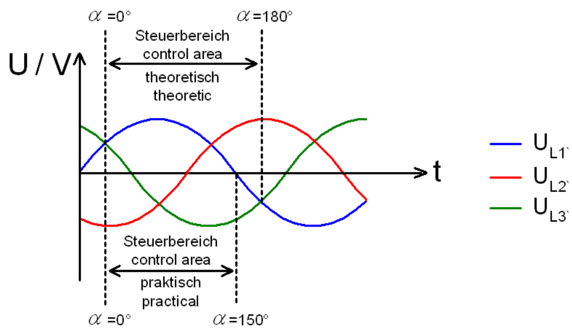


pic. 3.5.0.0 M3C controlled three-pulse center tapped circuit

Control Area:

The thyristor V_1 can only be fired in the control area, as voltage U_{L1}, here based on the fact of normal commutation moment α =0° is till the crossing with voltage $U_{L3'}$, at α =180° more positive than $U_{L3'}$. Same is true for the thyristors V_3, V_5 and the respective voltages.

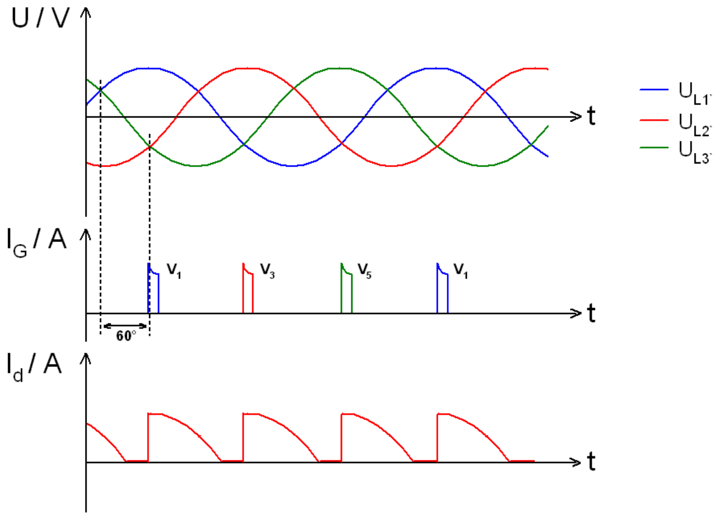
At inductive load the thyristor V_5 is conducting till V_1 fires. Theoretical control area at ind. load is α =0° bis α =180°.



pic. 3.5.0.1 M3C control area

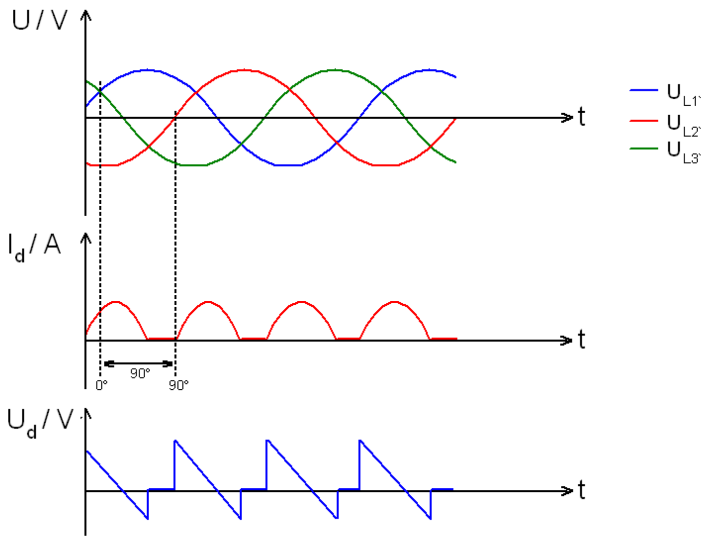
No negative voltages can occur at the output with all ohmic load. The thyristor blocks at α =150°. The thyristor is again forward biased after commutation – and circuit commutated recovery time (time, that is required to restore the barrier layer). A distance of 20° to 30° is maintained from the theoretical possible triggering angle of α =180°. This triggering angle limiter then is adjusted to e.g. α_w=150°. This critical angle is also called the inverter threshold.

From a triggering angle of α=30° current I_d gaps (gap operation). The bigger the triggering angle gets, the lower gets the DC voltage and the DC current. If triggering angle of α=150° is reached, current and voltage are zero.



pic. 3.5.0.2 M3C signal wave form at ohmic load, α=60°

With only inductive load (only possible in theory, as there are always ohmic losses) there is an ideal continuous DC current I_d. Because of the storage function of the inductance, I_d flows even though mains voltage has already negative polarity.
If the triggering angle α=30° is exceeded at this inductive load, there will be a negative voltage-time-area. To determine the average of the DC voltage, the negative voltage-time-area has to be subtracted from the positive voltage-time-area. Hence results, voltage values at inductive load and triggering angle of >30° are less than at an ohmic load. At an angle of α=90°voltage is zero.



pic. 3.5.0.3 M3C signal wave form at ohmic-inductive load

Notes to the measurements following:

- For measurements in this area the phase gate control needs voltage of +U. Therefore set the potentiometer between 0 V and +10 V. Connect the potentiometer output to the control input +U of the phase gate control I, II and III.
- Instead of the gate trigger voltage the number of the pulse initiator is stated on the thyristor. That means e. g. I_1 is the pulse initiator 1 of the phase gate control I. The upper connector of a pulse initiator has to be connected to the gate. The lower connector has to be connected to the cathode.
- For all oscillographs the oscilloscope has to be internally triggered at LINE. If mains voltage U_S and output voltage U_d do not have a common bench mark, they have to be measured separately one after the other.

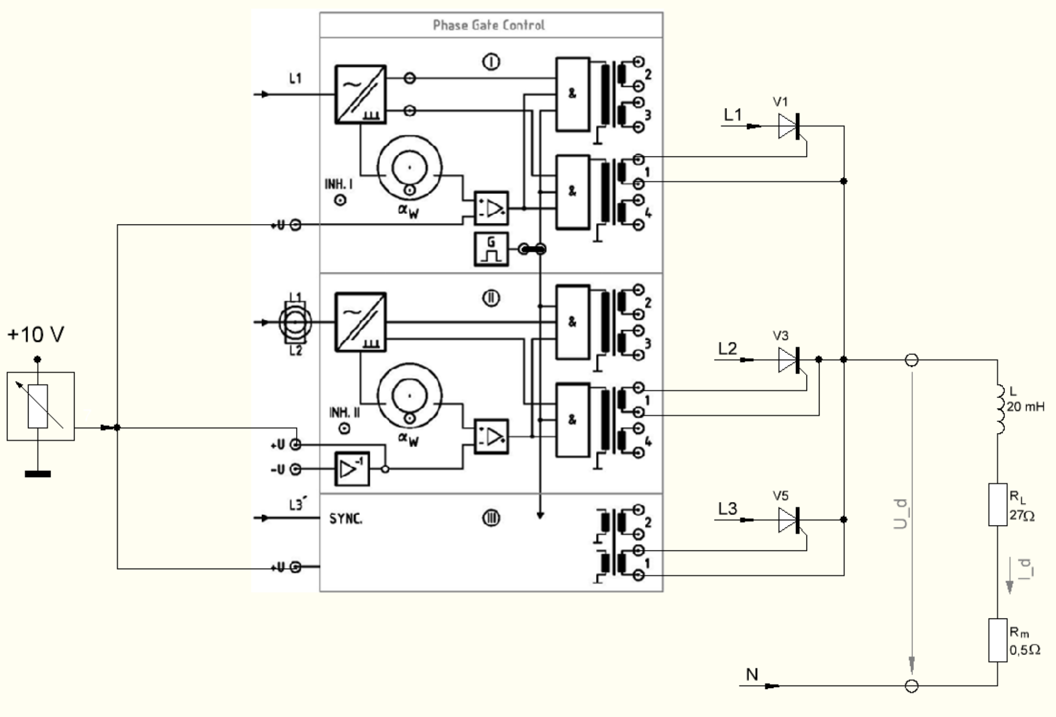
3.5.1 Test 1

Currents and voltages in the controlled three-pulse center tapped circuit M3C.

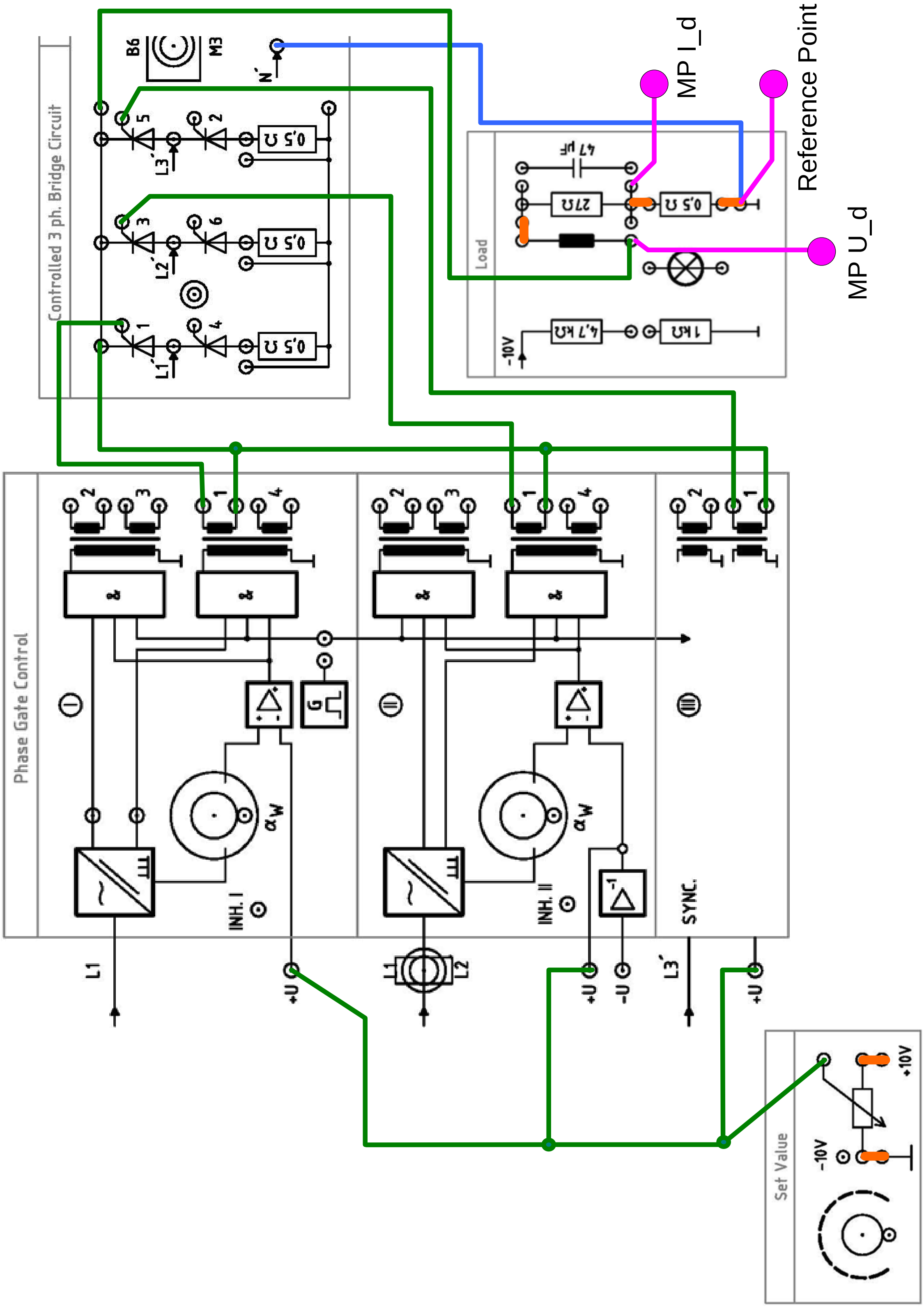
Test Configuration & Test Procedure

Build up the circuit in pic. 3.5.1.0 with the Power Electronic Panel pic. 3.5.1.1.

Note: ***At three-phase current the triggering angle α is not taken from the zero crossing of U_{L1}, but from the crossing of U_{L1} and U_{L3}. If you would like to orientate yourself on the oscilloscope at the zero crossing of $U_{L1,}$ you have to subtract 30° of your determined angle between trigger moment and zero crossing.***



pic. 3.5.1.0 circuit



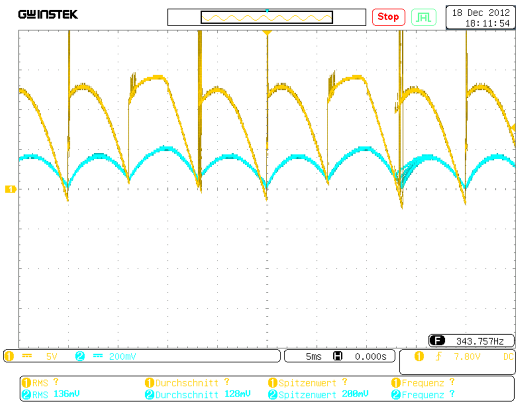
pic. 3.5.1.1 Circuit at the Power Electronic Panel

- Set the selector M3/B6 to position M3.
- Set the AC power supply into operation by bridging the three-phase source.
- Set synchronizing of the phase gate control II at switch L1/L2' to position L2'.
- Bridge phase gate control I and signal generator.
- Connect the 0,5 Ω resistor to ground potential.
- Set the inverter limit α_W at the phase gate control I and II, so all three thyristors fire at approx. the same phase length.

Procedure: Measure with the oscilloscope parameters $U_{L1'}$ and U_d.
Set the triggering angle to α = 90°.

With a suitable potentiometer, you can set each pulse of U_d to identical triggering angles α_W and identical amplitudes (variances due to component tolerances are possible).

- Measure following parameters with the oscilloscope for triggering angles α = 45°, α = 90° and α = 120°:
  - Output Voltage U_d,
  - Load Ccurrent I_d
- Draw the curves into pic. 3.5.1.2 to pic. 3.5.1.4.

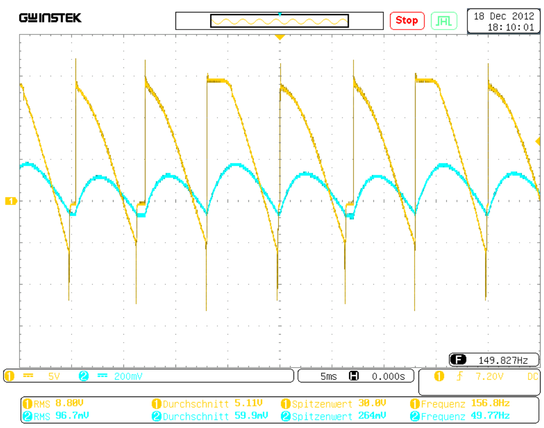


pic. 3.5.1.2 triggering angle α = 45°

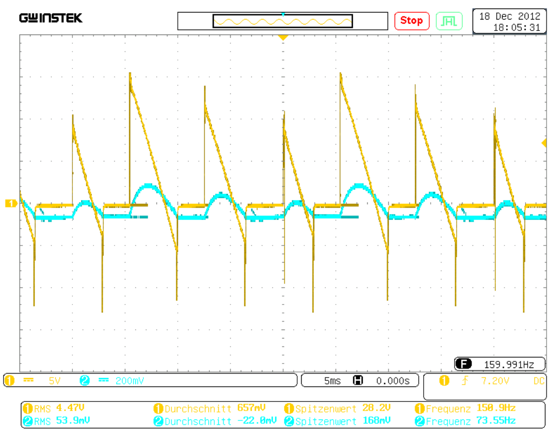
Oscilloscope Settings:

Output Voltage U_d:		5	V / div.
Output Current I_d:		0,4	A / div.
	=	0,2	V / div.
Time t:		5	ms / div.

Current Conversion with Rm = 0,5 Ohm



pic. 3.5.1.3 triggering angle α = 90°



pic. 3.5.1.4 triggering angle α = 120°

Oscilloscope Settings:

Output Voltage U_d: 5 V / div.
Output Current I_d: 0,4 A / div.
= 0,2 V / div.
Time t: 5 ms / div.

Current Conversion with Rm = 0,5 Ohm

Oscilloscope Settings:

Output Voltage U_d: 5 V / div.
Output Current I_d: 0,4 A / div.
= 0,2 V / div.
Time t: 5 ms / div.

Current Conversion with Rm = 0,5 Ohm

Question 1:	What co-related phasing must the three triggering signals I_1, II_1 and III_1 have?
Answer:	The three triggering signals have to be 120°offset each.

Question 2:	At what measurement is the DC current I_a "gaping"?
Answer:	At the triggering angel of α = 90° to α = 120° the current „gaps". That means the voltage breaks are so big, that inductance for reducing ripple is too low to make current flow until the next voltage pulse.

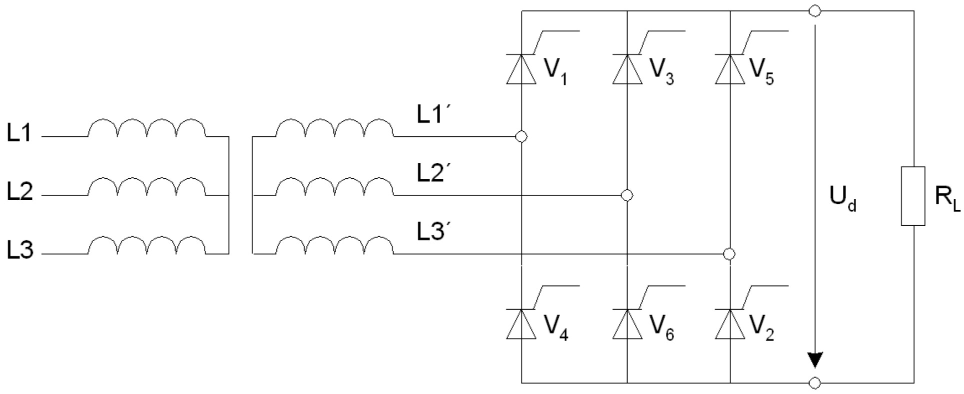
Question 3	Why does the current not „gap" at triggering angle 45°?
Answer:	At the measurement with α =45° the break between two voltage pulses is so minor, that due to the current smoothing of inductance, current does not drop to zero.

Question 4:	How does a „gap" in inductance of the load circuit affect the current?
Answer:	At inductance current begins to „gap" at bigger triggering angles than at all ohmic load.

3.6 Controlled Six-Pulse Bridge Circuit B6C

Practically the B6C controlled six-pulse bridge is the most common rectifier circuit. Unlike the M3C circuit, AC voltage flows in the feeder, thus the efficiency of the transformer heightens. Ripple of the DC voltage is less than with the M3C circuit.

Circuit:



pic. 3.6.0.0 B6C controlled six-pulse bridge circuit

At a B6C circuit two thyristors have to be “fired” at a time to make current flow.

The arithmetic average of the DC output voltage $\mathbf{U_{d\alpha}}$ is calculated with a triggering angle of α=0° as follows (U_L = phase conductor voltage):

$$U_{d\alpha} = 1{,}35 \cdot U_L$$

If triggering angle is α>60° at ohmic load, gap operation occurs.

The B6C bridge circuit can be considered a series connection of two M3C center tapped circuits (also see B6U circuit). Both M3C circuits have a natural triggering angle of α=30°. By adding the two offset partial voltages a six-pulse output voltage occurs.
Commutation of the output voltage therefore occurs in 60° steps. At ohmic load there is no gap until α=60°. True is then for output voltage:

$$U_{d\alpha} = U_{d0} \cdot \cos\alpha \qquad\qquad U_{d0} = 1{,}35 \cdot U$$

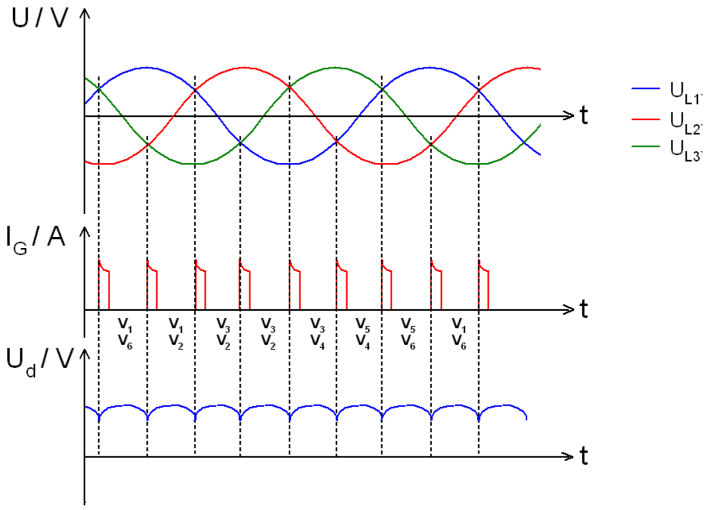
$\mathbf{U_{d\alpha}}$ = arithmetic average of DC output voltage
$\mathbf{U_{d0}}$ = arithmetic average of DC output voltage at α=0°

At a control area of α=60° to α=120° following equation is true:

$$U_{d\alpha} = 0{,}5 \cdot U_{d0}\left[1 + 1{,}154 \cdot \cos\left(30° + \alpha\right)\right]$$

With an all inductive load the wave form of the DC voltage in the range of α=0° to α=60 behaves like the wave form of all ohmic load. In the range of 60° to 90° there is negative voltage-time-area. At α=90° the positive and negative voltage-time-areas are identical.
If the triggering angle is more than α=90°, it is in inverting operation.
The utilizable control range is from α=0° to α=150°. In this range toppling of the inverter is prevented.

Signal Wave Form:



pic. 3.6.0.1 B6C signal wave form at α=0° and ohmic load

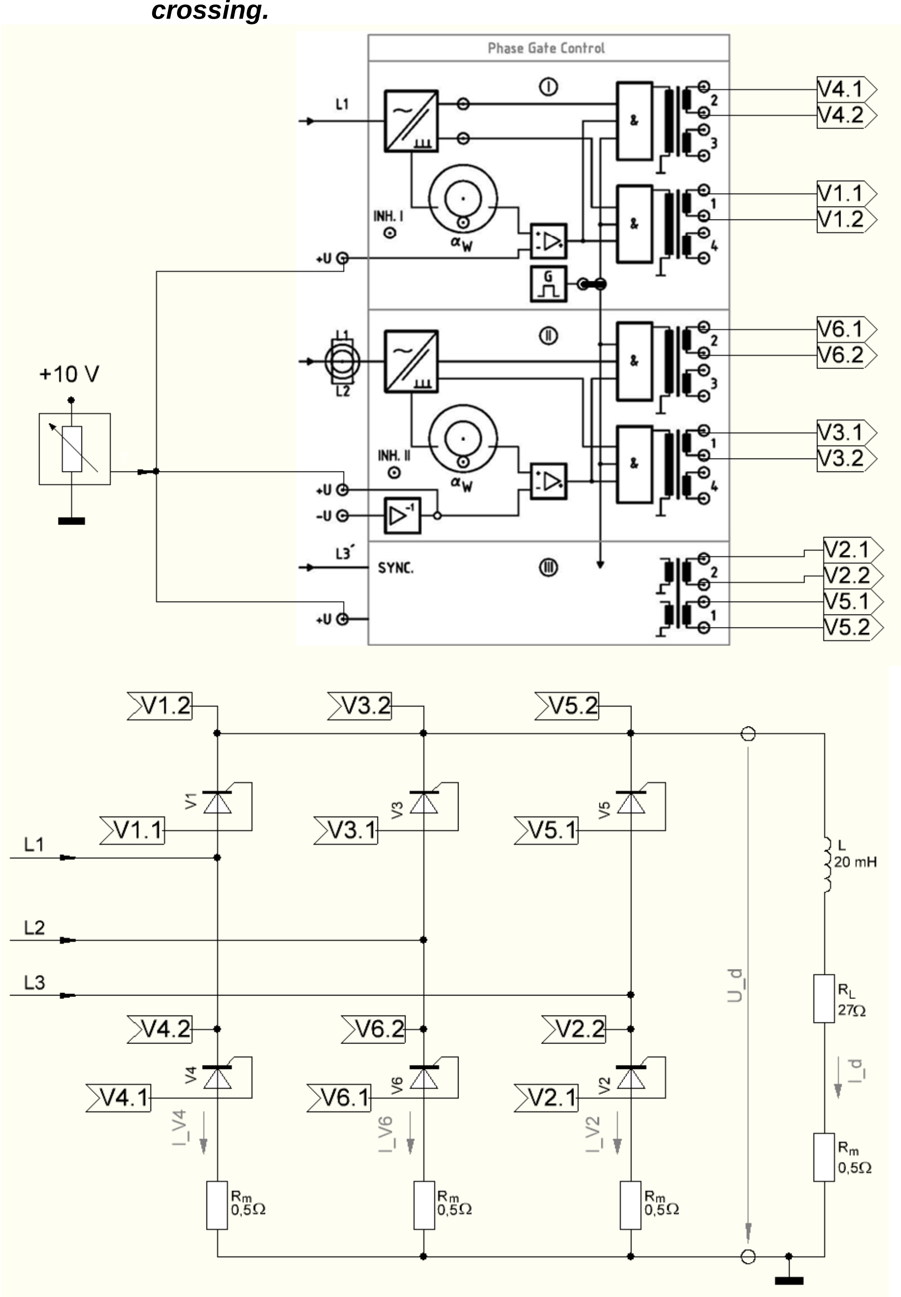
3.6.1 Test 1

Currents and voltages at the controlled six-pulse bridge circuit B6C.

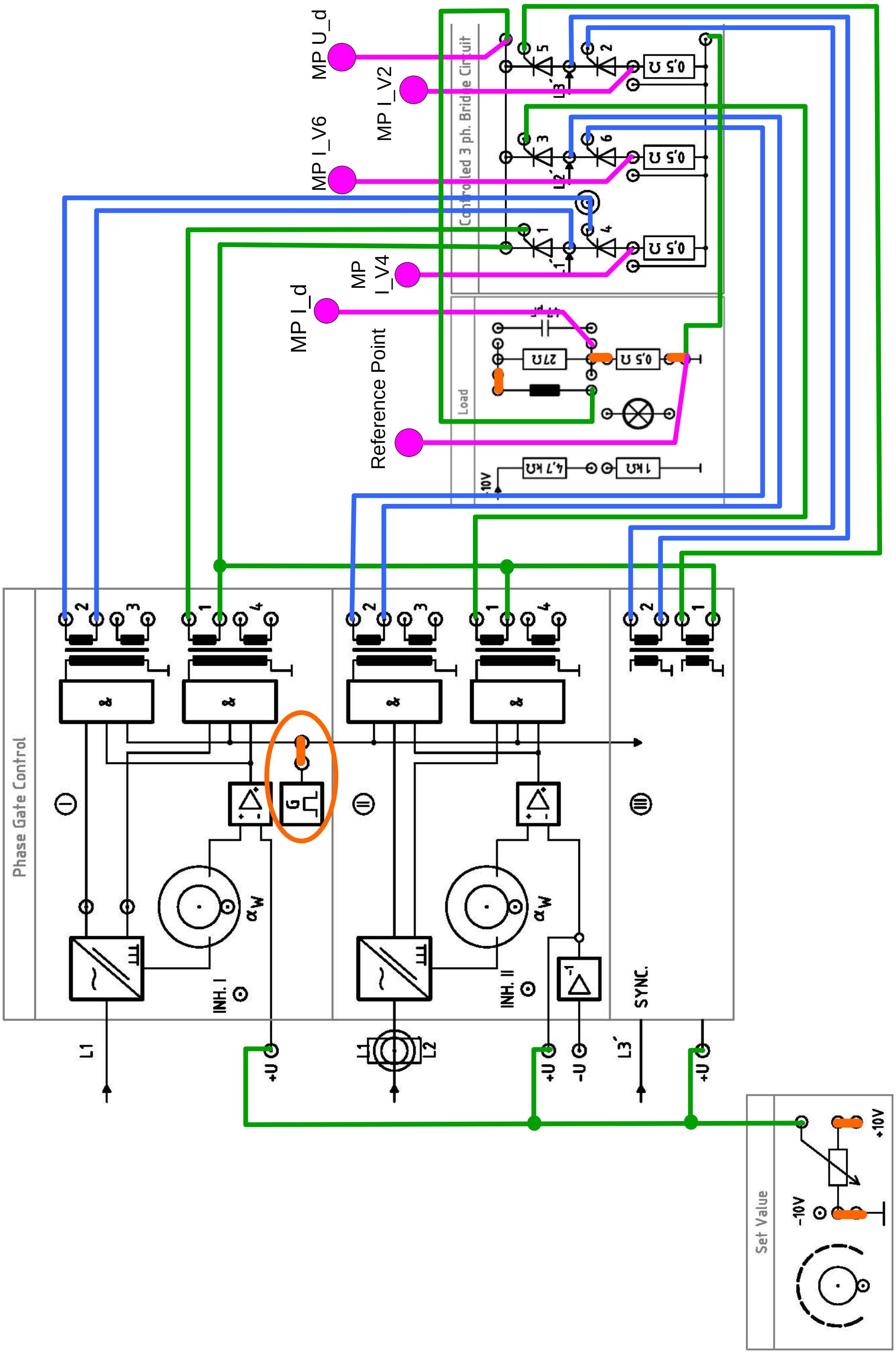
Test Configuration & Test Procedure

- Build up the circuit in pic. 3.6.1.0 / 3.6.1.1.

