POWER DEVICES AND SYSTEMS LABORATORY

Exercise 4$^\text{B}$

Insulated Gate Bipolar Transistor
Full-bridge DC Converter
DC Motor Control

Indicatory work plan

15′	30′	45′	1$^\text{h}$	1$^\text{h}$15′	1$^\text{h}$30′	After Class
3.1/1−13	3.1/14−20	3.2	3.3/1−6	3.3/7−10	3.4	4

Exercise and manual elaborated by
Łukasz Starzak
Part C based on translation of ver. 3.2 by
Henryk Błasiński

Łódź 2016

Contents

B

Exercise Introduction

1. Exercise Aim and Plan

The aim of this exercise is first to get acquainted with yet another work configuration of power semiconductor devices, the bridge. Second, electric motor control will be taken advantage of as a practical application example.

Generally speaking, both these issues are fairly complex due to the large number of possible control strategies for bridge switches as well as the multitude of motor solutions. For this reason, we will restrict to a control method that is simple and yet enables a complete analysis of the circuit. Also the motor chosen—a permanent magnet DC one—is among all the electric motors the easiest one to control. It will enable gaining the most basic knowledge about the specificity of power converter operation with RLE receivers. A DC/DC bridge converter will be the power converter used in this exercise.

Converter characteristics will be determined in this exercise, including those independent and those dependent on the receiver, as well as one of the typical characteristics of the electric motor. On the other hand, the operation of the DC/DC bridge converter will be investigated at the current and voltage level, including drive circuits of the transistor switches.

2. Motor Control in the Bridge Configuration

2.1.   Recommended reading

Ref.	Textbook	Excerpt	Equivalent in the Polish Manual	Complementary Reading	Complements in this Manual
A	Moh	7-7, 7-7-1, 7-7-2	2.1, 2.2.a, 2.4.a—b, 2.5		2.2.c
B	Moh	13-1, 13-2, 13-3	2.3, 2.4.c—e		2.2.a—b,d—e

2.2.   DC motor control using a full-bridge converter

2.2.a. Classification of electric motors

Motors are often the controlled systems for power electronic circuits. The complex system of their classification is based on two criteria: supply and control. With respect to supply, *AC motors* and *DC motors* may be discerned in first place. The first group is much more numerous as far as the diversity of solutions is concerned. Supply and control of AC motors is also much harder and more advanced technical solutions need fairly complex microprocessor systems.

DC motors are simpler to control. Several cases may be discerned in this respect:

(1) *series-wound motors* that have two windings generating the magnetic field, with an exciting winding, called the *field winding*, connected in series with a main winding, called the *armature*;

(2) *shunt-wound motors* where field winding and armature are connected in parallel;

(3) *compound-wound motors* where the connection is partially in series and partially in parallel;

(4) *separately excited motors* (or *sepex motors*) where field winding and armature are not connected:

    (a) with traditional (electromagnetic) excitation, where two windings are found as previously,

    (b) *permanent-magnet DC motors* (PMDC) that have only one winding—the armature, while the field winding is replaced with permanent magnets.

In the last design (4b) the excitation is constant and controlling the motor is only possible using the armature. Thanks to that, control is simpler although at the expense of some limitations. A motor from this group will be used in the present exercise.

2.2.b. Mechanical quantities describing motors

Rotational speed n is the number of rotations produced in a given time, expressed in 1/s or, customarily, in revolutions per minute (rpm). Rotation can also be described with angular velocity ω which is the angle by which on object rotates in a given time, expressed in rad/s (mathematically equivalent to 1/s). The values of these two quantities are related to each other as

$$\omega = 2\pi n \tag{2.1}$$

because one revolution means a change of 360° in angular position, which is 2π radians. Angular velocity is generally a vector, parallel to the axis of rotation, whereas rotational speed is considered a scalar.

Torque (or moment of force, or moment) is the measure of a force producing a rotational movement, defined as the vector product of the position vector $\boldsymbol{r}$, connecting the point of force application to the rotation axis, and this force $\boldsymbol{F}$:

$$\vec{T} \overset{\Delta}{=} \vec{r} \times \vec{F} \tag{2.2}$$

Expressed with scalars, this becomes

$$T = Fr \sin \theta = F_\perp r \tag{2.3}$$

where θ is the angle between the force vector and the position vector and $F_\perp$ is the value of the force $\boldsymbol{F}$ component perpendicular to the vector $\boldsymbol{r}$. The unit of the torque is 1 N×m.

In a motor, *electromagnetic torque* T_{em} is induced by the interaction of magnetic fields inside. As a result, *mechanical torque* T_m is created at the motor's shaft which can be regarded as