Note: ***At three-phase current the triggering angle α is not taken from the zero crossing of U_{L1}, but from the crossing of U_{L1} and U_{L3}. If you would like to orientate yourself on the oscilloscope at the zero crossing of $U_{L1,}$ you have to subtract 30° of your determined angle between trigger moment and zero crossing.***



pic. 3.6.1.0 circuit



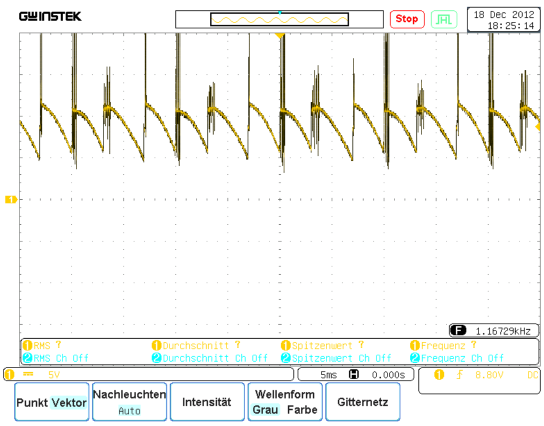
pic. 3.6.1.1 circuit

- Connect the bridge to the three-phase source.
- Set the selector M3/B6 to position B6.
- Set synchronizing of the phase gate control II at switch L1/L2' to position L2'.
- Set the inverter limit α_W at the phase gate control I and II, so all three thyristors fire at approx. the same phase length.

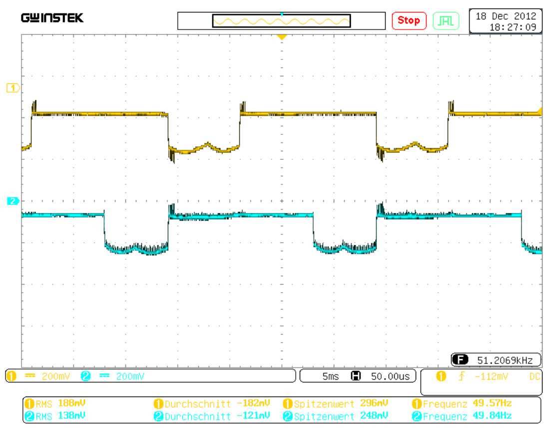
Procedure: Measure with the oscilloscope parameters $U_{L1'}$ and U_d.
Set the triggering angle to α = 90°.in.

With a suitable potentiometer, you can set the pulses of U_d to identical triggering angles α_W and identical amplitudes (variances due to component tolerances are possible).

- Set the triggering angle to α = 36°.
- Measure following parameters with the oscilloscope:
  - Output Voltage U_d,
  - Output Current I_d,
  - Thyristor Currents I_{V4}, I_{V6} and I_{V2}
- Draw the curves in pic. 3.6.1.2 to pic. 3.6.1.4.



pic. 3.6.1.2



pic. 3.6.1.3

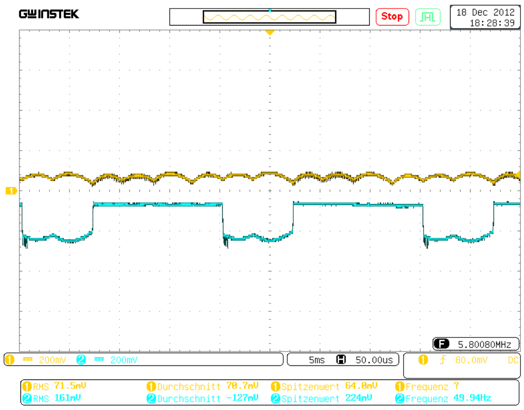
Oscilloscope Settings:

Output Voltage U_d: 5 V / div.
Time t: 5 ms / div.

Oscilloscope Settings:

Thyristor Current I_{V4}: 0,4 A / div.
= 0,2 V / div.
Thyristor Current I_{V2}: 0,4 A / div.
= 0,2 V / div.
Time t: 5 ms / div.

Current Conversion with Rm = 0,5 Ohm



pic. 3.6.1.4

Oscilloscope settings:

Output Current I_d:	0,4 A / div.
=	0,2 V / div.
Thyristor Current I_{V6}:	0,4 A / div.
=	0,2 V / div.
Time t:	5 ms / div.

Current Conversion with Rm = 0,5 Ohm

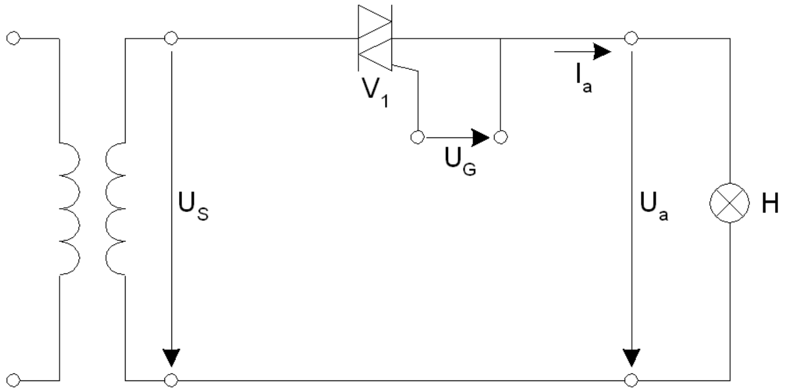
Question:	How can the wave forms of the thyristor currents be explained?
Answer:	With each triggering of a thyristor the current commutates to this thyristor,
	as long as the current does not "gap". With commutation the
	current in the valve increases by leaps. Respectively current drops to
	zero in leaps at clearing. While one thyristor in one bridge half is
	conducting, two thyristors in the second half take turns in being
	conducting. Therefore current flow is induced by two sinewave
	conducting. Therefore current flow is induced by two sinewave
	altering voltages. Current flow shows two peaks.

4 AC Inverter

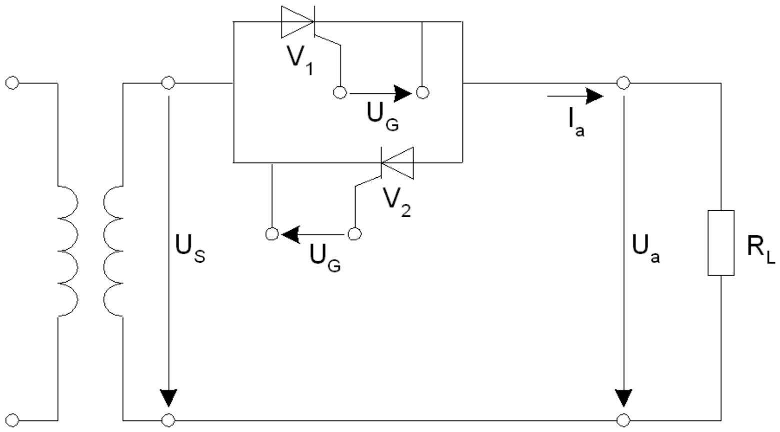
4.1 Controlled Single-Pulse Commutation Circuit W1C

Exemplarily for commutation circuits we examine a single-pulse commutation circuit W1C. As semiconductor device we use a TRIAC, although all circuits could be configured with two antiparallel connected thyristors.

Circuit:



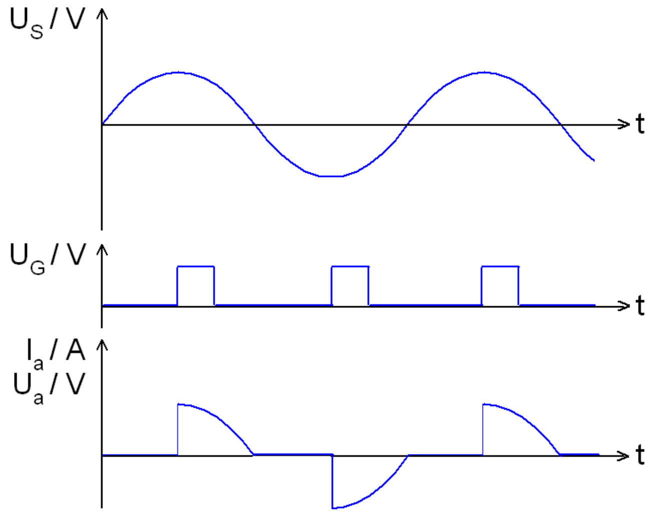
pic. 4.1.0.0 W1C with TRIAC



pic. 4.1.0.1 W1C with 2 anti-parallel thyristors

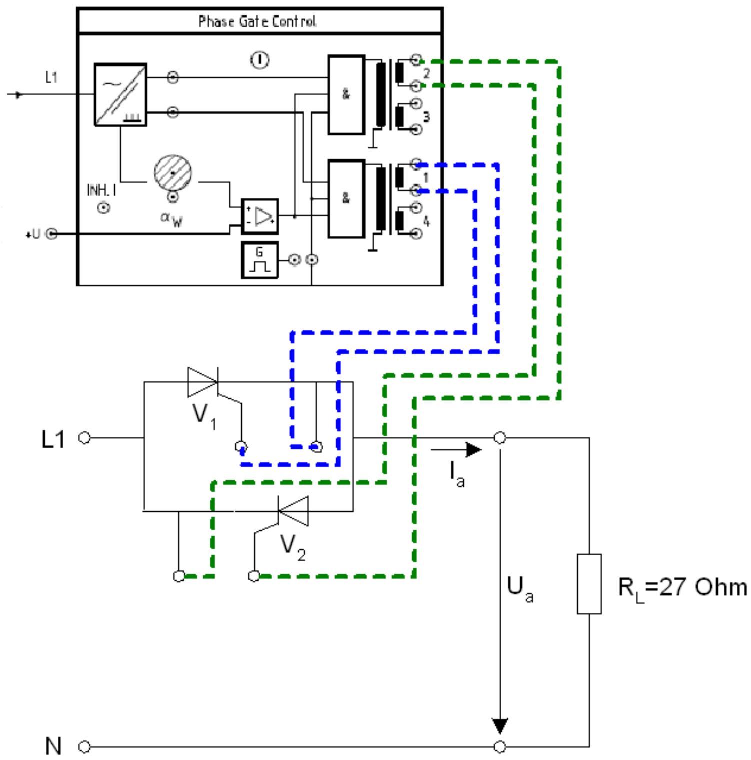
.

Signal Wave Form:



pic. 4.1.0.2 W1C signal wave form with phase control

As shown in the signal wave form, both half-waves of the mains voltage are phase cut. If the circuit is configured with two antiparallel thyristors, triggering could be affected as follows:

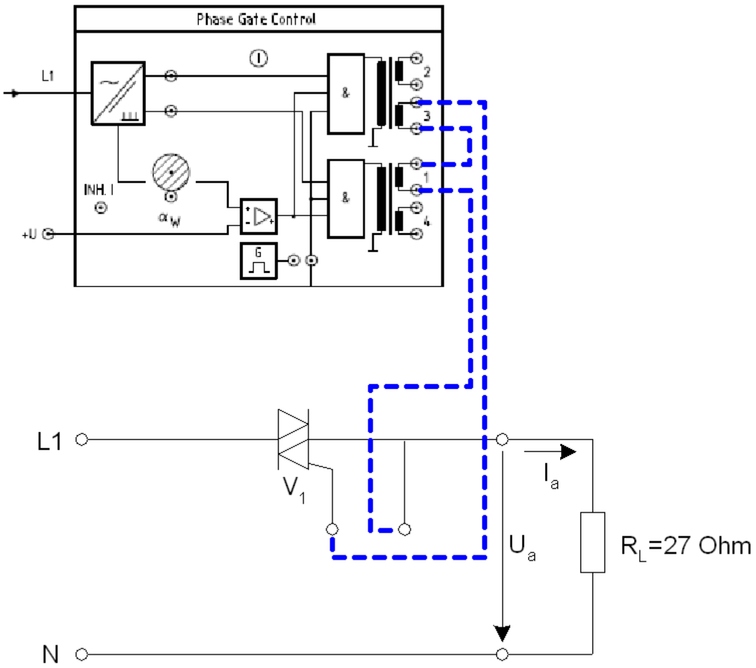


pic. 4. 4.1.0.3 W1C triggered by two thyristors

In this circuit $V_1$is biased by positive and V_2 by negative half-wave. V_1 gets its triggering signal from a pulse initiator, which carries a triggering signal (pulse initiator 1 on the panel) during the positive half-wave. Respectively V_2 gets its triggering signal (pulse initiator 2 on the panel) during the negative half-wave.

If the TRIAC is used instead of the two thyristors, the circuit has to be modified. Both half-waves of mains-voltage should be controlled, thus the TRIAC has to get triggering signals from both half-waves. The pulse initiator cannot supply triggering voltage for both half-waves at a time because of the channel separation. However, the essential signal can be supplied by series connection of the “positive group” (pulse initiator 3 and 1).

If pic. 4.1.0.3 is regarded more closely, you will find out, that output current of the AC power controller is not sinusoidal. Viewed from the mains input side, current and voltage do not have the same wave form. There‘s some harmonic distortion or reactive power. This harmonic distortion rises with bigger triggering angle α. Means it increases the more distant current wave and sine wave are.



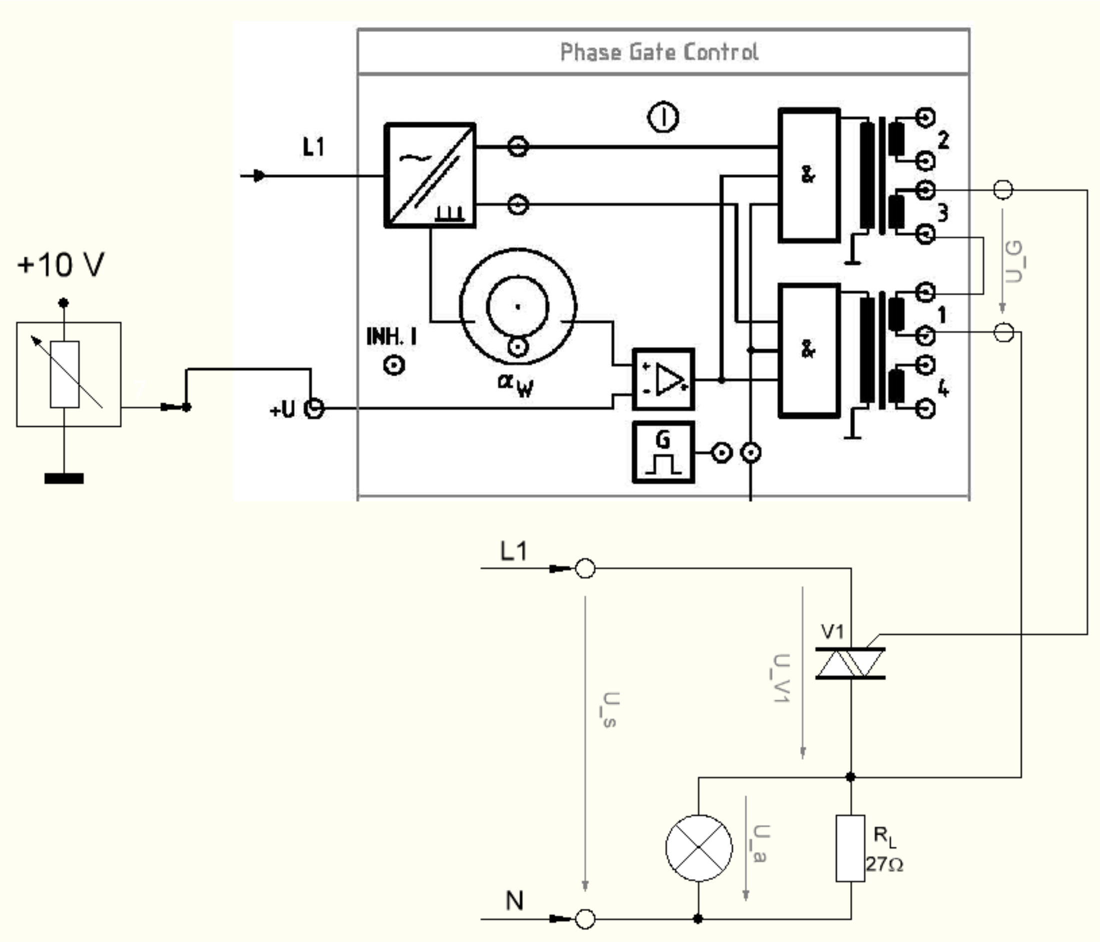
pic. 4.1.0.4W1C triggered with one TRIAC

4.1.1 Test 1

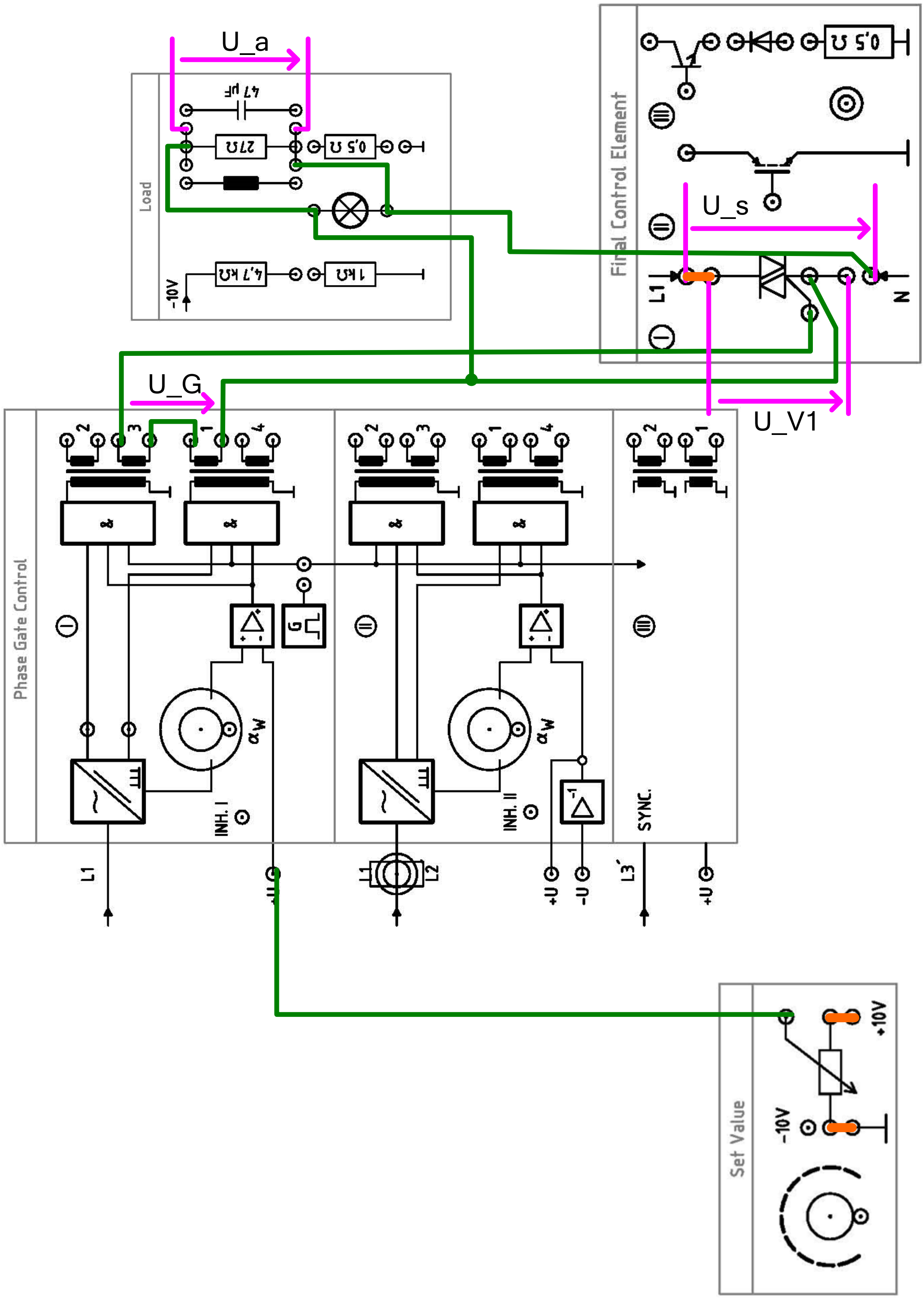
Signal wave form in phase gate control without rectifier function.

Test Configuration & Test Procedure

Build up the circuit in pic. 4.1.1.0 / 4.1.1.1.



pic. 4.1.1.0 circuit



pic. 4.1.1.1 Circuit at the Power Electronic Panel

- Use the load in parallel connection with the 27Ω resistor and the light bulb at the Power Electronic Panel.

- Form the triggering signals by series connection of the two initiators I_3 and I_1.

- Set the triggering angle to α = 90°.

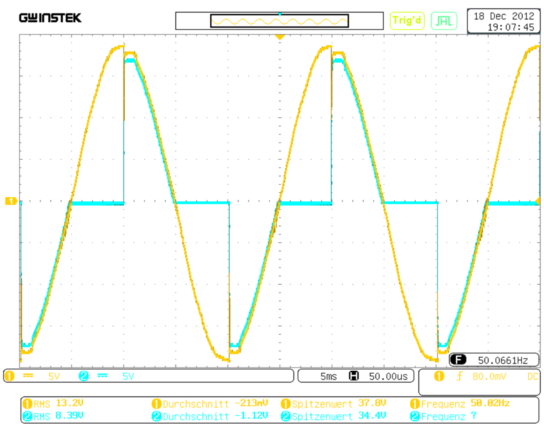
Note: ***The adjuster for the triggering angle α_W at the phase gate control should be non-effective. Therefore is has to be positioned on the right hand sided arrester.***

- Trigger the oscilloscope internally via LINE.

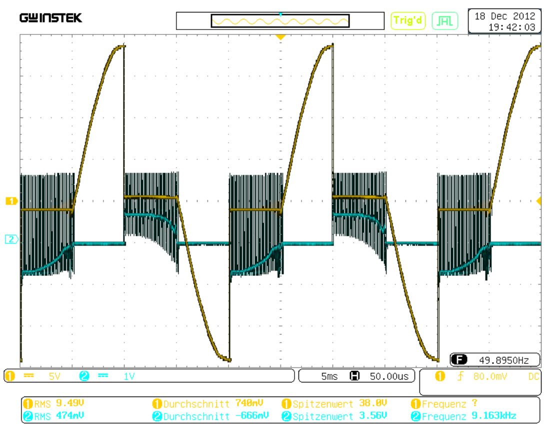
- Measure following parameters with the oscilloscope:
  - Mains Voltage U_S,
  - Output Voltage U_a,
  - TRIAC Voltage U_{V1},
  - Gate Voltage U_G

Note: ***At measurement of U_S and U_a, N has to be connected to ground potential. At measurement of U_{V1} and U_G, A1 has to be connected to ground.***

- Draw the curves in pic. 4.1.1.2 and pic. 4.1.1.3.



pic. 4.1.1.2



pic. 4.1.1.3

Oscilloscope Settings:

Mains Voltage U_S:	5	V / div.
Output Voltage U_a:	5	V / div.
Time t:	5	ms / div.

Oscilloscope Settings:

TRIAC Voltage U_{V1}:	5	V / div.
Gate Voltage U_G:	1	V / div.
Time t:	5	ms / div.

Question 1:	At which triggering angle does the lamp get the highest voltage?
Answer:	The lamp gets its highest voltage at the smallest control angle.

Question 2:	How does the triggering angle have to alter, if the lamp should glow continuously brighter beginning from zero?
Answer:	To brighten the lamp the control angle has to get smaller.

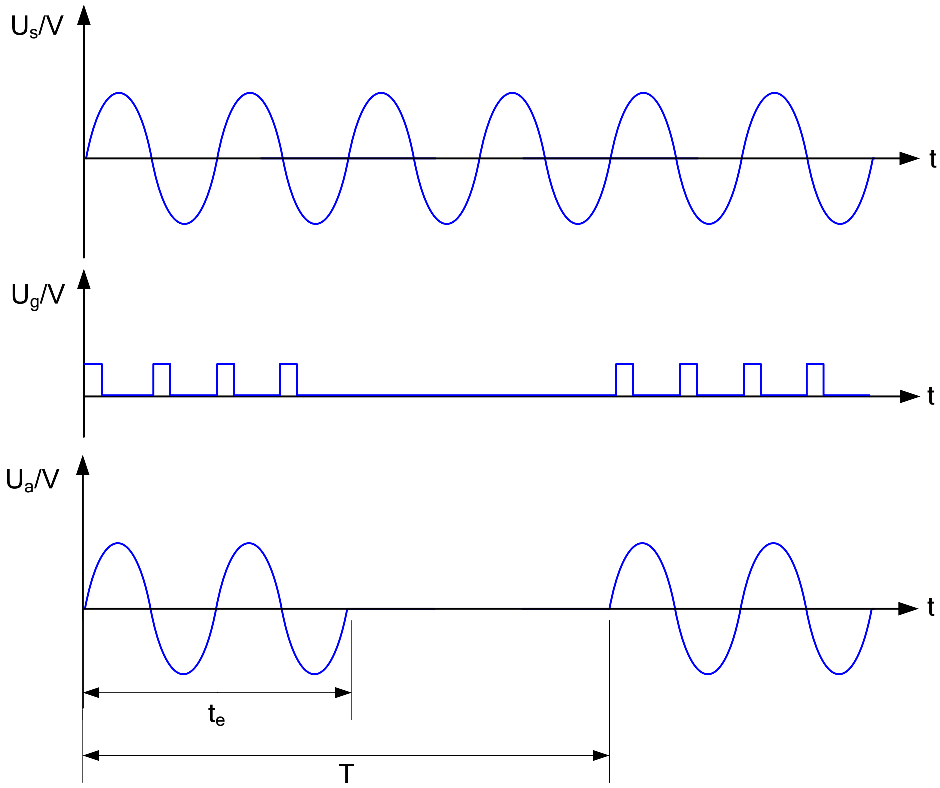
Question 3:	By triggering the TRIAC mains voltage gets a bit distorted. How do you explain this?
Answer:	By triggering the TRIAC current begins to flow. That means mains
	transformer is loaded and the input voltage drops a little when fired.
	Most voltage drop is in the range of α = 90°, as it is the biggest current
	rise.

Question 4:	Why do you need two pulse initiators I_1 and I_3 for the firing of a TRIAC?
Answer:	I_1 fires the TRIAC during the positive half-wave. I_3 fires the
	TRIAC during the negative half-wave.

Question 5:	Why does a low voltage occur between gate and anode when the TRIAC is fired? What polarity is it?
Answer:	At the TRIAC, same as at the thyristor, a portion of load current passes
	the gate. This load current between gate-anode produces a voltage
	drop with same polarity than load current.

4.2 Pulse Group Control

Even if the load is all ohmic an idle harmonic distortion occurs at the phase gate control. To keep this effect lowest possible, current and voltage have to be sinusoidal or at least as much to this wave form as possible.
If inert loads should be controlled (e.g. heating rods for boilers), it is possible to do so without the phase gate control but use the pulsating full-waves, the so called pulse group control. Triggering occurs here exactly at zero crossing. A phase with a certain off-period follows in which the TRIAC blocks.



pic. 4.2.0.0 signal wave form of pulse group control

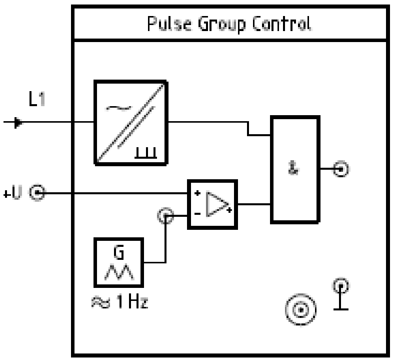
Current and voltage are always sinusoidal, that means idle harmonic distortion is very low. One more characteristic of this circuit is very low mains interference.
At the phase gate control there are very rapid switching operations respectively with interfering current peaks (high-frequency vibrations). The pulse group control however only switches at zero crossing.

A must for the TRIAC control:

- Switching at zero crossing
- Duty cycle variably adjustable $g = \frac{t_e}{T}$
- Switching period T in a run-time of seconds (requested by idle harmonic wave)

The respective element on the Power Electronic Panel is the “Pulse Group Control” (see left hand sided pic.).
By help of delta signal and a variably adjustable DC voltage a comparator generates a pulse-break-signal with a cycle duration of 1 s. The duty cycle g is variably adjustable.
Additionally the pulse-break-signal is linked to the zero voltage signals via AND-gates.

This configuration creates pulse groups in the zero crossing. Duration of a pulse group depends on the applied DC voltage.



pic. 4.2.0.1Pulse Group Control at Panel

To control complete sine waves, triggering of the TRIAC has to happen nearest possibly to zero crossing of the mains sinus. Therefore the first element on the “Pulse Group Control” is a so called „zero voltage detector“.
To make the full-waves adjustable, a squared signal with alterable in-/ output percentage is generated. At the last step the signals are AND-linked. Thus each group of triggering signals is available at zero crossing.

Note: The generated pulse group has GND for reference point. So voltage drops at the TRIAC for triggering, the GND has to be connected to the A2 contacts of the TRIAC.

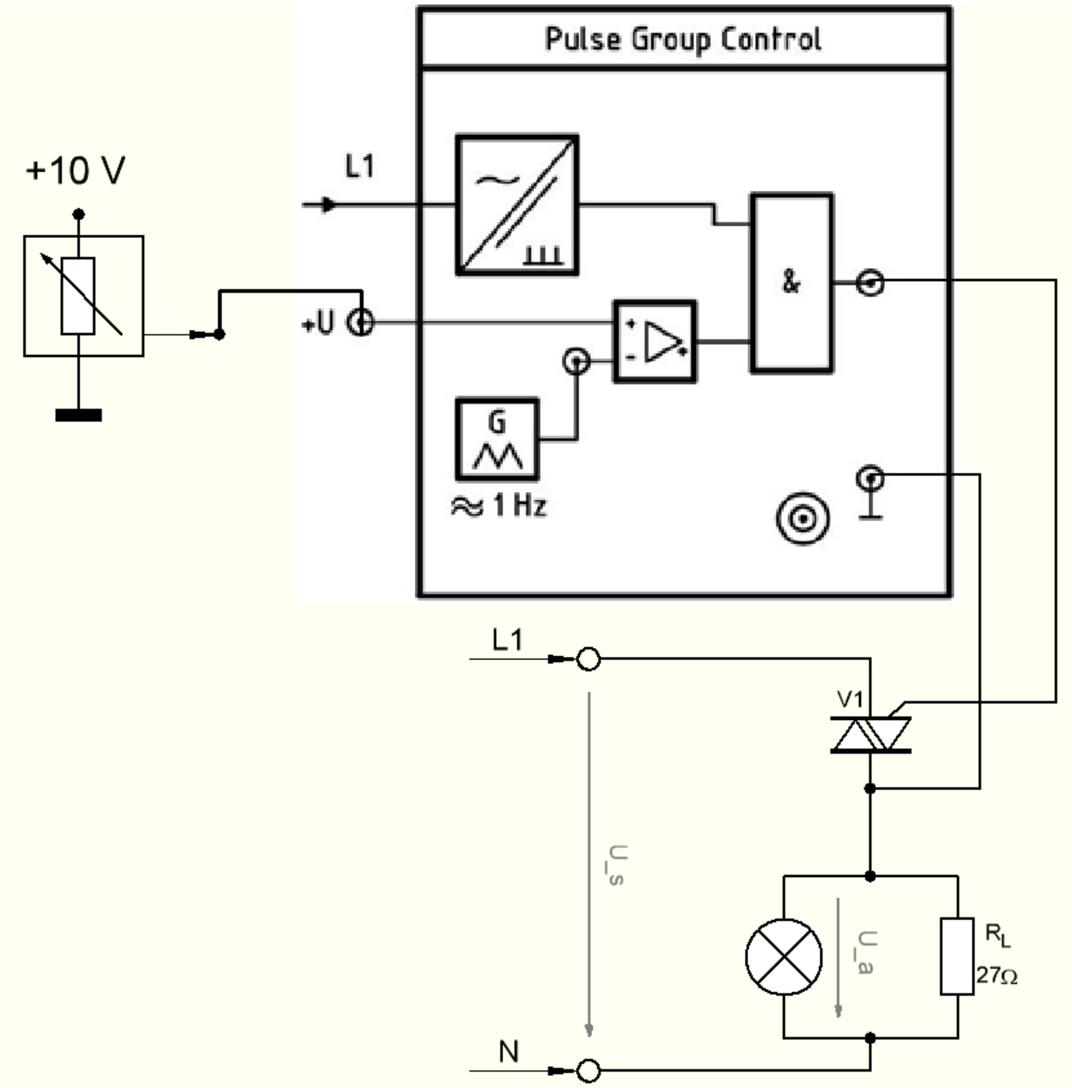
4.2.1 Test 1

Voltage curves in the Pulse Group Control with W1C circuit.

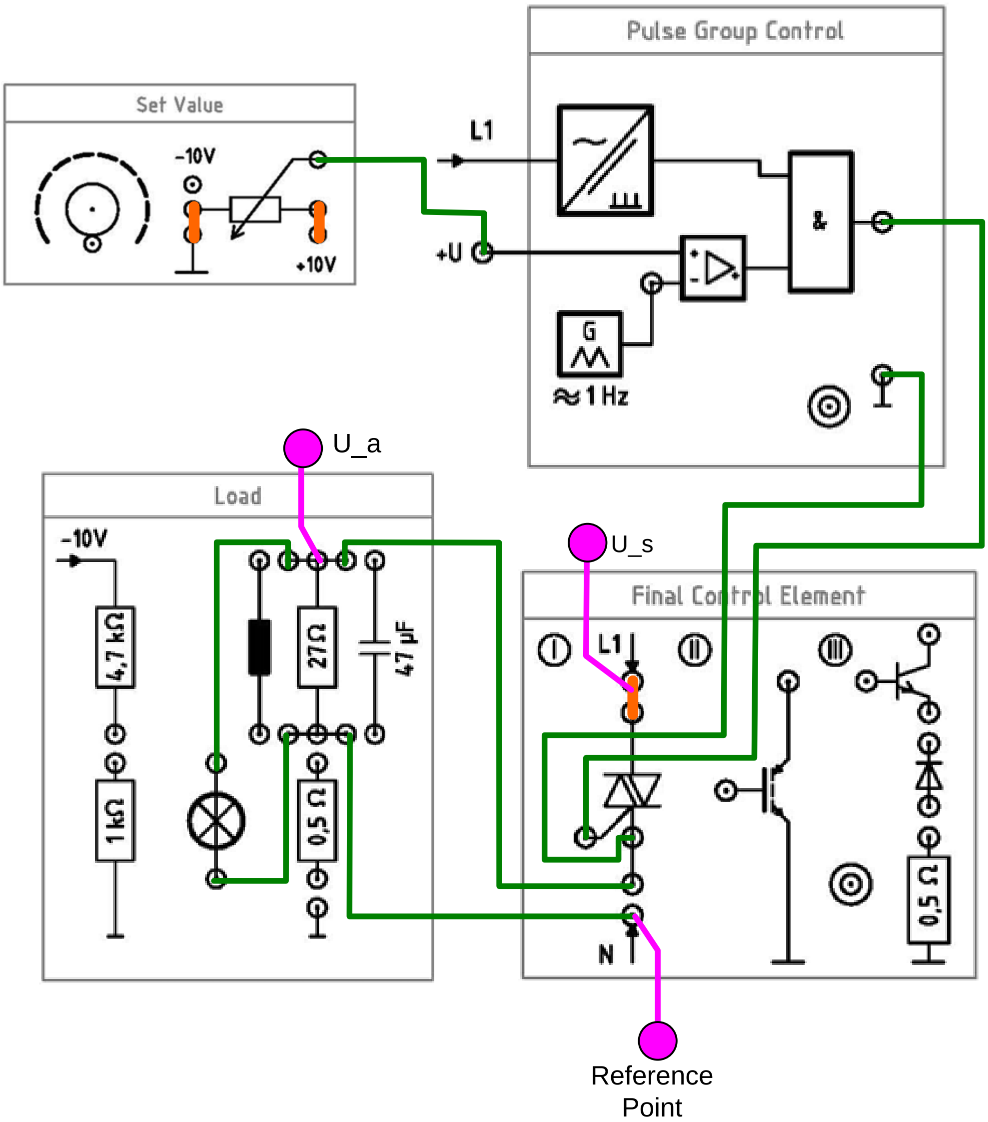
Test Configuration & Test Procedure

- Build up the circuit in pic. 4.2.1.0 / 4.2.1.1.

Note: Reference Point of the Oscilloscope in this case is not the GND connector.



pic. 4.2.1.0 circuit

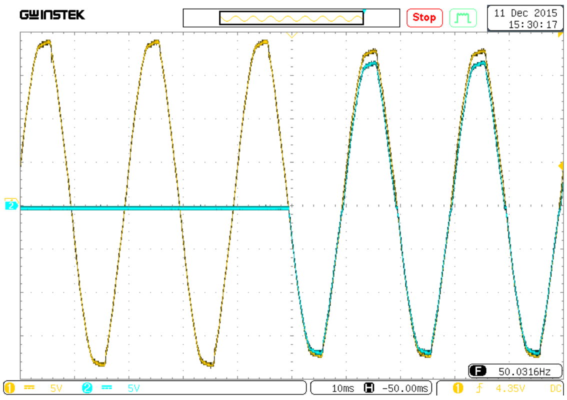


pic. 4.2.1.1 circuit

- Set control voltage to +U = 7 V.

Measure following parameters with the oscilloscope:
- Mains Voltage U_S,
- Output Voltage U_a,

- Draw the curves into pic. 4.2.1.2.



Oscilloscope Settings:

Mains Voltage U_S:	5	V / div.
Output Voltage U_a:	5	V / div.
Time t:	10	ms / div.

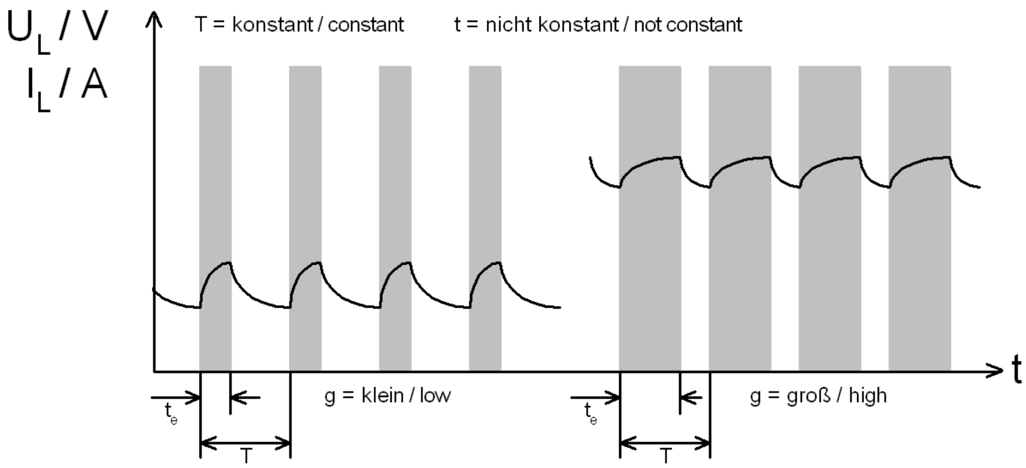
pic. 4.2.1.2

5 DC Current Converter

5.1 Pulse Width Modulation

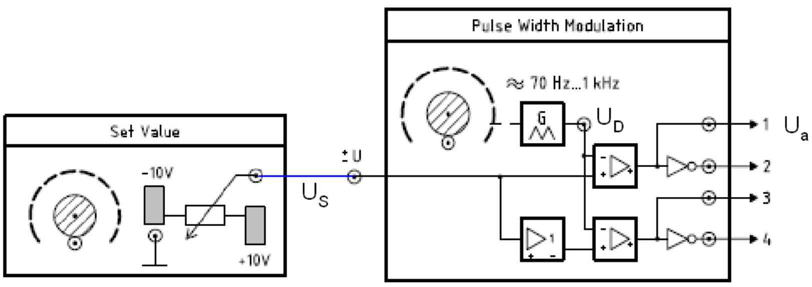
The Pulse Width Modulation is the most popular control for DC chopper and DC voltage converter. The average value of square wave voltage is manipulable by altering a regular interval T per on-time t_e.
If this method controls e.g. the voltage on load, the average load current I_L alters according to the duty cycle g.

$$g = \frac{t_e}{T}$$



pic. 5.1.0.0 signal wave for pulse width modulation

The circuit for control of pulse width modulation can be realized with a simple operation amplifier. The op-amp (wired as comparator) compares the delta AC voltage U_D with the control DC voltage U_S.

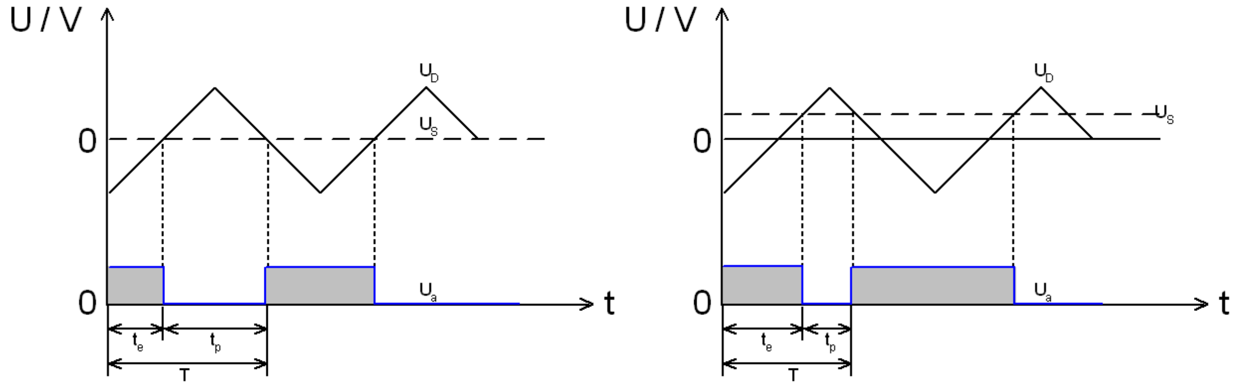


pic. 5.1.0.1 control circuit for PWM

If control voltage U_S is higher than the delta AC voltage U_D, the OP switches to LOW. Thus U_a is a square wave pulse sequence with pulse occurring within the duty cycle whenever the delta AC voltage is lower than the control voltage.

At U_S = 0V: $t_e = \frac{1}{2} \cdot T \quad or \quad t_e = t_p \qquad g = t_e / T = 0{,}5$

If U_S increase, pulses get wider and breaks get narrower. The duty cycle get closer to value 1, which is DC voltage.
If U_S decreases, pulses get narrower and breaks get wider. The duty cycle declines.
Fundamental for the output stage control is voltage U_a.



pic. 5.1.0.2 PWM signal wave forms

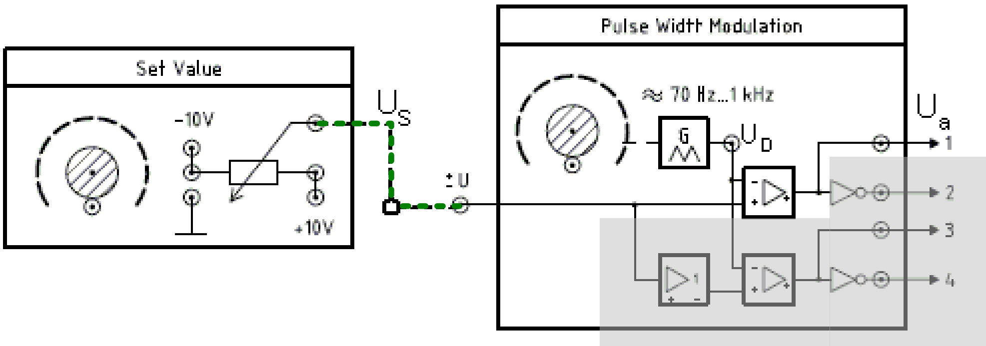
5.1.1 Test 1

Signals of control circuit for pulse wave modulation.

Test configuration & Test procedure

- Build up the circuit in pic. 5.1.1.0

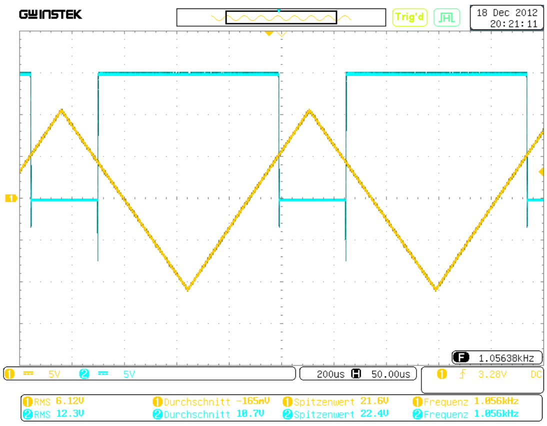
Note: ***At first do only regard the circuit without the grey highlighted part for the single PWM control in this chapter.***



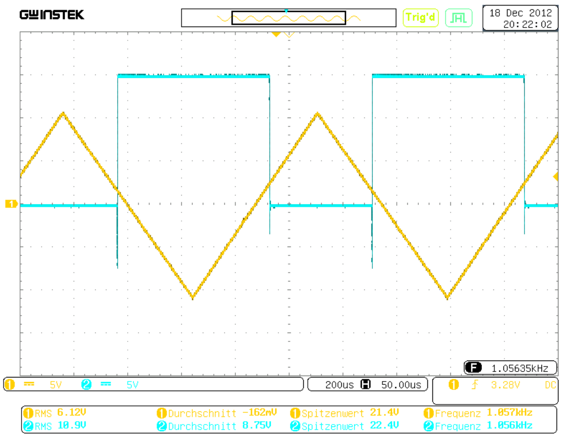
pic. 5.1.1.0 circuit

- Externally trigger to delta voltage U_D.
- Set the delta generator to a frequency of 500 Hz.
- Measure following parameters with the oscilloscope for the control voltages of U_S = +5V, +2V and -2V:
  - Delta Voltage U_D,
  - Output Voltage U_a

- Draw the curves in pic. 5.1.1.1 to pic. 5.1.1.3.



pic. 5.1.1.1 control voltage U_s = +5V



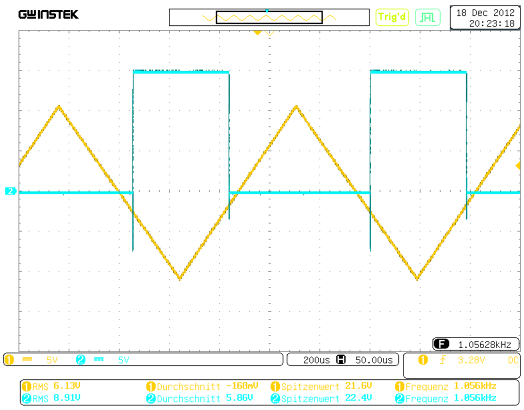
pic. 5.1.1.2 control voltage U_s = +2V

Oscilloscope Settings:

Delta Voltage U_D: 5 V / div.
Output Voltage U_a: 5 V / div.
Time t: 0,2 ms / div.

Oscilloscope Settings:

Delta Voltage U_D: 5 V / div.
Output Voltage U_a: 5 V / div.
Time t: 0,2 ms / div.



pic. 5.1.1.3 control voltage U_S = -2V

Oscilloscope Settings:

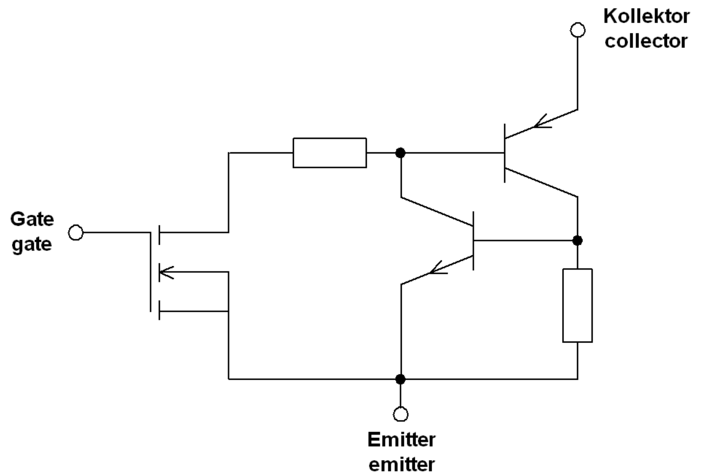
Delta Voltage U_D: 5 V / div.
Output Voltage U_a: 5 V / div.
Time t: 0,2 ms / div.

Question 1:	How does on-time t_e, alters, if control voltage U_S is increased?
Answer:	If control voltage U_S is increased, the range in which the control voltage
	is higher than U_D increases.
	Thus on-time t_e increases,too.

Question 2:	How does duty cycle g alter, if control voltage U_S gets more negative?
Answer:	If U_S gets more negative, t_e will decrease, and thus duty
	cycle $g = t_e / T$ decreases, too.

5.2 Pulse Width Modulated Direct Current Chopper with IGBT

IGBT stands for „Insulated Gate Bipolar Transistor“, means a bipolar transistor with insulated gate-electrode. The IGBT is a semiconductor device, used more and more in applications with power electronics. That device offers all the advantages of the bipolar transistor (high conductance, high blocking voltage, stability) and the field-effect transistor (control with almost no power). Furthermore IGBTs have short-circuit-withstanding-capability, as load current is internal limited.



pic. 5.2.0.0 equivalent circuit diagram of IGBT

The IGBT is an advanced version of the vertical power MOSFET. The IGBT is a four layer semiconductor device that is gate controlled. Mostly it has a highly doped p-substrate (n-channel IGBT) with a special accomplished p-n junction at its rear side. On the substrate a poorly doped n-epitaxial layer is deposited, after that the p-cathode drain and highly doped n-source are added by diffusion. The outcome of this method is a n^+pnp^+ structure for a n-channel IGBT. P-channel IGBTs do have a p^+npn^+ structure.

P-n junction and the gate are responsible for the functioning of the IGBT. A Darlington-circuit from n-channel FET and a pnp bipolar junction transistor is given.

Positive potential is applied to the collector (in respect to the emitter), so the rear junction is in forward conduction and not inverse blocking. Forward conduction is split in two modes: in blocking – and conduction region. As long as threshold voltage (Gate-Emitter-Voltage, U_{GE}) of the FET is not reached, the IGBT is in blocking region. If the voltage U_{GE} increases, the IGBT gets in conduction area. Like the normal MOS-FET below the gate in the p-cathode drain there forms a conducting n-channel. This enables transportation of the electrodes from emitter to the epitaxial layer.
As the rear sided p-n junction is in forward conduction, holes from the p^+ substrate will be injected into the epitaxial layer, that plasma of minority carriers is responsible for conduction. This plasma has to be recombined at each switching operation, thus the drift region gets much more complex compared to the FETs, and the switching loss is much higher. At the destruction of the plasma, the IGBT possibly gets conducting temporarily.

Characteristics:

- Fixed portion of voltage drop at the emitter-collector-connection (typically 2,3V)
- Switching loss at high currents lower than with comparable FETs
- Low conducting resistance
- Voltage controlled device (like FET)
- Only limited blocking capability in reverse direction

Applications:

- Switching power supply
- Frequency converter (drive engineering)
- DC chopper controller
- UPS (uninterrupted power supply)
- Dimmer
- Inverter
- Semiconductor relay

5.3 DC to DC Voltage Converter

The function of a DC to DC converter is to get following voltages from value and polarity given:

- Higher voltage of same polarity
- Lower voltage of same polarity
- Higher voltage of opposite polarity
- Lower voltage of opposite polarity

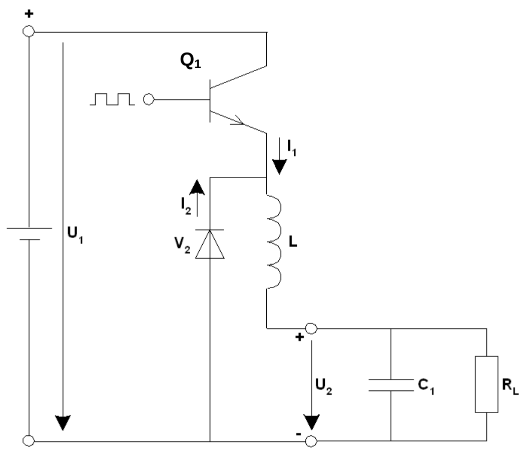
The basic configuration of DC chopper controller and DC to DC converter is similar in principle, but the function is very different. Common function is the switching of the semiconductor „check valve“, and the reduction of ripple with coil, as well as the non-stabilized input voltage.

The main function of the DC chopper controller is to change very high voltages with altering polarity in high speed. A typical example for practical application is a power stage of a servo drive. Therefore bi-polar conduction is essential, so the servo motor can be actuated and decelerated. At DC to DC converters value and polarity of the output voltage are fixed. As a result current flow is only possible with single direction.

In following the three most popular basic circuits of voltage converters are explained. For easier comprehension input voltage is pictured as battery. A RC-combination is used for load at the output.

Buck (step-down) converter:

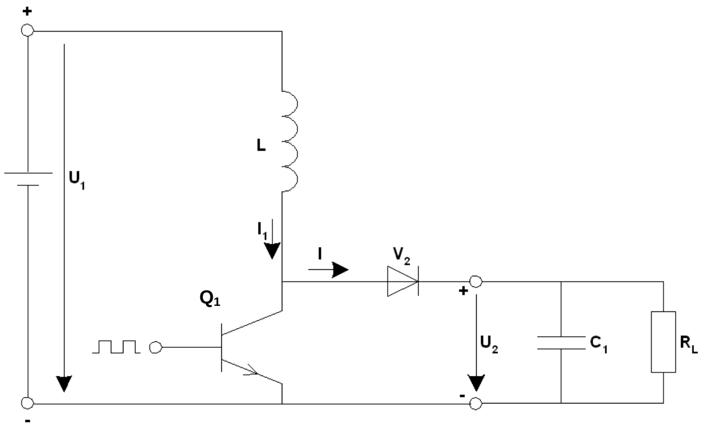
A buck converter generates an output voltage lower than the input voltage.
Typical application is in a circuit with +-15V voltage supply and the necessity of a +5V TTL-level. This circuit operates as forward converter. While transistor V_1 is conducting, current I_1 flows. When the transistor opens, the coil drives current I_2 as freewheeling current through diode V_2 and transports energy from its magnetic field to the load. Same functionality than a DC chopper controller.



pic. 5.3.0.0 buck converter

Boost (step-up) converter:

The input voltage is boost into higher output voltage with the boost or step-up converter. Here the circuit acts like a flyback converter. Energy flows from source to load, only when the transistor is blocked (current I_1 flows). During the conducting phase of the transistor the current source drives the current I_2 through the coil and its magnetic energy content rises. If the transistor gets conducting, the coil tries to sustain current flow. That induces a voltage boost of higher value than the diodes threshold voltage and the current value of capacitor voltage. The capacitor is additionally energized. U_2 is higher than U_1.

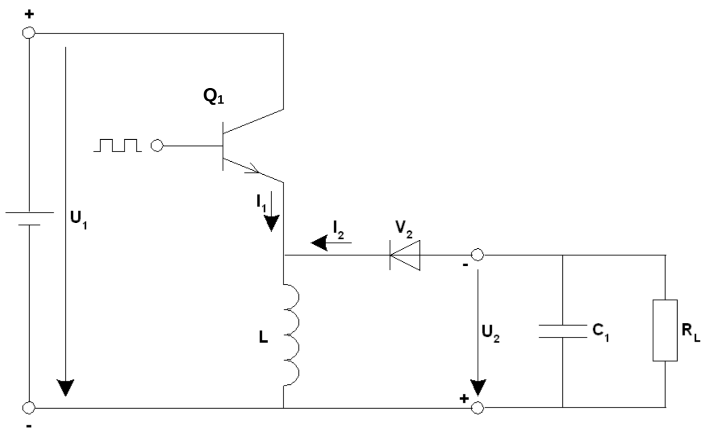


pic. 5.3.0.1 boost converter

Note: We left out one test configuration by purpose, as this may generate very high voltages!

Buck-boost (inverse) converter:

The buck-boost converter has the same principle than a flyback converter. With conducting transistor, current I_2 is driven from the source through the coil and the energy content is boost. Diode V_2 blocks in this time period. If the transistor gets conducting, high negative induction voltage arises at that moment, which drives current I_1 through the now conducting diode V_2. The capacitor is energized by negative polarity.
If a transformer is used instead of the coil, electrical isolation between output and input is possible.



pic. 5.3.0.2 buck-boost converter

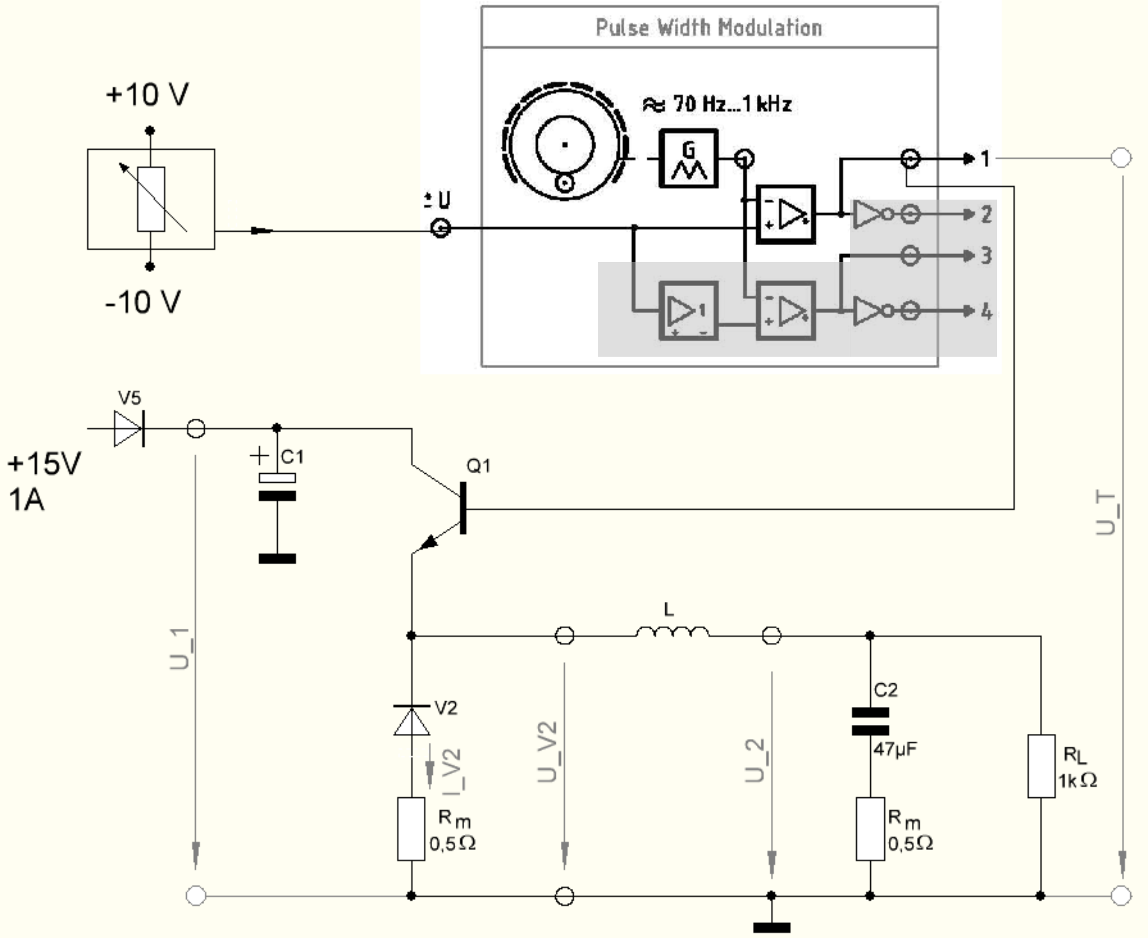
5.3.1 Test 1

Currents and voltages at buck converters.

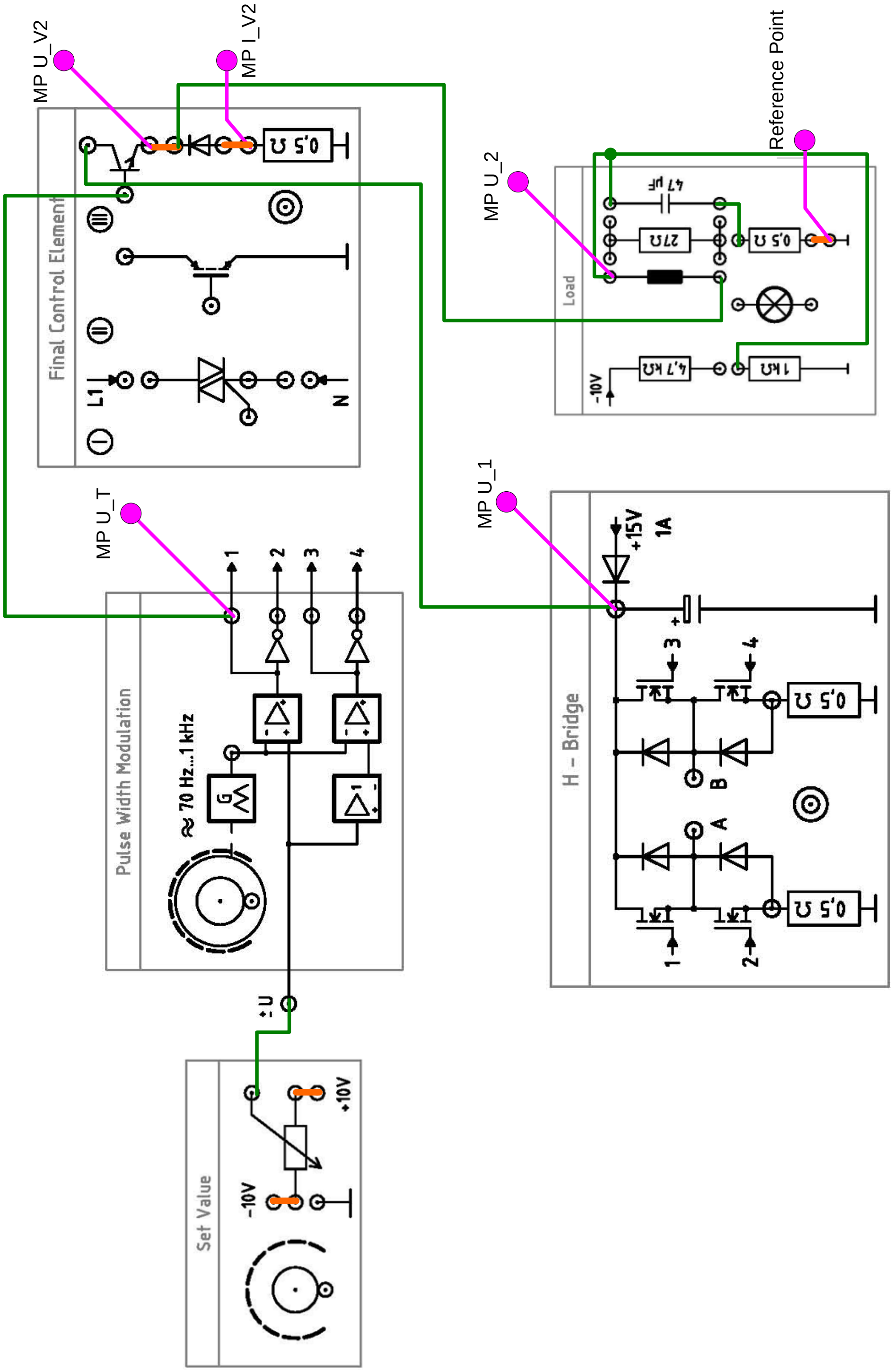
Test Configuration & Test Procedure

- Build up the circuit in pic. 5.3.1.0 and the Power Electronic Panel in pic.5.3.1.1.

Note: ***At first do only regard the circuit without the grey highlighted part for the single PWM control in this chapter. Capacitor C_1 is already wired to the voltage supply +15V. Function of the diode V_3 is to block current flow to the voltage supply.***

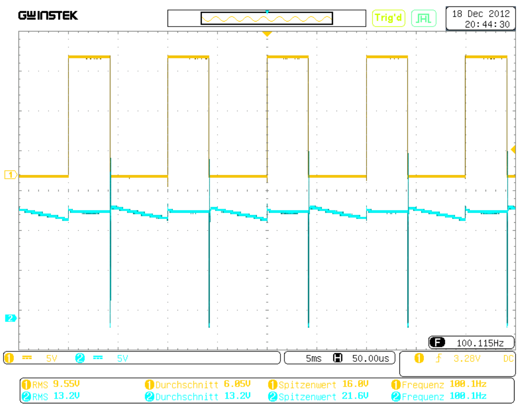


pic. 5.3.1.0 circuit

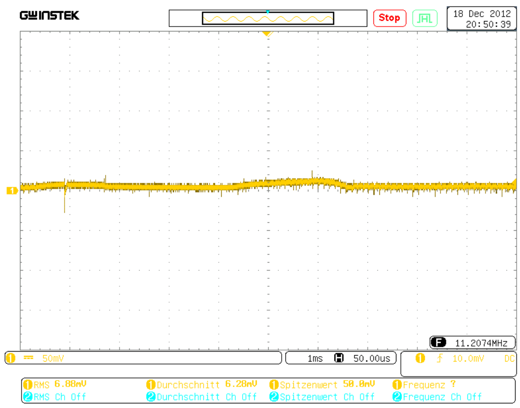


pic. 5.3.1.1 Circuit at the Power Electronic Panel

- Set the signal generator to a pulse frequency of 100 Hz.
- Set a duty cycle of g = 0,18 with the control voltage U_S.
- Measure following parameters with the oscilloscope:
  - Pulse Voltage U_T,
  - Diode Voltage U_{V2},
  - Diode Current I_{V2},
  - Output Voltage U_2,
  - Input Voltage U_1
- Draw the curves into pic. 5.3.1.2 to pic. 5.3.1.4.



pic. 5.3.1.2



pic. 5.3.1.3

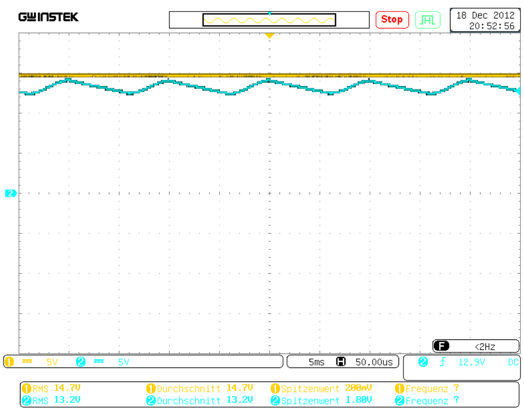
Oscilloscope Settings:

Pulse Voltage U_T:	5	V / div.
Diode Voltage U_{V2}:	5	V / div.
Time t:	5	ms / div.

Oscilloscope Settings:

Diode Current I_{V2}:	0,1	A / div.
=	0,05	V / div.
Time t:	1	ms / div.

Current Conversion with Rm = 0,5 Ohm



pic. 5.3.1.4

Oscilloscope Settings:

Input Voltage U_1:	5	V / div.
Output Voltage U_2:	5	V / div.
Time t:	5	ms / div.

Question :	What function does the diode V_2 have and why does at its cathode occur a weak negative potential if transistor V_1 is blocked?
Answer:	Diode V_2 is wired as free-wheeling diode. It provides an even current
	flow. Without this diode, current flow due to inductance L would
	interrupt and a highly negative induced voltage peak would occur,
	when cutting off the IGBT.
	If the diode is conducting, voltage drop at the cathode will be -0,7 V.

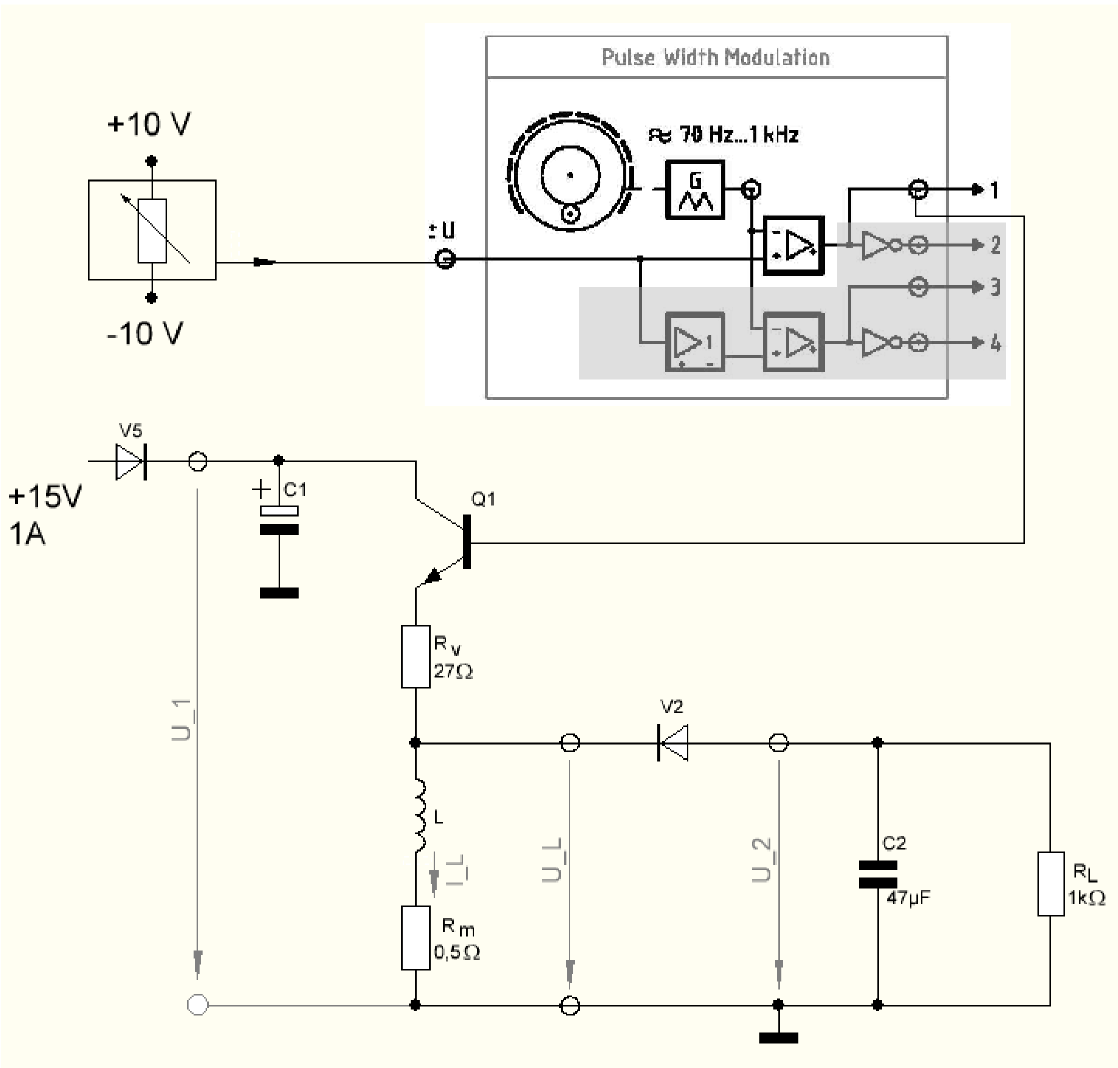
5.3.2 Test 2

Currents and voltages at buck-boost converters.

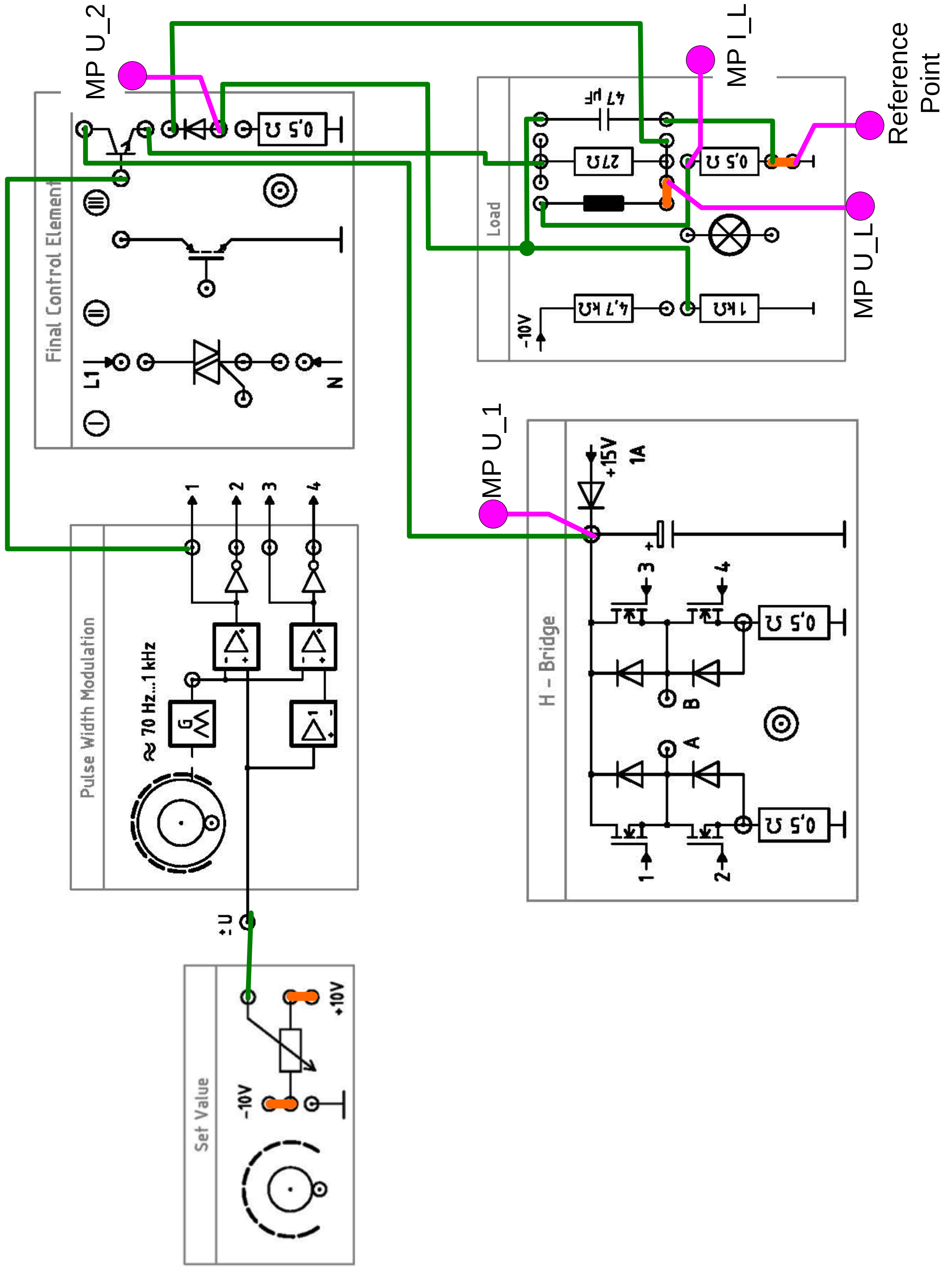
Test Configuration & Test Procedure

- Build up the circuit in pic. 5.3.2.0 and the Power Electronic Panel in pic 5.3.2.1.

Note: ***At first do only regard the circuit without the grey highlighted part for the single PWM control in this chapter. Capacitor C_1 is already wired to the voltage supply +15V. Function of the diode V_3 is to block current flow to the voltage supply.***

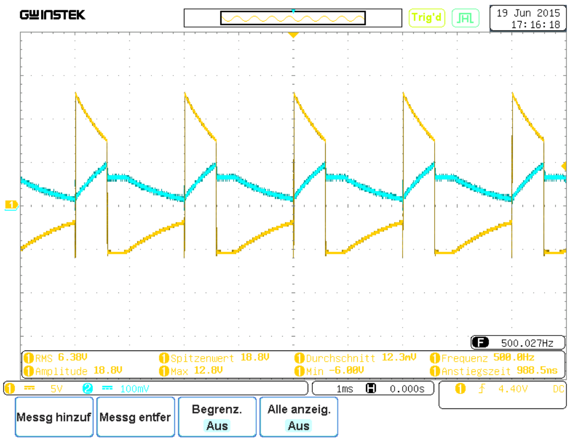


pic. 5.3.2.0 circuit

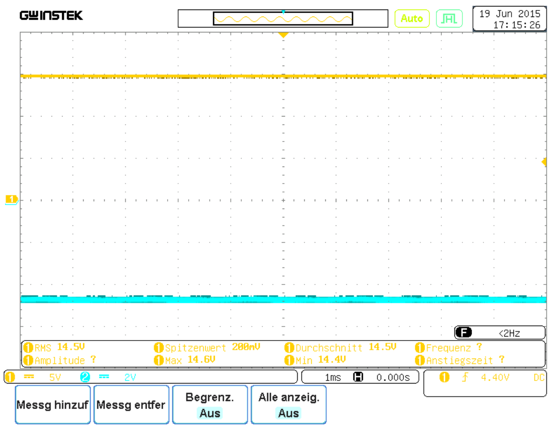


pic. 5.3.2.1 Circuit at the Power Electronic Panel

- Set the signal generator to a pulse frequency of 500 Hz.
- Set a duty cycle of g = 0,4 with the control voltage U_S.
- Measure following parameter with the oscilloscope:
  - Coil Voltage U_L,
  - Coil Current I_L,
  - Output Voltage U_2,
  - Input Voltage U_1
- Draw the curves into pic. 5.3.2.2 and pic. 5.3.2.3.



pic. 5.3.2.2



pic. 5.3.2.3

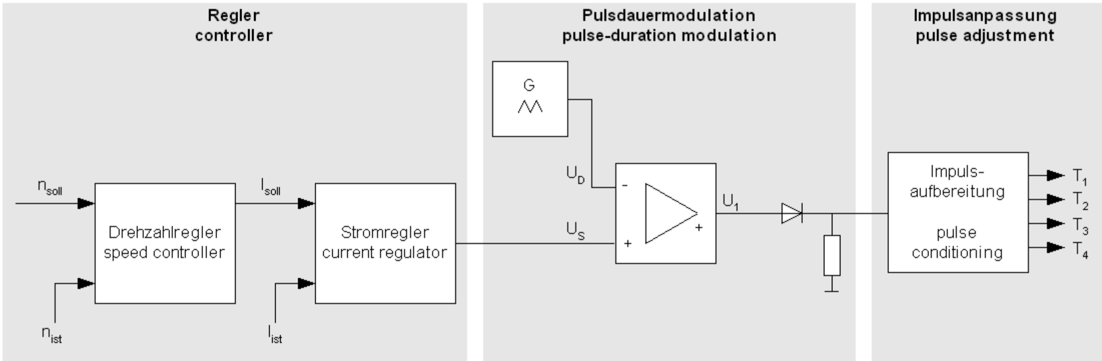
Oscilloscope Settings:				Oscilloscope Settings:		
Coil Voltage U_L:		5	V / div.	Input Voltage U_1:	5	V / div.
Coil Current I_L:		0,2	A / div.	Output Voltage U_2:	2	V / div.
	=	0,1	V / div.			
Time t:		1	ms / div.	Time t:	1	ms / div.

Current Conversion with Rm = 0,5 Ohm

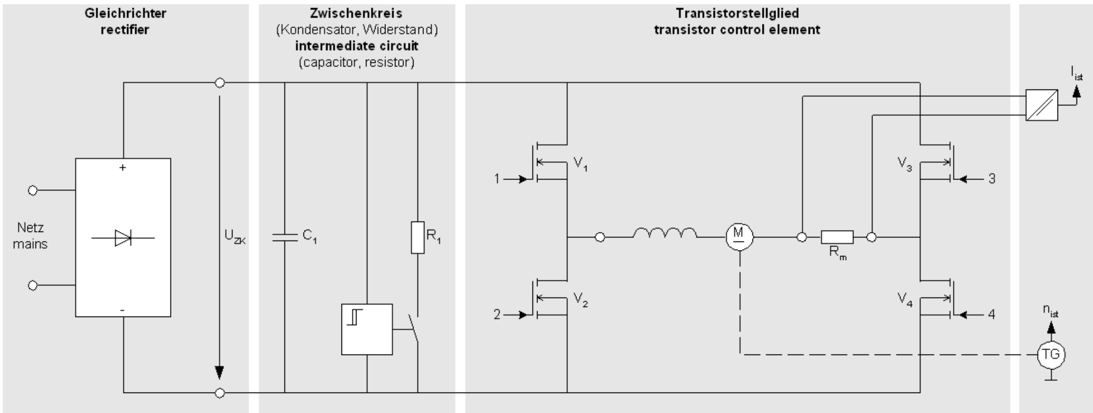
Question :	What function does the diode V_2 have?
Answer:	Diode V_2 blocks positive induced voltages and therefore ensures
	negative load voltage.

5.4 MOSFET H-Bridge with Shifted Pulse Width Modulation

Presently the actual DC servo drives (brush-type) for medium power are increasingly controlled by DC chopper controller with pulse width modulation.
Same system is used for control of electromagnetic breaks and stepper motors.



pic. 5.4.0.0 simplified diagram of a DC pulse controller-drive (control)



pic. 5.4.0.1 simplified digram of a DC pulse controller drive (power section)

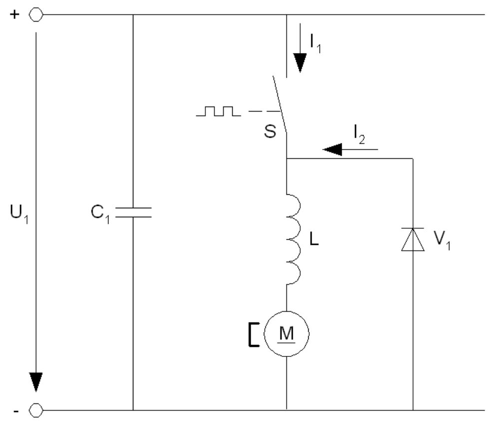
Control:

On control site there is the controller for speed and current, the pulse-duration modulation and pulse adjustment (for processing of the PWM-signal [pulse-duration modulation] for the output stage). The speed set value is set to the controller by a processor (e.g. at a NC tool machine) or for simpler applications by a potentiometer.
The speed actual value n_{ist} is generated by a tacho-sensor. The current actual value I_{ist} is collected in the power section at an isolated measuring resistor R_m.

Power Section:

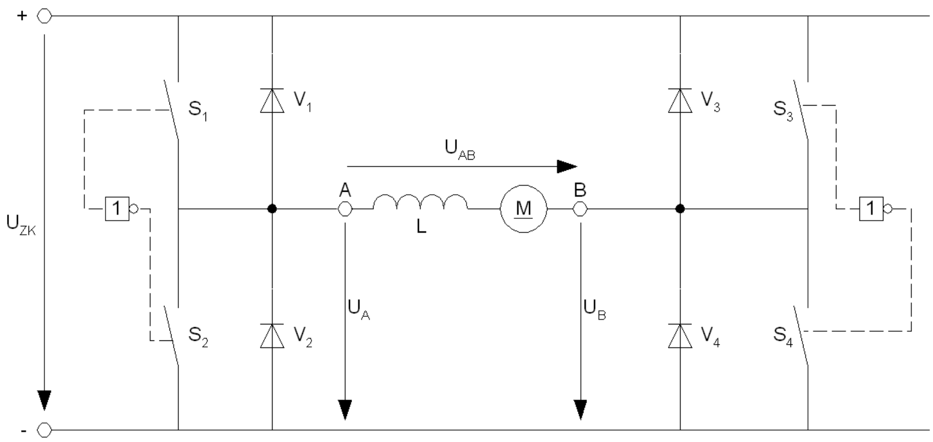
On power section site is a rectifier, which supplies DC voltage to the intermediate circuit. The back-up capacitor C_1 in the intermediate circuit supplies the higher current for acceleration. At deceleration C_1 is energized from power section site. The intermediate circuit voltage U_{ZK} rises at deceleration. If U_{ZK} exceeds a defined value the breaking resistor R_1 is activated. If the voltage decreases again, R_1 is deactivated. The breaking resistor is a so called “chopper resistor”.

Exemplarily we are looking at a DC chopper controller with MOSFETs in this manual. This kind of circuit is used for a variety of semiconductor devices with PWM-drives. Simplest kind of PWM chopper controller-drive is shown in the adjoining circuit.
The intermediate circuit includes the capacitor C1 as energy storage. Opposed at the load side is inductance L for energy storage. In the pause, when no current is supplied from the intermediate circuit, inductance supplies the stored magnetic energy and therefore acts as a smoothing choke.
The power transistor (pictured as switch) is controlled by a PWM signal. At closed switches the drive is fed by the intermediate circuit, current I_1 flows.



pic. 5.4.0.2 PWM chopper controller-drive

If the switch is opened, inductance tries to sustain current flow and supplies inductive voltage U_L. As the motor is still running, although the switch is opened, it generates generator voltage U_0. Due to U_L and U_0 freewheeling current I_2 is flowing now, pic.5.4.0.2.



pic. 5.4.0.3 transistor bridge / basic circuit for four quadrant-drives

The function of a servo drive is to accelerate, as well as to decelerate. Therefore bipolar current flow is essential. This can be realized with the above pictured H-bridge.
Positive current will flow through a motor (point A to point B) if switch S_1 and S_4 are closed synchronized. For a negative current flow (point B to point A) switch S_2 and S_3 have to close synchronized.

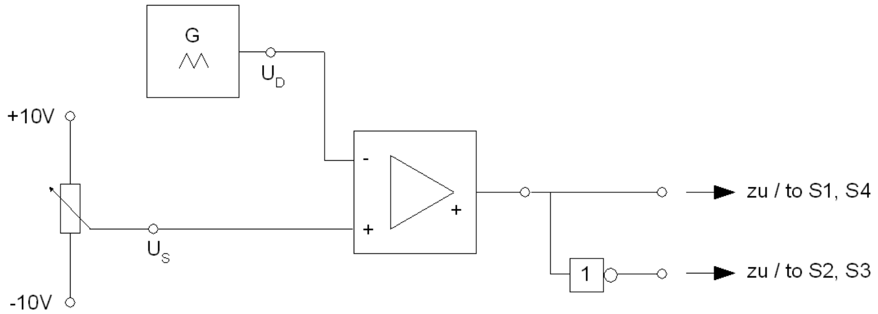
For a static actuation following would be true:

- There must never be two closed switches within a bridge section (S_1 and S_2 or S_3 and S_4). A short of U_{ZK} would be caused.
- If S_1 is closed, voltage U_A would be applied to A earthed. If S_3 is closed, voltage U_B would be applied to B earthed.
- The voltage difference U_{AB}, that drives the motor, only exists, when S_1 and S_3 are switched unequally.
- If S_1 is closed and S_3 is opened (S_4 closed), $+U_S$ is applied to terminal A and earth to terminal B. The motor drives in right-hand motion with max. speed. Current from the intermediate circuit flows from A to B, here it forms a magnetic field in the inductance and generates the required torque for the motor. Voltage U_{AB} is the product of intermediate circuit voltage minus voltage drop at the switches.

- If S_1 is opened (S_2 closed) and S_3 closed, earth is applied to A and $+U_S$ to B, the motor drives in left-hand motion with max. speed. The current from the intermediate circuit flows from B to A, here it forms a magnetic field in the inductance and generates the required torque for the motor.
- If S_1 and S_3 are synchronized the motor is short-circuited on plus. If S_2 and S_4 are switched synchronized the motor is short-circuited on minus.
- If all switches are opened and the drive operates as right-hand motion generator (respectively with high speed), diode V_1 gets conducting with positive terminal A and diode V_4 with negative terminal. Generator voltage U_{AB} is higher than the intermediate circuit by the threshold voltage of the diodes.
  Analogical is true for the opposite rotating direction. The generator current then passes V_3 and V_2 for the intermediate circuit.

The bridge also should operate as controlling element for drive speed. Therefore the switches are not pulsed statically but with a frequency of e.g. 10 Hz. Speed control here is done by pulse duration modulation. The four switches are controlled, so a continuous transition from right-hand motion to left-hand motion is possible.

The circuit below shows a relative simple type of controller. The respective diagonal positioned switches are activated in the same phase of the switching cycle and therefore always have the same switching distance. The switches in one section therefore always have different switching status. At a signal frequency of 10 kHz a complete switching cycle is 100 µs.

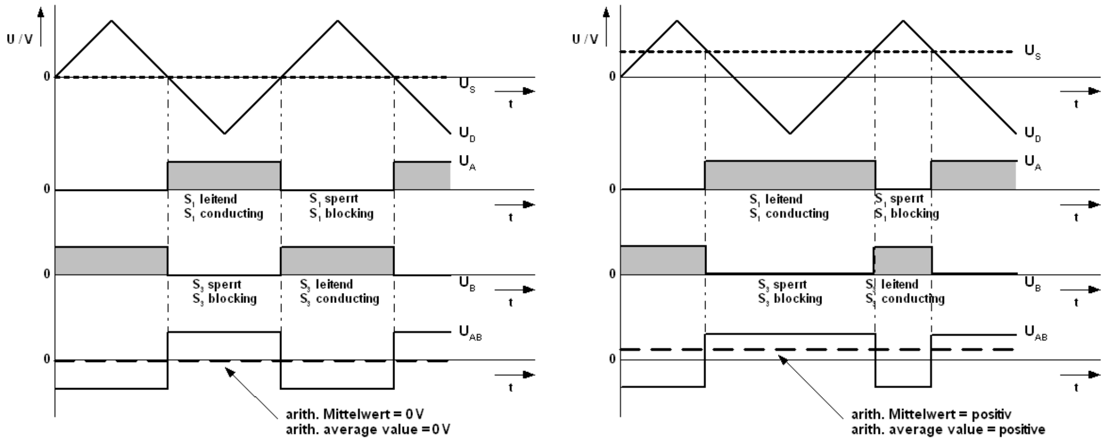


pic. 5.4.0.4 co-phasal control of PWM

Determination:

- At a symmetric control the signals are always applied for a period of 50 µs. U_{AB} is positive for half of the period, for the other half it is negative. U_{AB} is a symmetrical, rectangular AC voltage without DC potential. The DC current drive at terminal A and B stands still. The choke limits the now flowing AC current.
- If the pulse duration alters at positive control voltage, so S_1 for example is conducting for 60 µs and respectively S_3 is conducting for only 40 µs, the applied duration for positive voltage is longer than for negative. U_{AB} is biased by a positive DC voltage portion, thus the motor rotates in right-hand motion.
- If pulse duration is altered oppositely (S_1 30 µs / S_3 70 µs conducting), then U_{AB} is longer negative. The motor rotates in left-hand motion because of the negative DC voltage portion.

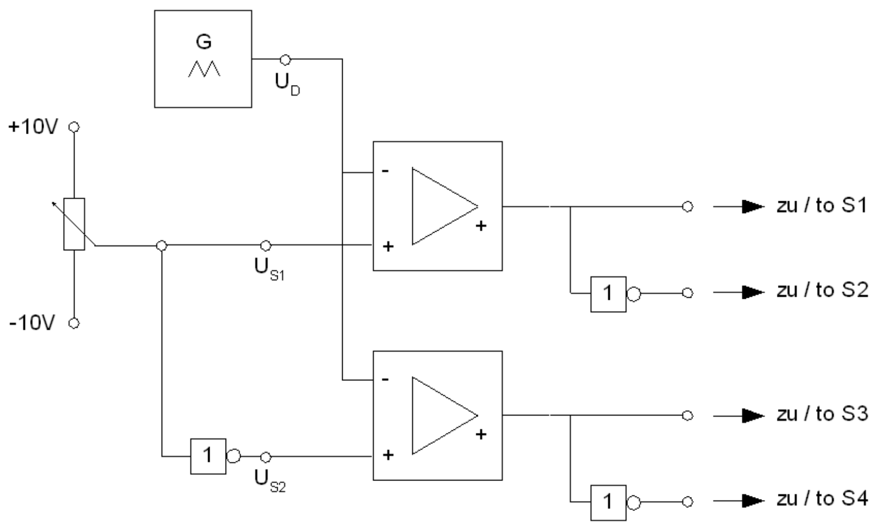
The longer the conductance duration of one digital array (S_2 and S_3) in respect to the other (S_1 und S_4), the more positive portion gets the DC voltage, thus the motor speed increases. The AC voltage portion decreases and the AC voltage portion increases. Frequency of AC voltage is equal to the switching frequency of the transistors. A shutdown of the machine is affected only by an altering torque.



pic. 5.4.0.5signal wave form of a co-phasal PWM control

Industry uses another, more practical version, the shifted pulse width modulation. This circuit does not synchronously switch the bridge diagonals (S_1 / S_4, S_3 / S_2), like co-phasal pulse width modulation does, but uses two separate PWM-signals for the control of the diagonals in point A and point B.
If the two PWM-controls are preset that $U_A > U_B$, voltage U_{AB} will be positive biased. If $U_B > U_A$, voltage U_{AB} will be biased negative. If U_A and U_B are of identical value, voltage $U_{AB} = 0$ V (Precondition: switching edges U_A and U_B are synchronized).

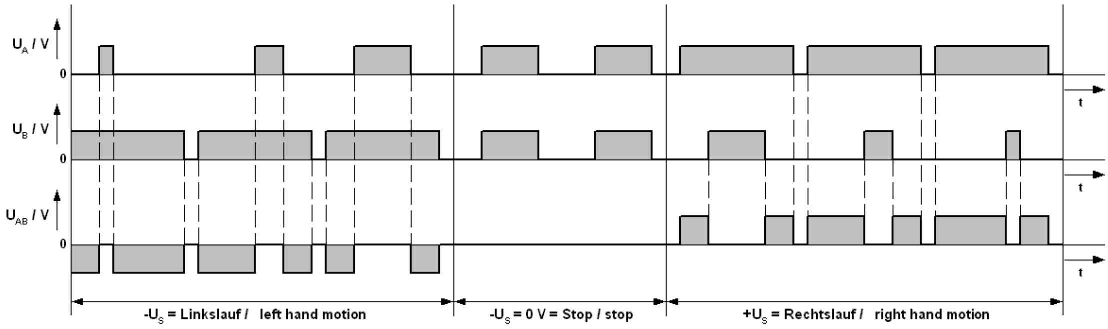
A circuit as shown below is used to achieve synchronized control via potentiometer.



pic. 5.4.0.6 control circuit „shifted PWM“

The applied delta signal is shared between the two comparators. The comparator allocated to bridge half A is controlled by control voltage U_{S1}. The comparator of bridge half B is controlled by the inverted signal U_{S2}. U_A and U_B therefore are self-explanatory inverted (reversed).

If U_S is altered to more positive polarity, U_A would get more positive, too, and U_B would get more negative. Thus results a more positive voltage U_{AB}. If U_S is altered to more negative polarity, U_A would get more negative, too, and U_B would rise. Therefore voltage U_{AB} would get more negative. Just if U_S = 0 V, U_{S1} and U_{S2} are identical. As a consequence the comparators supply identical output signals. U_A and U_B have synchronized switching edges. Resultant U_{AB} = 0 V, thus the drive shuts-down. Following picture shows that kind of the wave form.



pic. 5.4.0.7 signal wave form of a shifted PWM control

5.4.1 Operation Modes of a MOSFET H-Bridge

Application

Main application for the demonstrated bridge circuit is drive engineering technology. In the basic circuit the bridge circuit is the power output stage of brush-type DC servo motors.

Typical application for servo motors are feed drives of machine tools, handling equipment or drives for robots. Demands on those applications are high-speed operation, as well as high range of manipulated variable.

Precondition for high-speed operation is for the drive the ability to continuously accelerate and decelerate quickly within a positioner cycle.

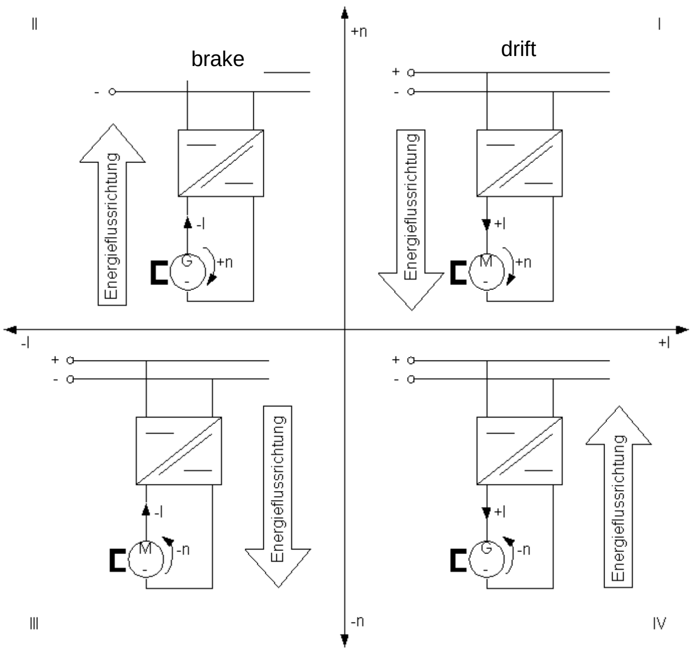
Acceleration

While acceleration the machine consumes electrical energy from the intermediate circuit and transforms it to kinetic energy. Current flow and rotating direction of the machine are positive. It is the so-called one-quadrant operation.

Deceleration

At deceleration the energy flow reverses. The machine operates as generator. It transforms the drive energy stored in the mechanical system into electrical energy. The backflow energy energizes the capacitor of the intermediate circuit. It is the so-called two-quadrant operation.

Operation with three- and four-quadrant is accordingly, however, in reversed rotation direction. Operation with four-quadrant is explained more precisely in the manual “controlled systems, Art-No. 570.038.001).



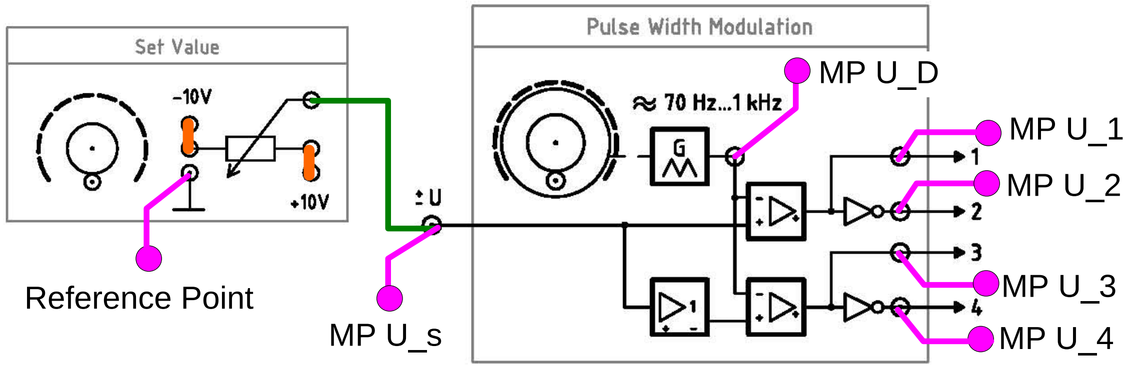
pic. 5.4.1.0 operation mode of DC machine in four-quadrant DC chopper control
the arrow indicates the direction of energy flow

5.4.1.1 Test 1

Signal wave form in shifted pulse width modulation.

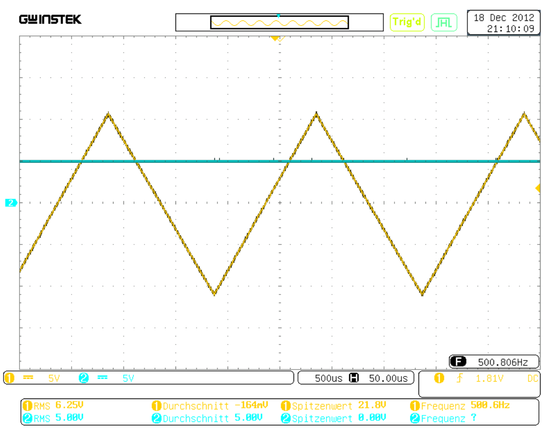
Test Configuration & Test Procedure

- Build up the circuit in pic. 5.4.1.1.0.



pic. 5.4.1.1.0 circuit

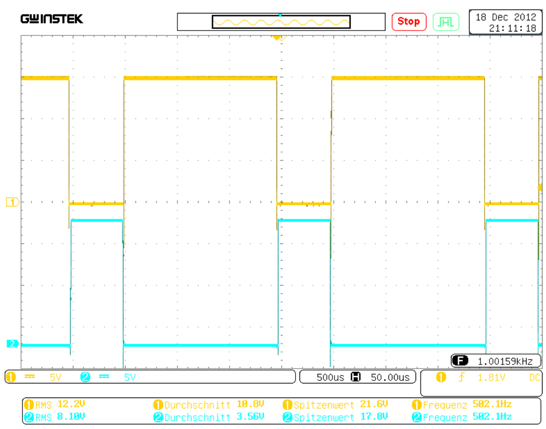
- Externally trigger the oscilloscope with delta voltage U_D
- Set the delta generator to a frequency of 500 Hz.
- Measure following parameters with the oscilloscope for control voltages of U_S = +5V, +0V, -5V:
  - Delta Voltage U_D
  - Control Voltage U_S,
  - Output Voltages U_1, U_2, U_3, U_4
- Draw the curves in pic. 5.4.1.1.1 to pic. 5.4.1.1.9.



pic. 5.4.1.1.1 control voltage U_S = +5 V

Oscilloscope Settings:

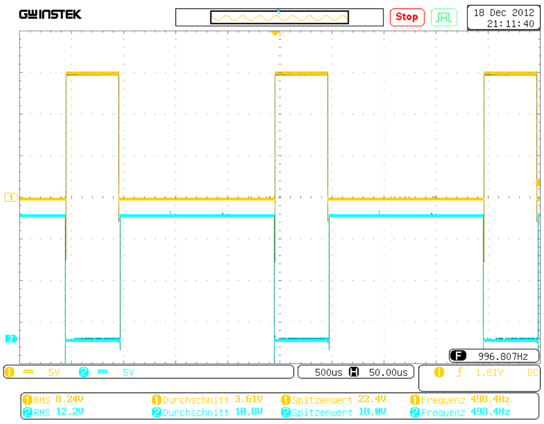
Delta Voltage U_D:	5	V / div.
Control Voltage U_S:	5	V / div.
Time t:	0,5	ms / div.



pic. 5.4.1.1.2 control voltage U_S = +5 V

Oscilloscope Settings:

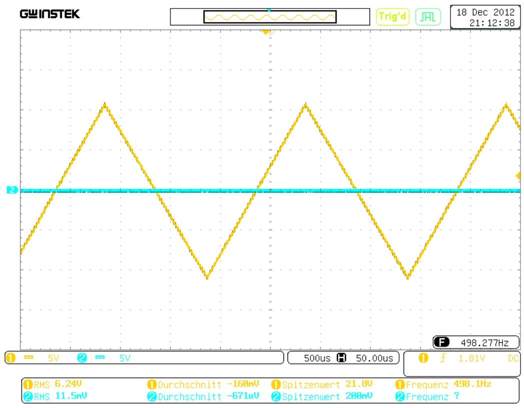
Output Voltage U_1:	5	V / div.
Output Voltage U_2:	5	V / div.
Time t:	0,5	ms / div.



pic. 5.4.1.1.3control voltage U_S = +5 V

Oscilloscope Settings:

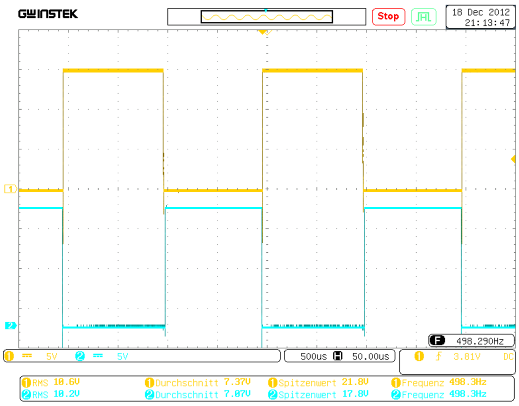
Output Voltage U_3: 5 V / div.
Output Voltage U_4: 5 V / div.
Time t: 0,5 ms / div.



pic. 5.4.1.1.4 control voltage U_S = + 0 V

Oscilloscope Settings:

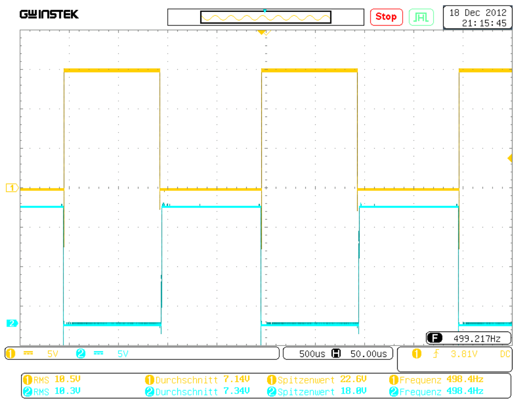
Delta Voltage U_D: 5 V / div.
Control Voltage U_S: 5 V / div.
Time t: 0,5 ms / div.



pic. 5.4.1.1.5 control voltage U_S = +0 V

Oscilloscope Settings:

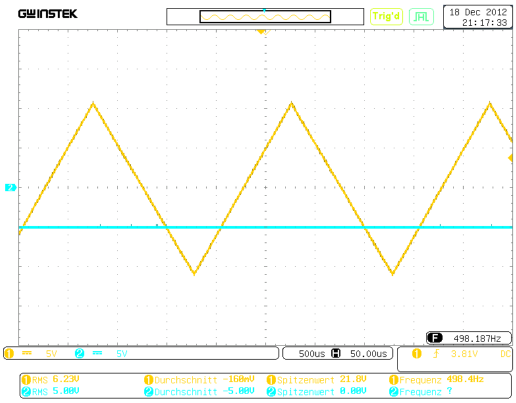
Output Voltage U_1: 5 V / div.
Output Voltage U_2: 5 V / div.
Time t: 0,5 ms / div.



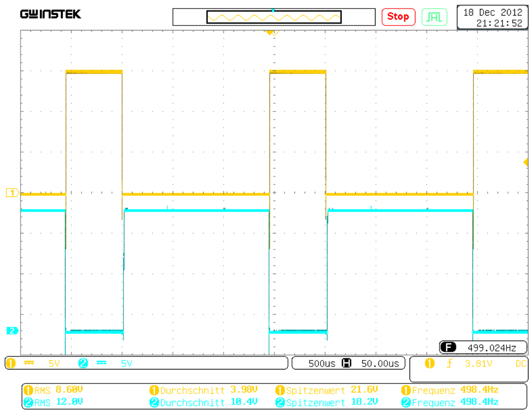
pic. 5.4.1.1.6 control voltage U_S = +0 V

Oscilloscope Settings:

Output Voltage U_3: 5 V / div.
Output Voltage U_4: 5 V / div.
Time t: 0,5 ms / div.



pic. 5.4.1.1.7 control voltage U_S = -5 V



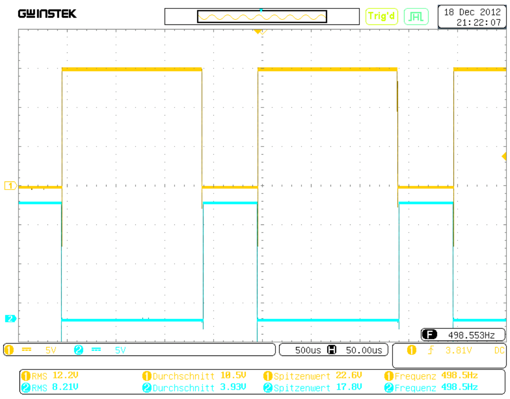
pic. 5.4.1.1.8 control voltage U_S = -5 V

Oscilloscope settings:

Delta voltage U_D:	5	V / div.
Control voltage U_S:	5	V / div.
time t:	0,5	ms / div.

Oscilloscope settings:

Output voltage U_3:	5	V / div.
Output voltage U_4:	5	V / div.
time t:	0,5	ms / div.



pic. 5.4.1.1.9 control voltage U_S = -5 V

Oscilloscope settings:

Output voltage U_3:	5	V / div.
Output voltage U_4:	5	V / div.
time t:	0,5	ms / div.

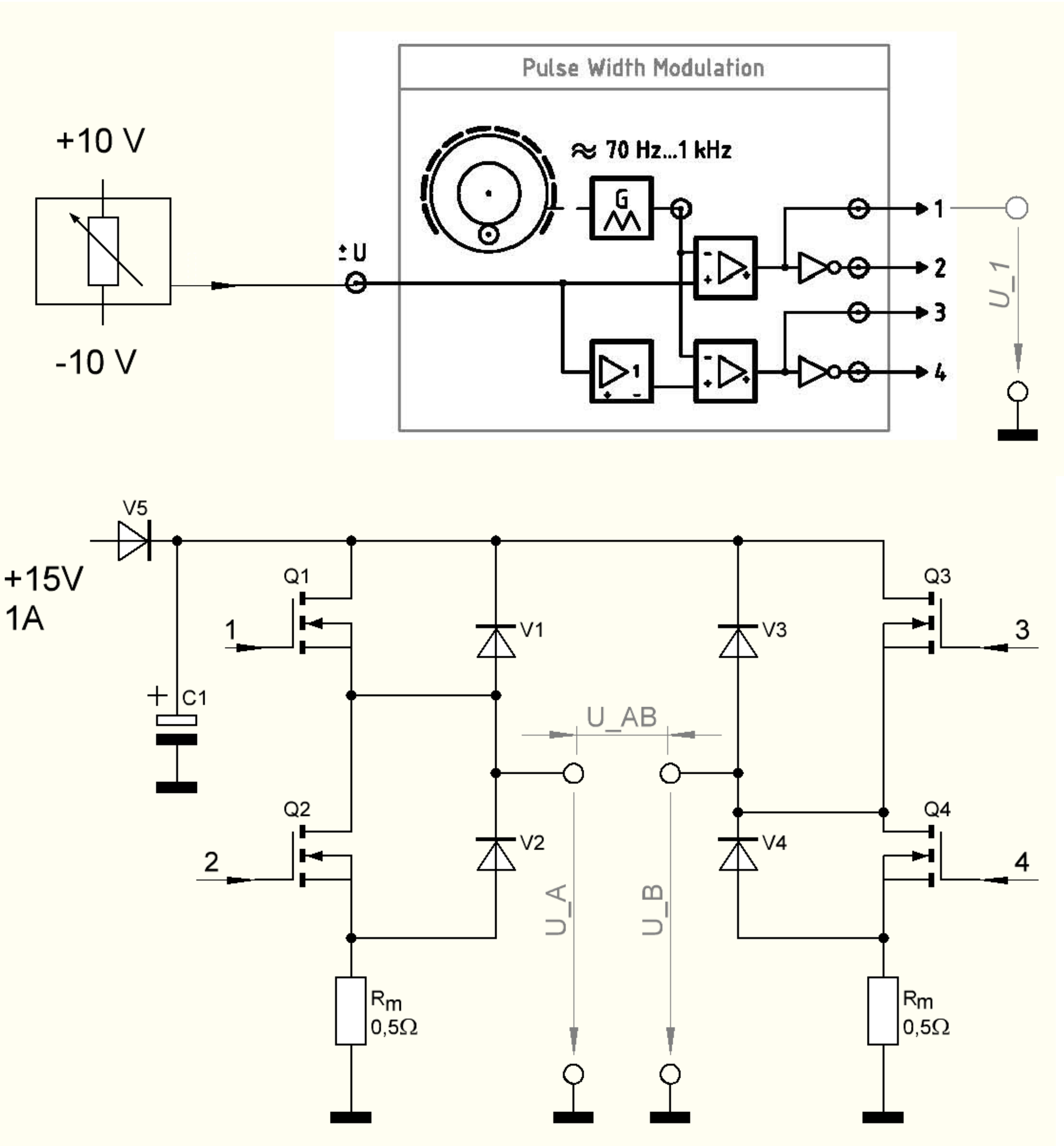
Question:	How does pulse width alter if control voltage U_S is increased?
Answer:	If control voltage U_S is increased, pulse width increase, too.
	This is true for output voltage U_1 aund U_2.
	With control voltages U_3 and U_4 it is totally contrary.
	If control voltage U_S is increased, pulse width decrease.

5.4.1.2 Test 2

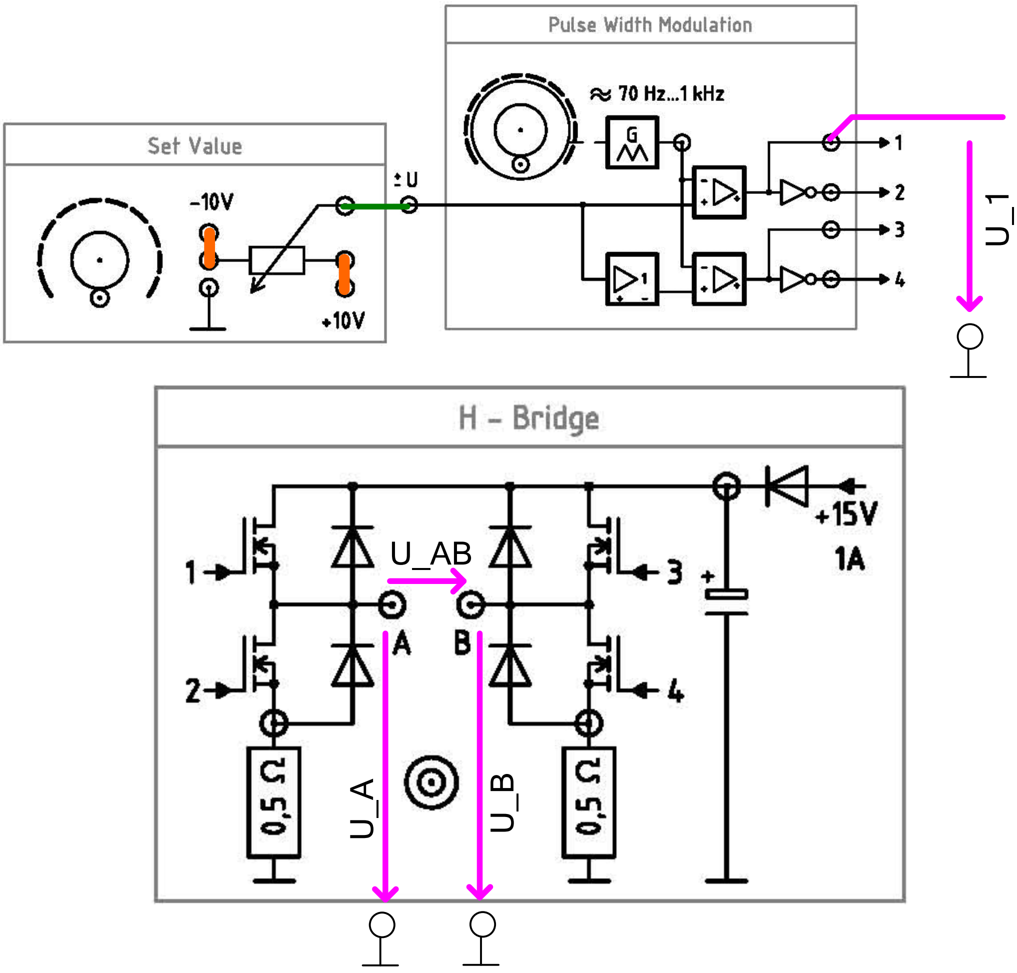
Generation of bridge voltage U_{AB} with two PWM signals.

Test Configuration & Test Procedure

- Build up the circuit in pic. 5.4.1.2.0 / 5.4.1.2.1. Control signals U_1 to U_4 are internally wired to the MOSFET.
-



pic. 5.4.1.2.0 circuit

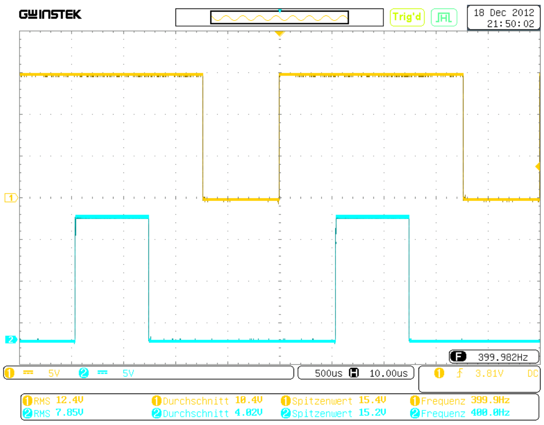


pic. 5.4.1.2.1 Circuit at the Power Electronic Panel

- Set the delta generator to a frequency of 400 Hz.
- Measure following parameters with the oscilloscope for duty cycles g = 0,7, g = 0,5 and g = 0,3:
  - Bridge Section Voltage U_A,
  - Bridge Section Voltage U_B,
  - Bridge Voltage U_{AB}

Note: ***Duty cycle g = t_e/T here refers to the control signal U_1.***

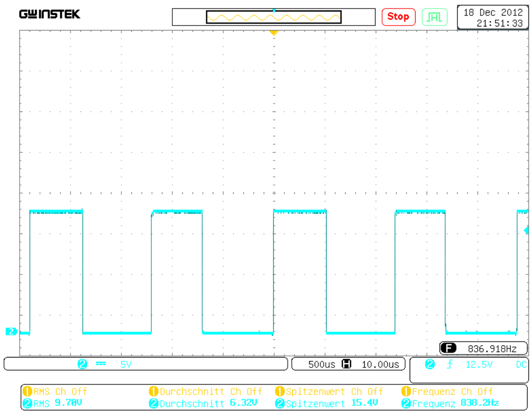
- Draw the curves in pic. 5.4.1.2.2 to pic. 5.4.1.2.7.



pic. 5.4.1.2.2 duty cycle g = 0,7

Oscilloscope Settings:

Bridge Section Voltage U_A: 5 V / div.
Bridge Section Voltage U_B: 5 V / div.
Time t: 0,5 ms / div.

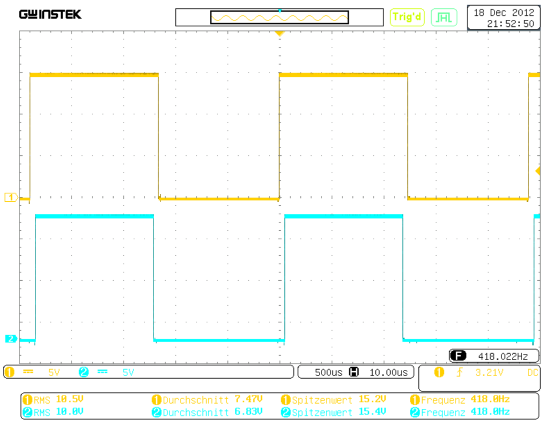


pic. 5.4.1.2.3 duty cycle g = 0,7

Oscilloscope Settings:

Bridge Voltage U_{AB}: 5 V / div.

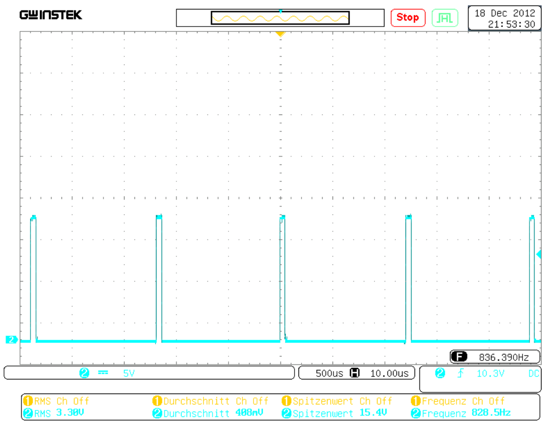
Time t: 0,5 ms / div.



pic. 5.4.1.2.4 duty cycle g = 0,5

Oscilloscope Settings:

Bridge Section Voltage U_A: 5 V / div.
Bridge Section Voltage U_B: 5 V / div.
Time t: 0,5 ms / div.

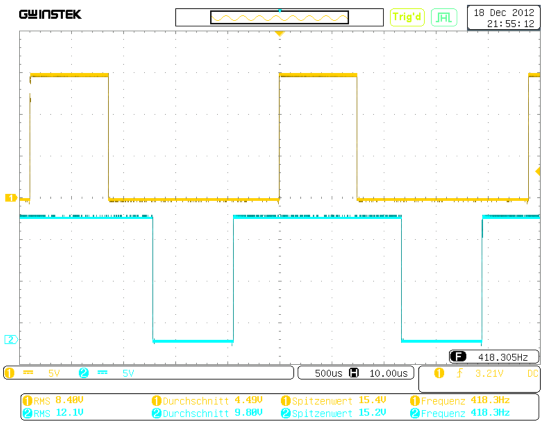


pic. 5.4.1.2.5 duty cycle g = 0,5

Oscilloscope settings:

Bridge voltage U_{AB}: 5 V / div.

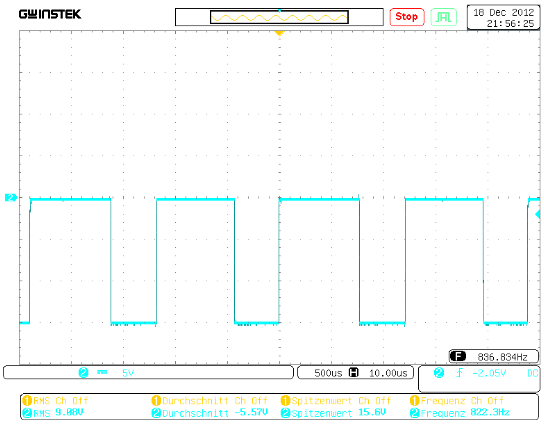
Time t: 0,5 ms / div.



pic. 5.4.1.2.6 duty cycle g = 0,3

Oscilloscope Settings:

Bridge Section Voltage U_A:	5	V / div.
Bridge Section Voltage U_B:	5	V / div.
Time t:	0,5	ms / div.



pic. 5.4.1.2.7 duty cycle g = 0,3

Oscilloscope settings:

Bridge Voltage U_{AB}:	5	V / div.
Time t:	0,5	ms / div.

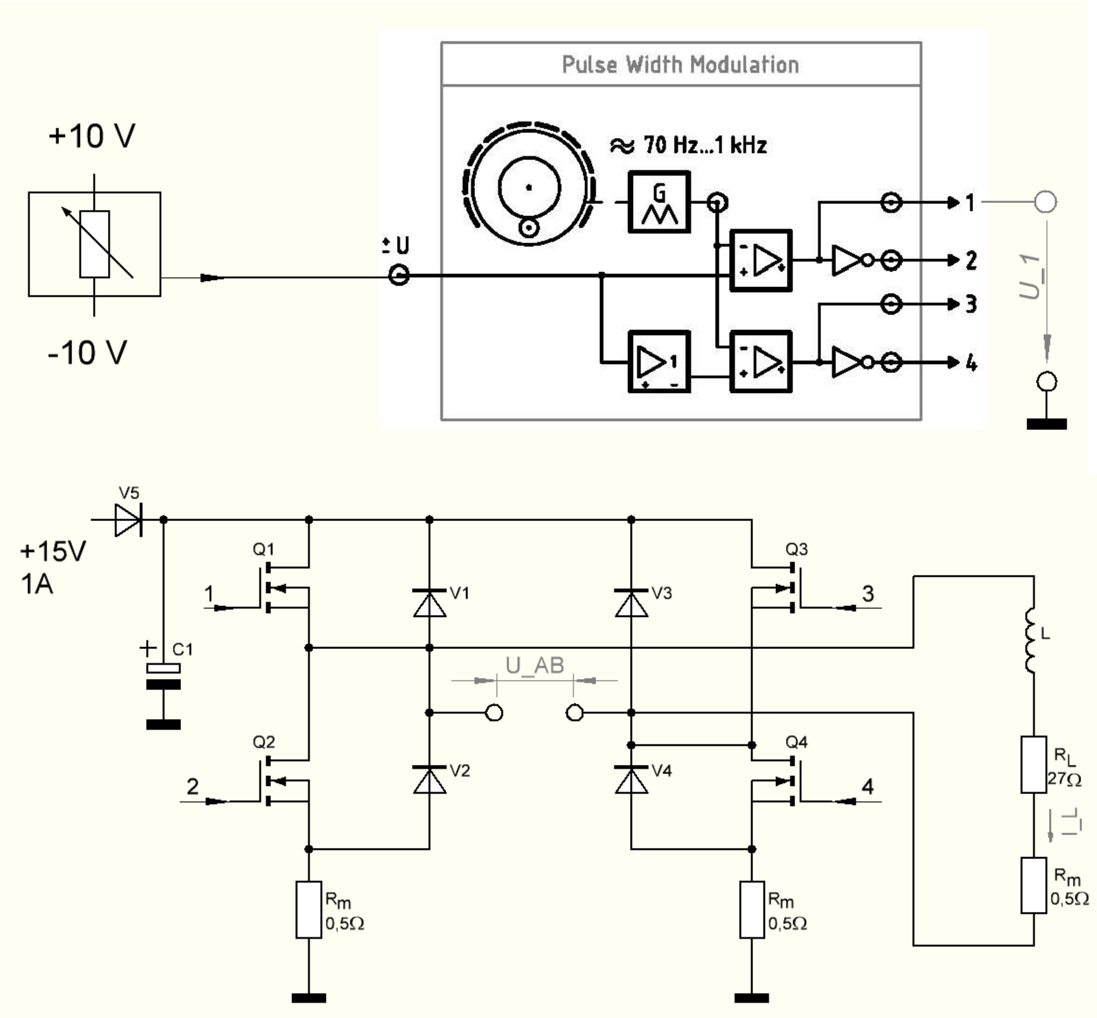
.

5.4.1.3 Versuch 3

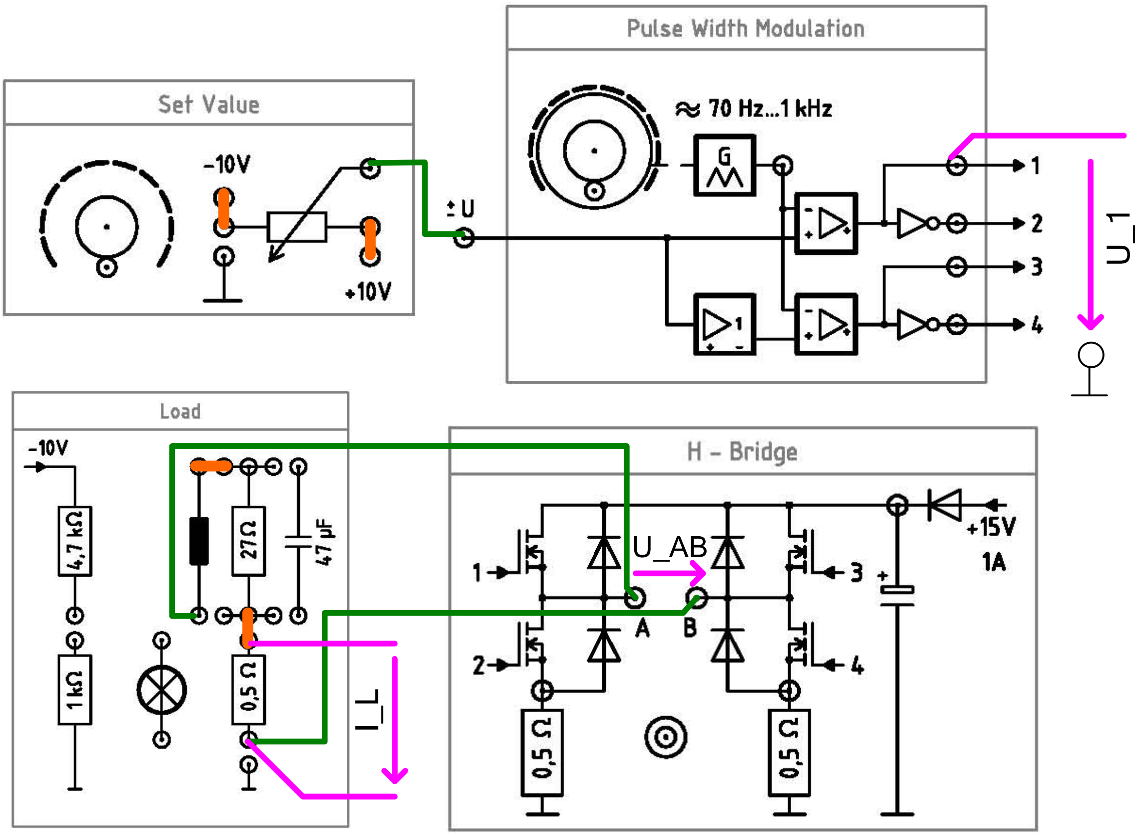
Wave form of current and voltage at the H-bridge in relation with ripple of frequency.

Test Configuration & Test Procedure

- Build up the circuit in pic. 5.4.1.3.0 / 5.4.1.3.1. The control signals U_1 to U_4 are already internally wired to the MOSFET.



pic. 5.4.1.3.0 circuit



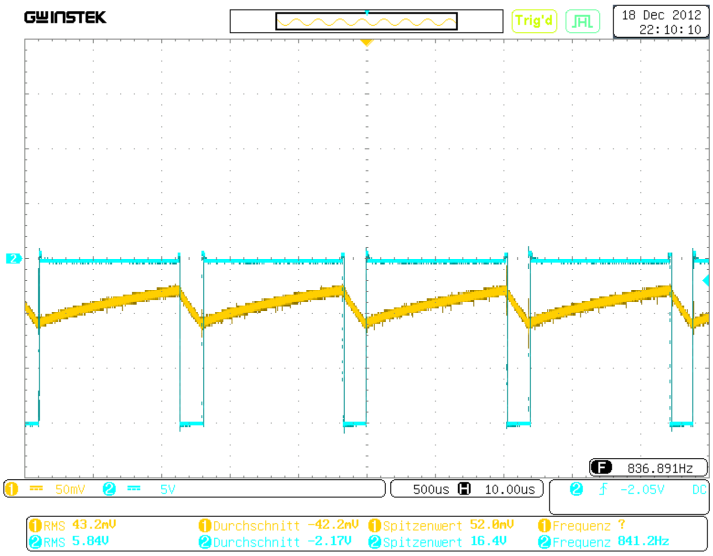
pic. 5.4.1.3.1 circuit

- Set the delta generator to a frequency of 400 Hz.

- Measure following parameters with the oscilloscope for duty cycles g = 0,4 and g = 0,6:
  - Bridge voltage U_{AB},
  - Load current I_L

Note: ***The duty cycle g = t_e/T here refers to control signal U_1.***

- Draw the curve into pic. 5.4.1.3.2 and pic. 5.4.1.3.3.

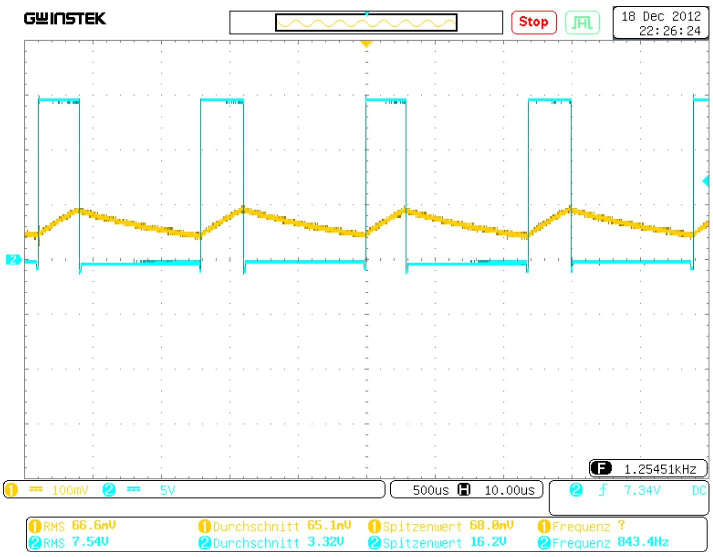


pic. 5.4.1.3.2 duty cycle g = 0,4 and f_D = 400 Hz

Oscilloscope Settings:

Bridge Voltage U_{AB}:	5	V / div.
Load Current I_L:	0,1	A / div.
=	0,05	V / div.
Time t:	0,5	ms / div.

Current Conversion with Rm = 0,5 Ohm



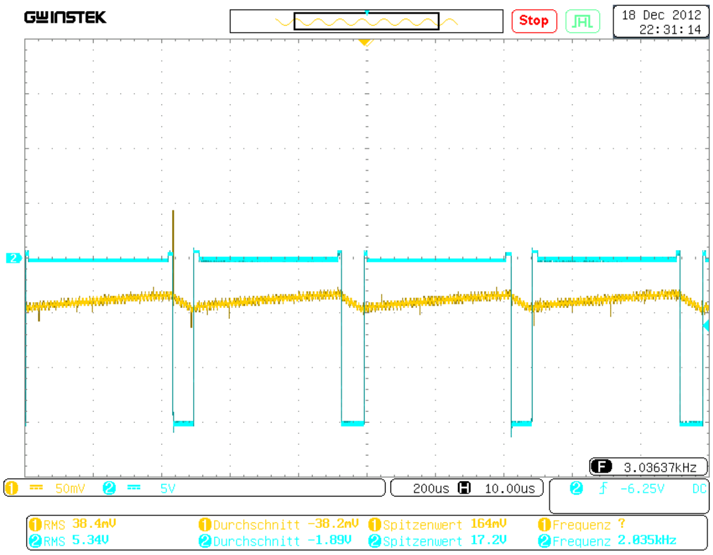
pic. 5.4.1.3.3ducty cycle g = 0,6 and f_D = 400 Hz

Oscilloscope Settings:

Bridge Voltage U_{AB}:	5	V / div.
Load Current I_L:	0,2	A / div.
=	0,1	V / div.
Time t:	0,5	ms / div.

Current Conversion with Rm = 0,5 Ohm

- Repeat the measurement in higher frequency. Therefore set the frequency at the signal generator to 1 kHz.
- Draw the curves in pic. 5.4.1.3.4 and pic. 5.4.1.3.5.

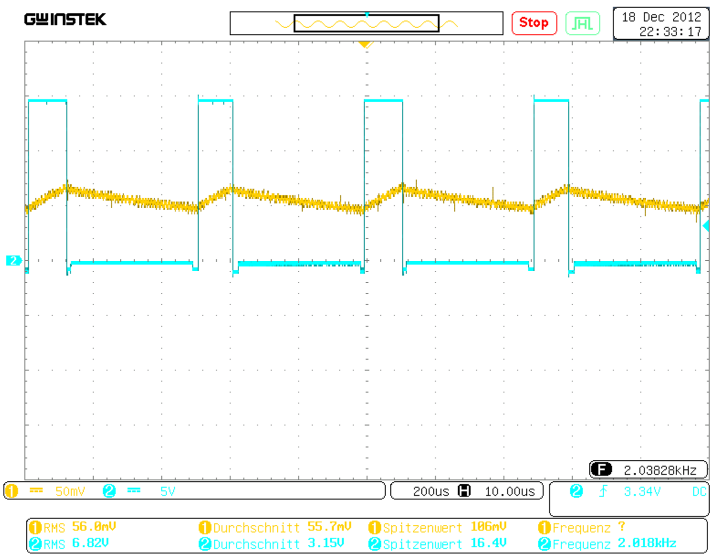


pic. 5.4.1.3.4duty cycle g = 0,4 and f_D = 1 kHz

Oscilloscope Settings:

Bridge Voltage U_{AB}:	5	V / div.
Load Current I_L:	0,1	V / div.
=	0,05	V / div.
Time t:	0,2	ms / div.

Current conversion with Rm = 0,5 Ohm



pic. 5.4.1.3.5 duty cycle g = 0,6 and f_D = 1 kHz

Oscilloscope Settings:

Bridge Voltage U_{AB}:	5	V / div.
Load Current I_L:	0,1	V / div.
=	0,05	V / div.
Time t:	0,2	ms / div.

Current conversion with Rm = 0,5 Ohm

Question 1:	What influence does the frequency of the signal generator have on the wave forms of bridge voltage U_{BA} and load current I_L?
Answer:	Influence on bridge voltage U_{AB}:
	At high frequency pulse duration and cycle duration decrease.
	At low frequency pulse duration and cycle duration increase.
	Influence on load current I_L:
	At high frequency pulse duration and cycle duration decrease.
	At low frequency pulse duration and cycle duration increase.

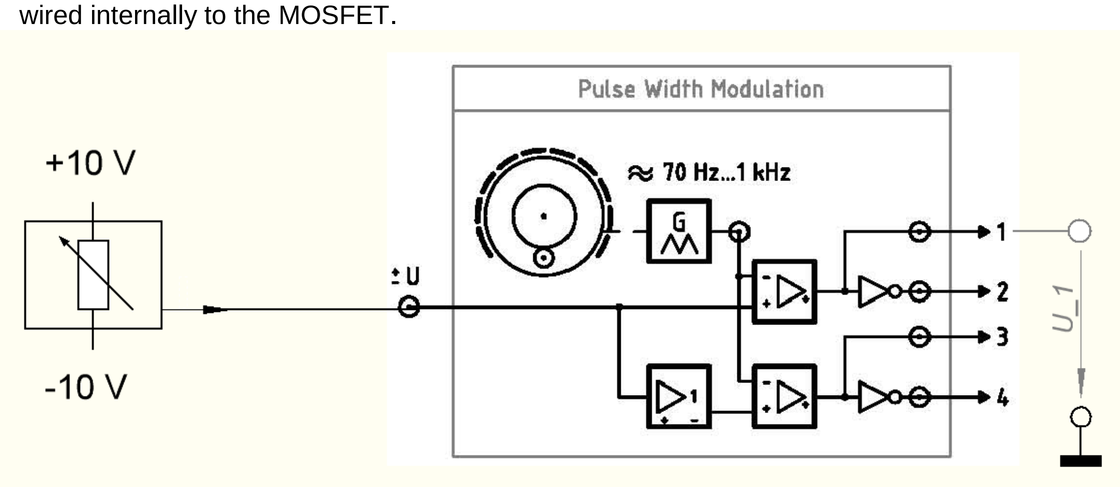
Question 2:	What advantage and disadvantage does high frequency has on electrical drives?
Answer:	Advantage:
	- reduction of the ripple current
	- reduction of noise emission
	- dynamic advantages
	Disadvantage:
	- additional heating of the device

5.4.1.4 Test 4

Averages of currents and voltages in the MOSFET H-bridge.

Test Configuration & Test Procedure

- Build up the circuit in pic. 5.4.1.4.0 / 5.4.1.4.1. The control signals U_1 to U_4 are already wired internally to the MOSFET.



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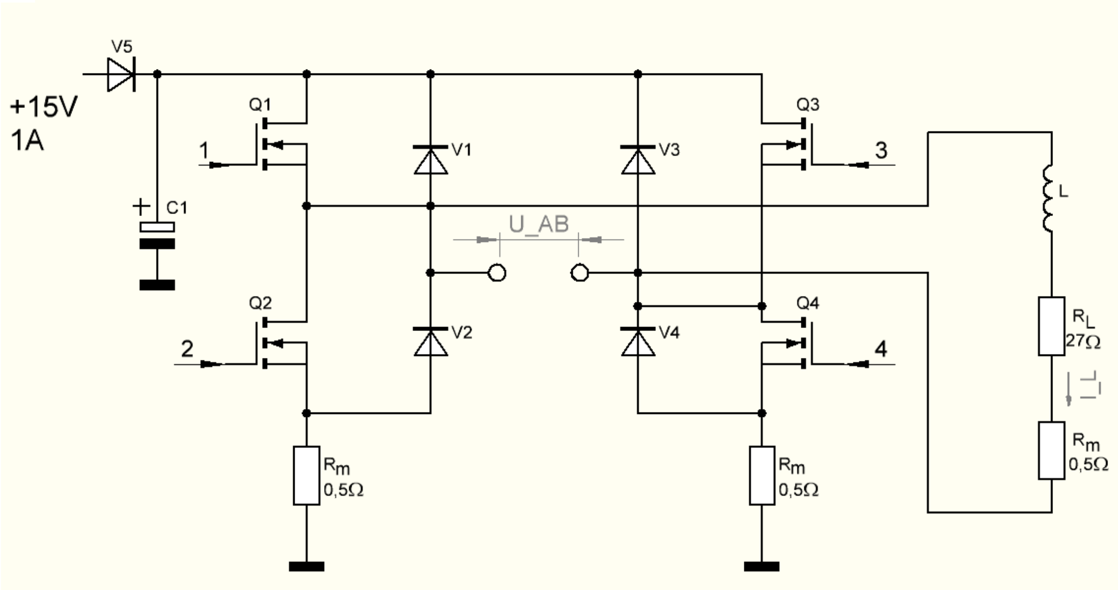
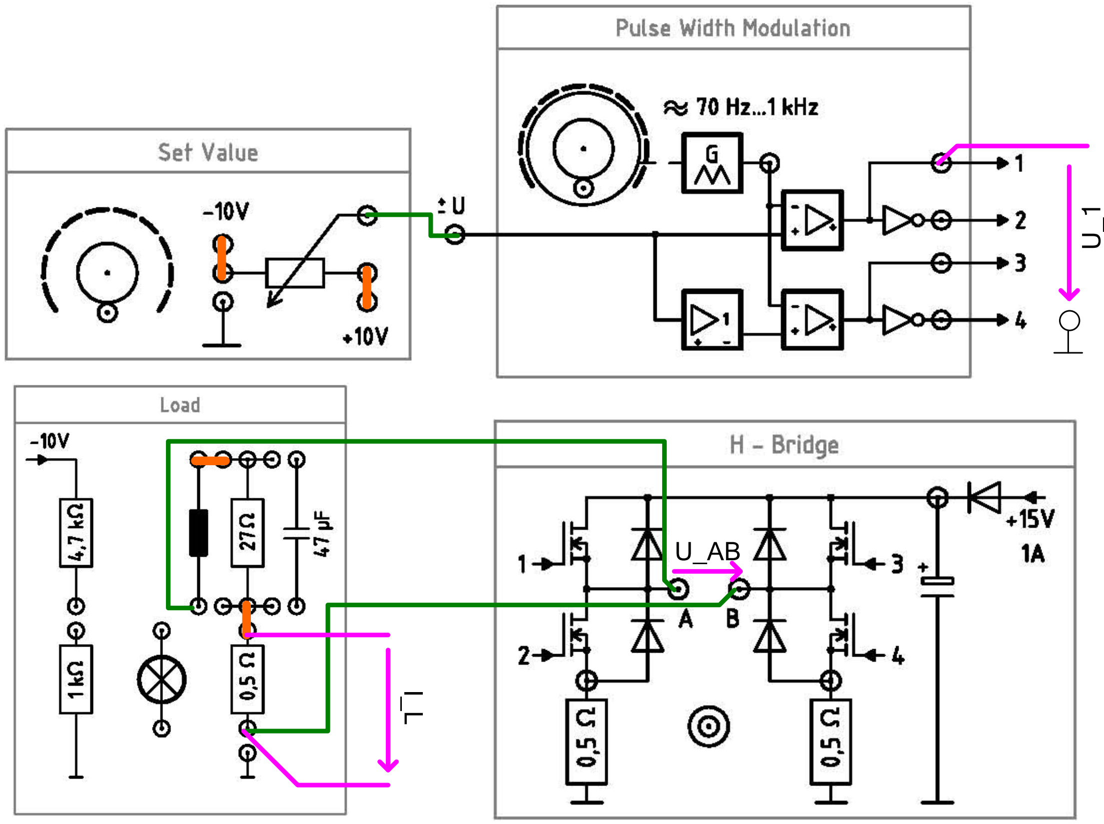


pic. 5.4.1.4.0 circuit



pic. 5.4.1.4.1 Circuit at the Power Electronic Panel

- Set the delta generator to a frequency of 1 kHz.
- Measure the average value with a multimeter for various duty cycles:
  - Bridge Voltage U_{AB},
  - Load Current I_L

Note: The duty cycle g = t_e/T refers to the control signal U_1.

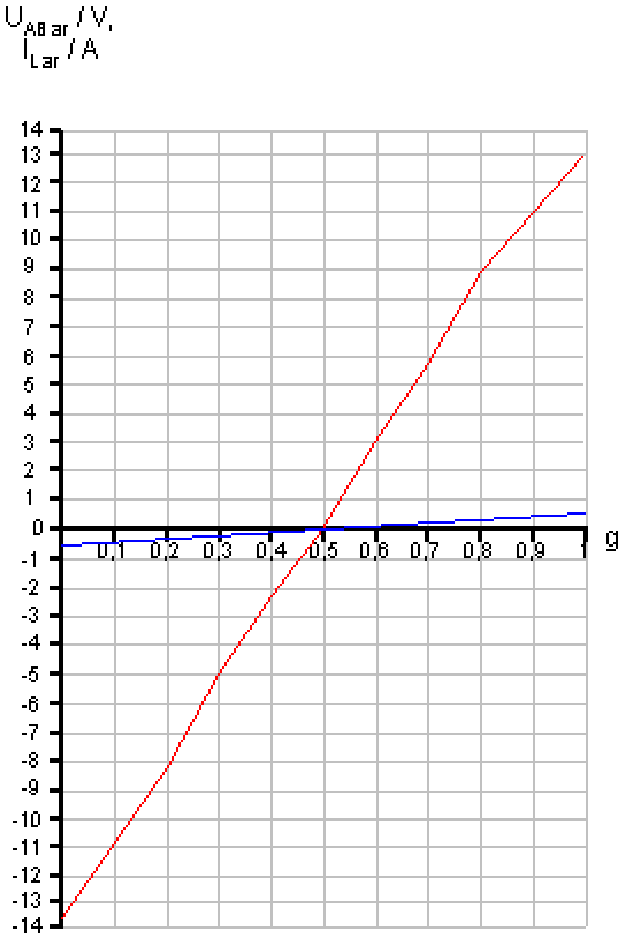
- Add the measured values to chart 5.4.1.4.2.

g	Minimum	0,2	0,3	0,4	0,5	0,6	0,7	0,8	Maximum
$U_{AB\ ar}$ / V	-13,5	-8,1	-5,42	-4,1	0,284	2,88	5,61	9,01	13,0
$I_{L\ ar}$ / A	-0,52	-0,32	-0,20	-0,16	0,002	0,10	0,2	0,34	0,48

chart 5.4.1.4.2

Current Conversion with Rm = 0,5 Ohm

- Graphically present the measured values in pic. 5.4.1.4.3.



pic. 5.4.1.4.3 $U_{AB\ ar}$ = red; $I_{L\ ar}$ = blue

Question 1:	What knowledge could we obtain from pic. 5.4.1.4.3 (controllability at 0 V and linearity)?
Answer:	The arithmetic bridge voltage $U_{AB\ ar}$ and the arithmetic
	load current $I_{L\ ar}$ run linear. In ideal case their curve progressions
	are stright lines.
	At a duty cycle of g = 0,5 $U_{AB\ ar}$ crosses $I_{L\ ar}$.
	$U_{AB\ ar}$ is at crossing 0 V. $I_{L\ ar}$ is at crossing 0 A.

6 Inverter Circuit

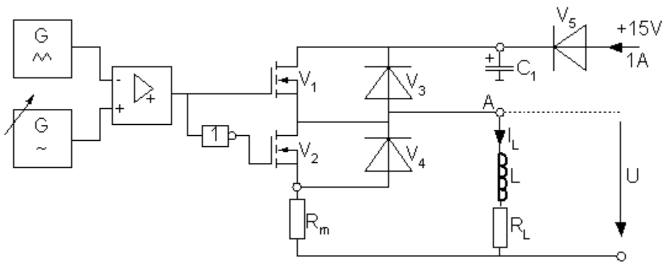
6.1 H-Bridge for Inverter Circuit

Sine rated pulse modulation

To form AC voltage from DC voltage, so called sine rated pulse modulation often is used. Therefore control AC voltage is applied to the conventional PWM (see chapter 5.1 and 5.2) but not control DC voltage. At the conventional PWM the duty cycle g of a preset control voltage U_S is constant.

Duty cycle of sine rated PWM

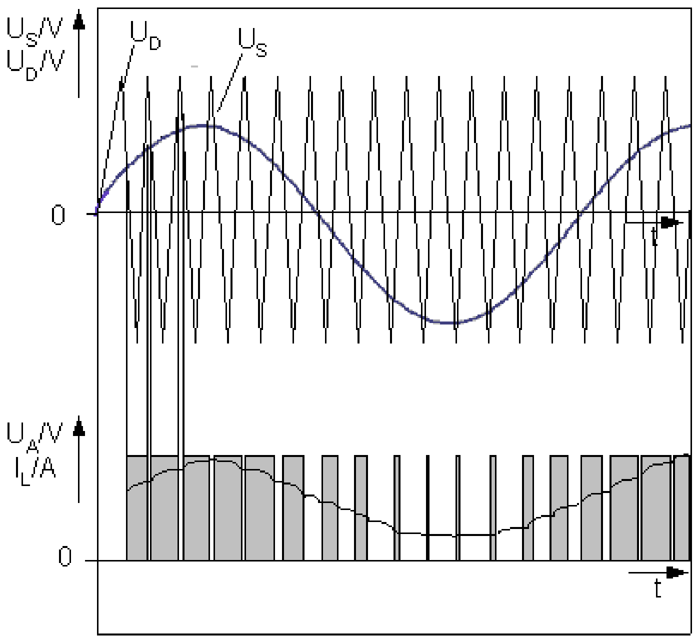
Duty cycle g alters with wave progression at the sine rated PWM. Output amplitude and fundamental wave of the output frequency depend on the amplitude and frequency of the control voltage. The ripple of load current is biased by the frequency of the signal generator.



pic. 6.1.0.0 sine rated pulse width modulation

True is:

The higher the frequency of a delta signal, and thus the frequency of single pulses of an output voltage, the lower the ripple.



pic. 6.1.0.1 wave form of the sine rated PWM

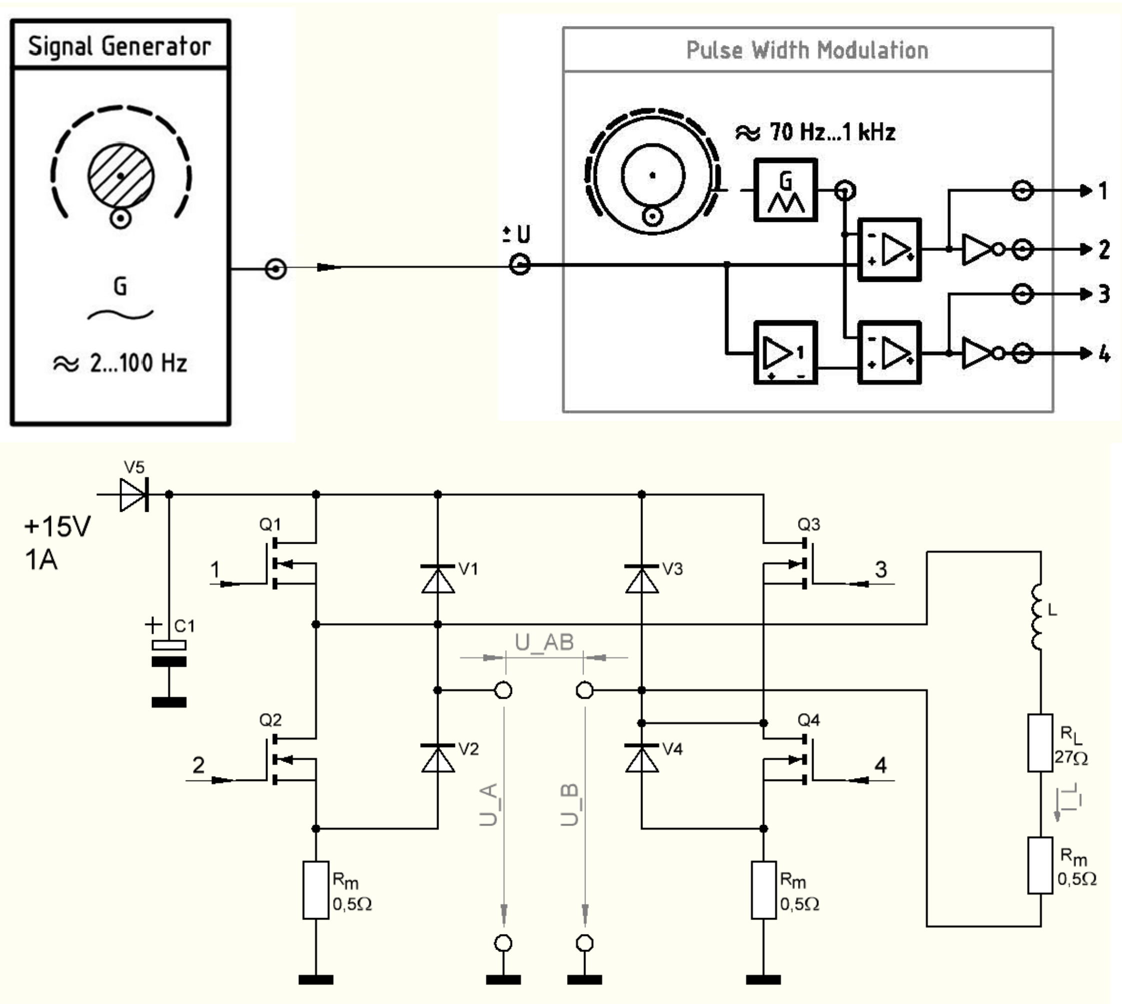
The so generated voltage is only positive polarity. To transform this in alternating voltage, there are two possibilities.

Possibility 1:

One contact of the intermediate circuit is connected to minus, not to earth.

Possibility 2:

The principle of the shifted pulse width modulation (see chapter 5.4) is used.
The circuit is as follows:



pic. 6.1.0.2 sine rated pulse width modulation

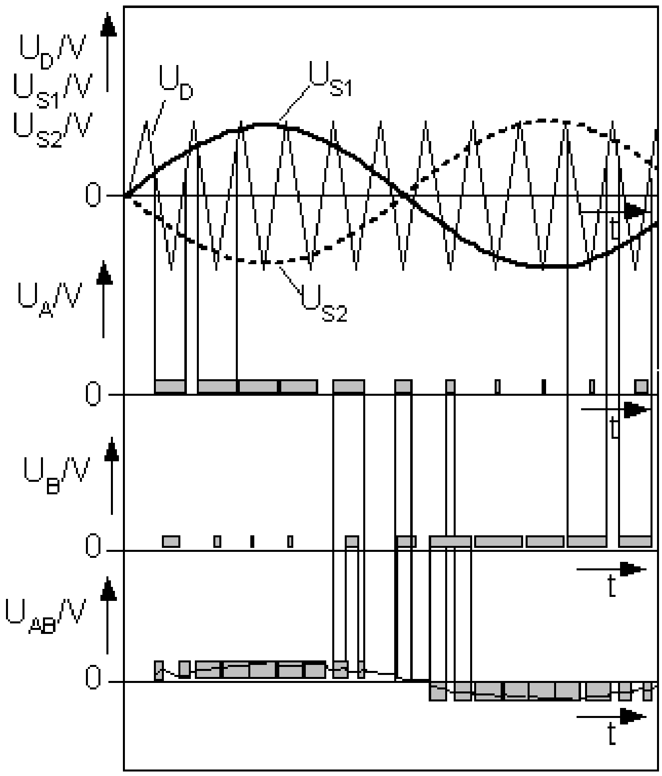
Within the pulse width modulation, voltage U_{S1} and inverted voltage U_{S2} are generated from control voltage U_S. By interaction of the purely positive pulses from bridge section voltage U_A and $U_{B,}$ the bridge voltage U_{AB} is generated. This is biased positive as well as negative.

With this circuit a single-phase AC voltage is realized. In practice the pulse frequency of an inverter is multiple higher than the output frequency, thus a sine wave form of output current is given.

In the graphical presentation of this manual low pulse frequency is chosen from the frequency range of control voltage, thus the principle coherency is easier to picture.

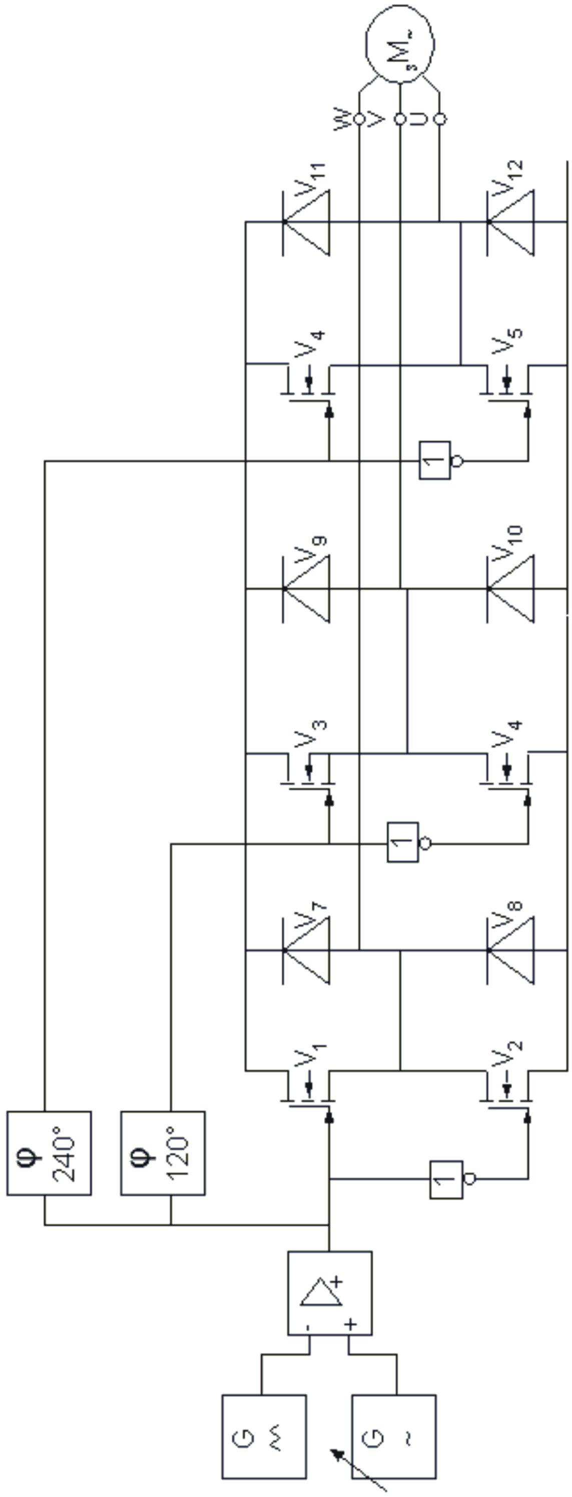
In practice an output frequency of e.g. 0 to 100 Hz is normally given with a pulse frequency of approx. 10 to 30 kHz. On the Power Electronic Panel the output frequency of also max. 100 Hz operates with a reduced pulse frequency of 60 Hz to 1 kHz, so control frequency and pulse frequency can be displayed at a time.

Display of signals in original frequency is very difficult, as the oscilloscope could either be triggered to high-frequency or low-frequency, thus always one signal is not captured.



pic. 6.1.0.3 wave form of a H-bridge as inverter

If 3-phase AC current should be generated with a PWM inverter, three individual bridge sections are needed, their PWM control has to be phase-shifted by 120°. On the Power Electronic Panel only the single-phase option is realizable.



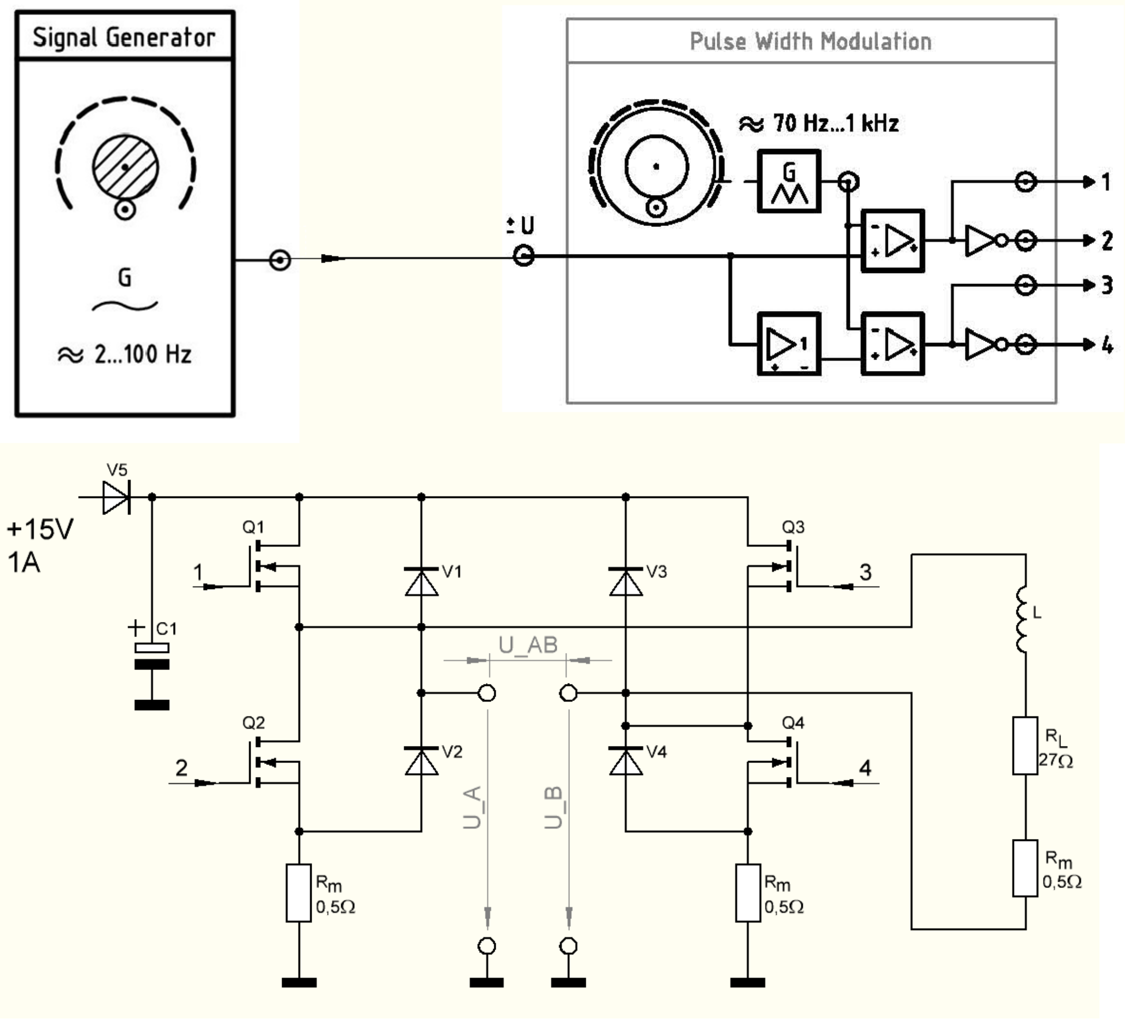
pic. 6.1.0.4 principle of a three-phase inverter

6.1.1 Test 1

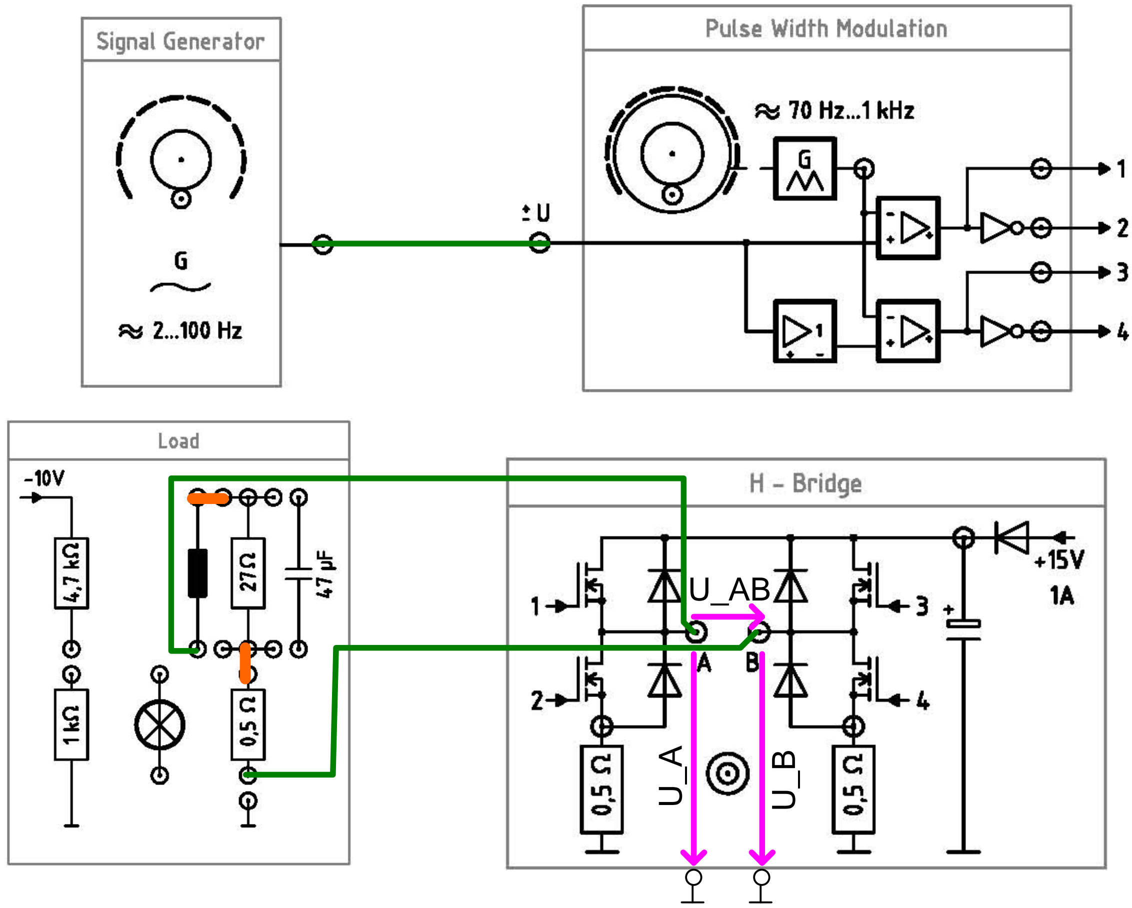
Generating AC voltage with a H-bridge.

Test Configuration & Test Procedure

- Build up the circuit in pic. 6.1.1.0 / 6.1.1.1. The control signals U_1 to U_4 are already internally wired to the MOSFET.



pic. 6.1.1.0 circuit



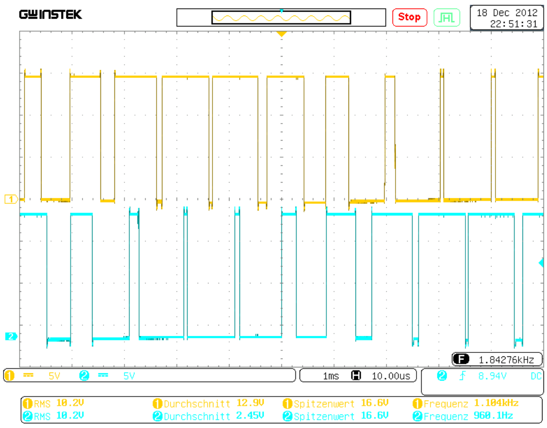
pic. 6.1.1.1 Circuit at the Power Electronic Panel

- Set the delta generator to a frequency of 1 kHz.
- Set the signal generator to a frequency of 100 Hz.
- Measure following parameters with the oscilloscope:
  - Bridge Section Voltages U_A, U_B,
  - Bridge Voltage U_{AB}

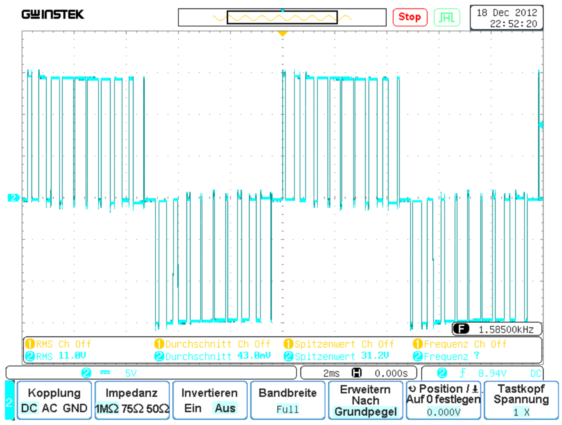
Note: ***Pay attention to the ground potential of the oscilloscope.***

Note: ***Trigger LF (Low Frequency), if existent.***

- Draw the curves in pic. 6.1.1.2 and pic. 6.1.1.3.



pic. 6.1.1.2



pic. 6.1.1.3

Oscilloscope Settings:

Bridge Section Voltage U_A: 5 V / div.
Bridge Section Voltage U_B: 5 V / div.
Time t: 1 ms / div.

Oscilloscope Settings:

Bridge Voltage U_{AB}: 5 V / div.

Time t: 1 ms / div.

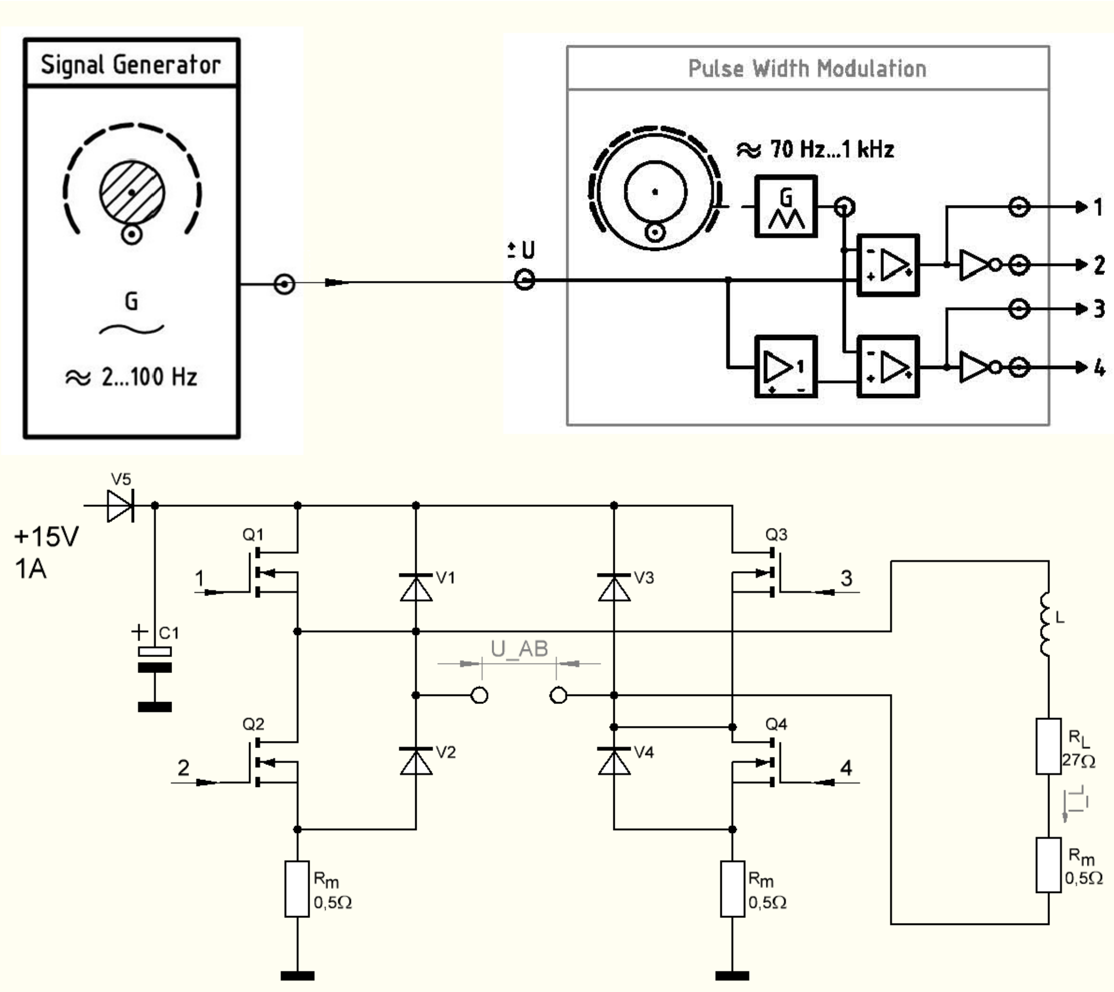
Question:	What switching states do the transistors V_1, V_2, V_3 and V_4 need during the negative pulse of the bridge voltage U_{AB}?
Answer:	☐ V_1 conducting
	☒ V_1 blocking
	☒ V_2 conducting
	☐ V_2 blocking
	☒ V_3 conducting
	☐ V_3 blocking
	☐ V_4 conducting
	☒ V_4 blocking

6.1.2 Test 2

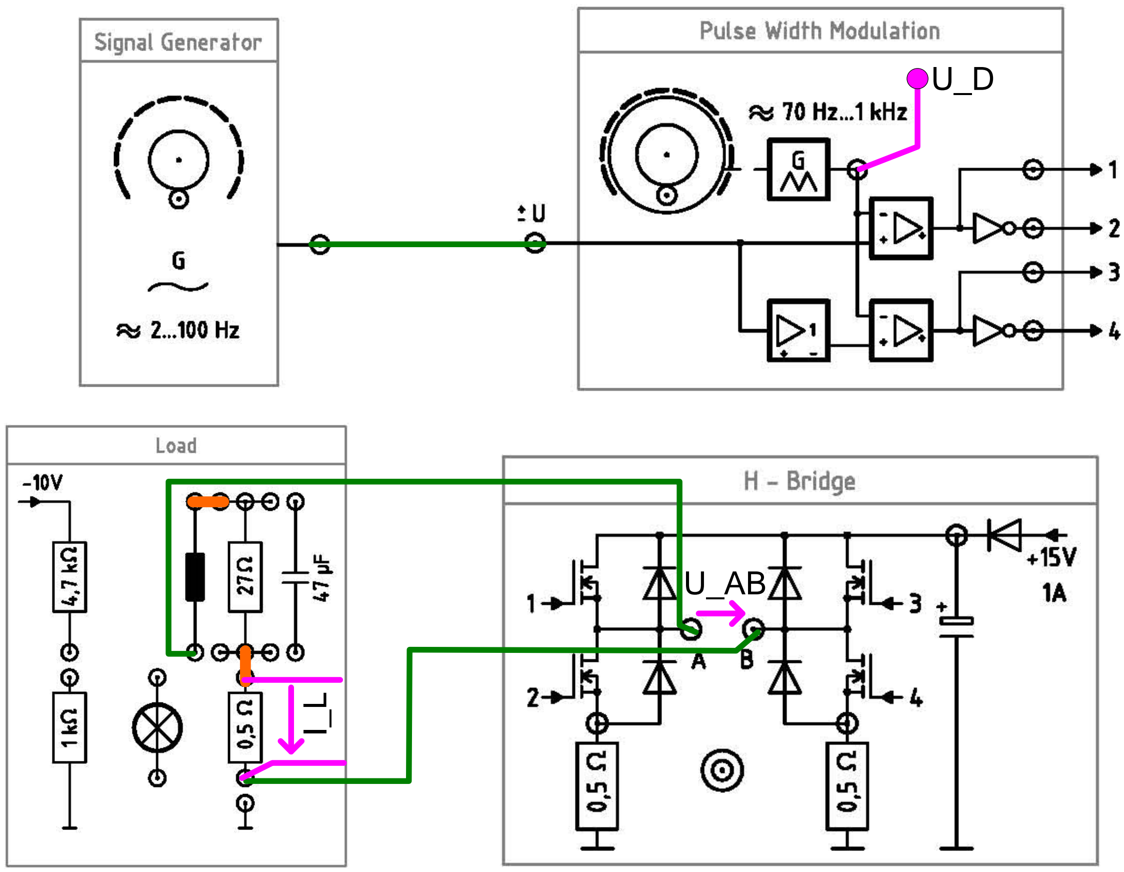
Influence of pulse frequency to ripple at the sine rated pulse width modulation.

Test Configuration & Test Procedure

- Build up the circuit in pic. 6.1.2.0 / 6.1.2.1. The control signals U_1 to U_4 are already internally wired to the MOSFET.



pic. 6.1.2.0 circuit



pic. 6.1.2.1 Circuit at the Power Electronic Panel

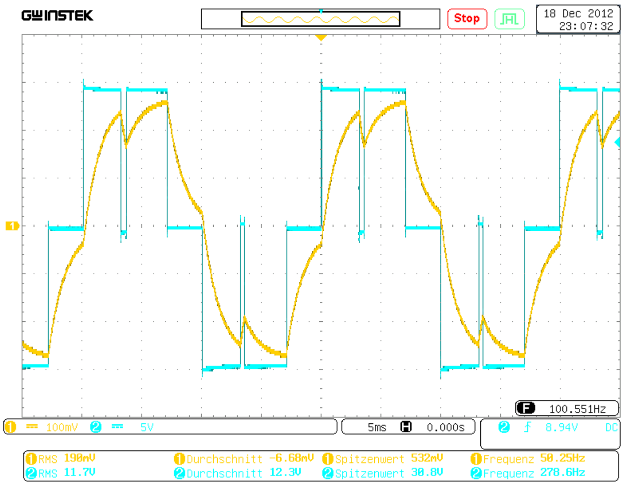
- Set the control voltage U_S to a frequency of 50 Hz.

- Measure following parameters with the oscilloscope at U_D, for a pulse frequency of 100 Hz, 500 Hz and 1 kHz:
  - Bridge Voltage U_{AB},
  - Load Current I_L

Note: ***Pay attention to the ground potential of the oscilloscope.***

Note: ***Trigger LF (Low Frequency), if existent.***

- Draw the curves into pic. 6.1.2.2 to pic. 6.1.2.4.

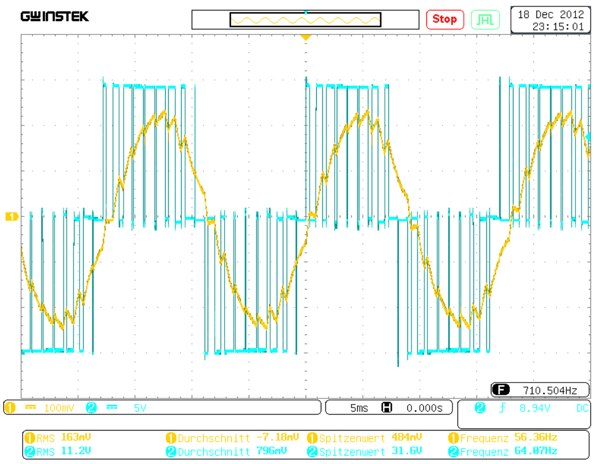


pic. 6.1.2.2 pulse frequency = 100 Hz

Oscilloscope Settings:

Bridge Section Voltage U_{AB}: 5 V / div.
Load Current I_L: 0,2 V / div.
= 0,1 V / div.
Time t: 5 ms / div.

Current Conversion with Rm = 0,5 Ohm

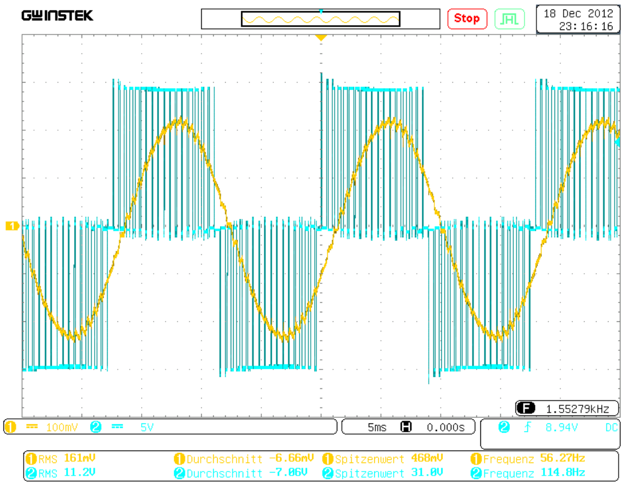


pic. 6.1.2.3 pulse frequency = 500 Hz

Oscilloscope Settings:

Bridge Section Voltage U_{AB}: 5 V / div.
Load Current I_L: 0,2 V / div.
= 0,1 V / div.
Time t: 5 ms / div.

Current Conversion with Rm = 0,5 Ohm



pic. 6.1.2.4 pulse frequency = 1 kHz

Oscilloscope Settings:

Bridge Section Voltage U_{AB}: 5 V / div.
Load Current I_L: 0,2 V / div.
= 0,1 V / div.
Time t: 5 ms / div.

Current Conversion with Rm = 0,5 Ohm

Question 1:	What influence does pulse frequency have on the ripple of load voltage I_L?
Answer:	The higher the pulse frequency, the lower is the ripple of load current.

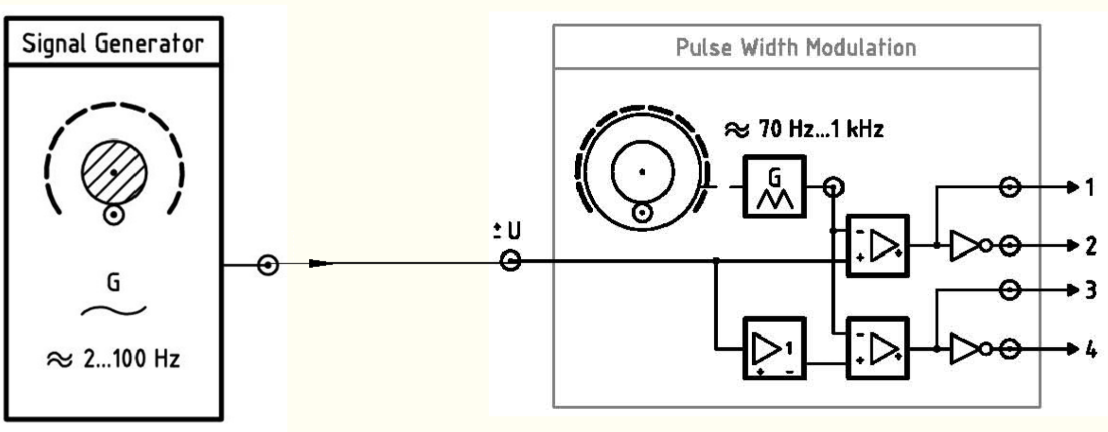
Question 2:	What is the pulse frequency of the bridge voltage U_{AB}? Explain your decision!
Answer:	Frequency of the bridge voltage U_{AB} is twice of the pulse frequency.
	Because during the conducting phase of a transistor, the respective
	transistor on the other bridge section blocks and gets conductive, so
	bridge voltage switches on, and off and on again.

6.1.3 Test 3

Influence of rated frequency on the amplitude of load current.

Test Configuration & Test Procedure

- Build up the circuit in pic. 6.1.3.0 / 6.1.3.1. The control signals U_1 to U_4 are already wired internally to the MOSFET.



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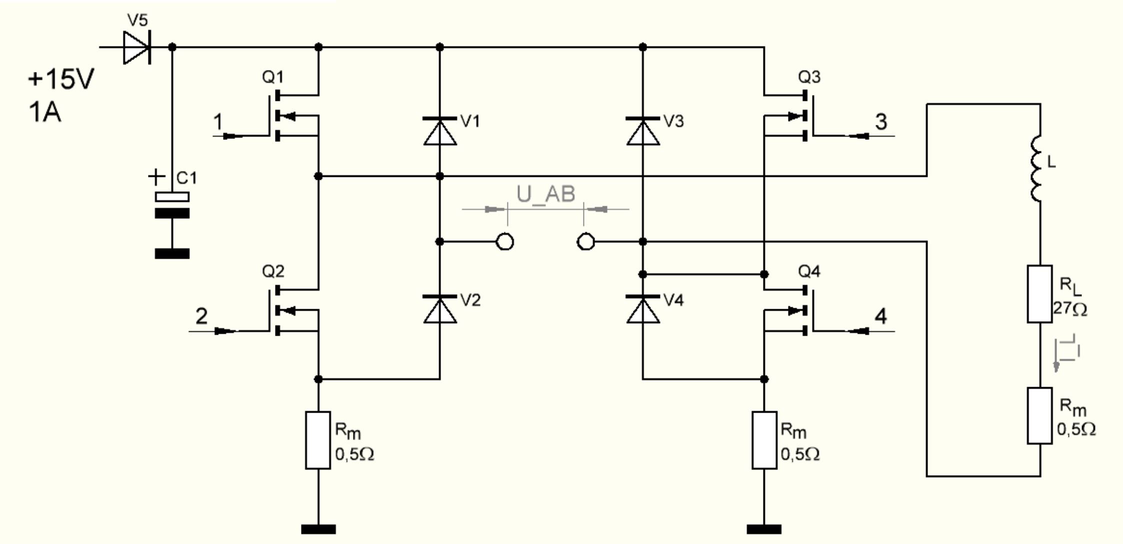
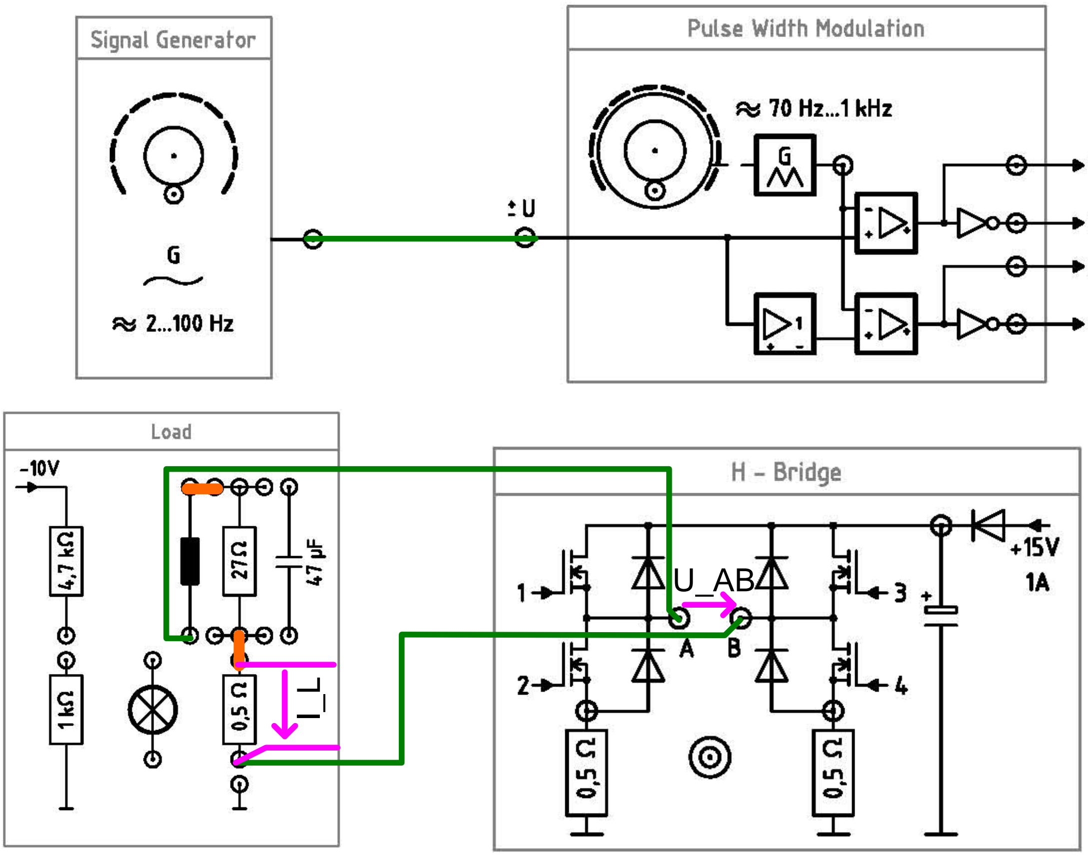


pic. 6.1.3.0 circuit

- Set voltage U_D with a frequency of 1 kHz.
- Measure following parameters with the oscilloscope at U_S, for pulse frequency of 10 Hz, 50 Hz and 100 Hz:
  - Bridge Voltage U_{AB},
  - Load Current I_L

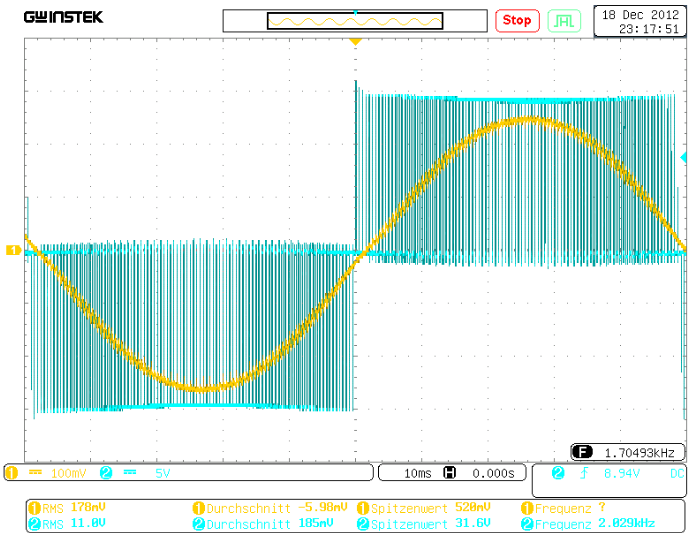
Note: ***Pay attention to the ground potential of the oscilloscope.***

Note: ***Trigger LF (Low Frequency), if existent.***



pic. 6.1.3.1 Circuit at the Power Electronic Panel

- Draw the curves into pic. 6.1.3.2 to pic. 6.1.3.4.

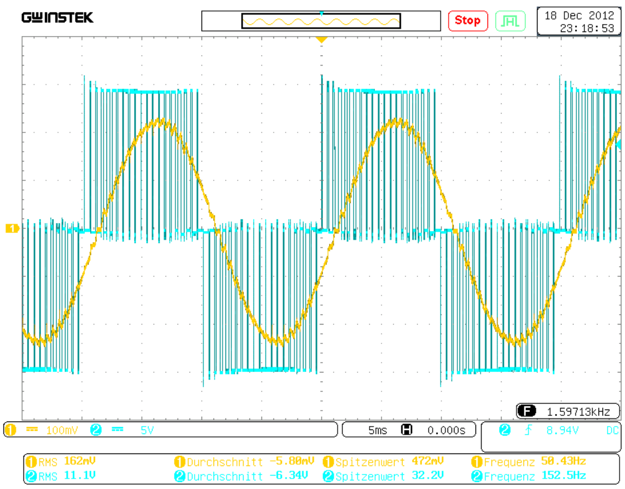


pic. 6.1.3.2 pulse frequency = 10 Hz

Oscilloscope Settings:

Bridge Voltage U_{AB}:	5	V / div.
Load Current I_L:	0,2	V / div.
=	0,1	V / div.
Time t:	10	ms / div.

Current Conversion with Rm = 0,5 Ohm

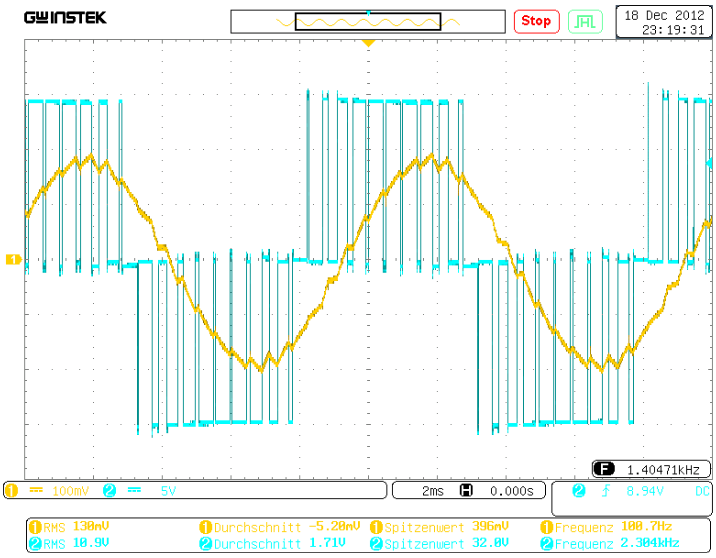


pic. 6.1.3.3 pulse frequency = 50 Hz

Oscilloscope Settings:

Bridge Voltage U_{AB}:	5	V / div.
Load Current I_L:	0,2	V / div.
=	0,1	V / div.
Time t:	5	ms / div.

Current conversion with Rm = 0,5 Ohm



pic. 6.1.3.4 pulse frequency = 100 Hz

Oscilloscope Settings:

Bridge Voltage U_{AB}:	5	V / div.
Load Current I_L:	0,2	V / div.
=	0,1	V / div.
Time t:	2	ms / div.

Current Conversion with Rm = 0,5 Ohm

Question :	What effect does control frequency have on the amplitude of load current? Explain this!
Answer:	The lower control frequency is, the higher is load current.
	Load current is defined by total resistance Z. This consists of
	ohmic resistance R and the inductive reactance X_L.
	At a decreasing frequency X_L decreases, too.
	Z gets lower and current increases. For this reason industrial
	frequency converter do have integrated adjustment of output voltage to
	output frequency. Thus constant current flow is given.

7 FAQ

- **Are the voltages on the panel galvanically isolated?**

  The voltages are distinguished in 3 groups:

  1. Three-phase AC voltage supply L1´, L2´, L3´, N´
  2. One-phase AC voltage supply L1, N
  3. DC voltage supply GND, +15V, +10V, -10V, -15V

  The three groups are galvanically isolated.
  For more information see chapter 1.1.1.1 Voltages and reference potentials.

- **What to do if I cannot cannot measure any signals?**

  Make sure that the all voltage supplies are available.
  See chapter 1.3.2 Controlling the input voltages

- **What to do if voltages L1 or L1´ are not available?**

  Control the micro fuse at the front panel.

- **What to do if voltages L2´and L3´ are not available?**

  Phases L2´and L3 ´are generated by a phase shifter and hast o be activated with a jumper.
  See chapter 1.1.1 Voltage supplies

- **What to do if there is no voltage in spite of the three phase jumper?**

  The phase shifter is internally protected by a self-healing fuse.
  Make sure this is not tripped. Switch off the panel at the main switch and check your test for errors. Switch on the panel at the main switch again.

- **When do you I have to position the generator jumper at the phase gate?**

  The generator jumper has to be placed if a phase gate control with three phase AC voltage is configured.

- **I still have unsolved technical troubles, what can I do?**

  Please contact our service team:

  Email: sales@hera.de
  Phone: +49 (0) 7953 882-0

Personal Notes: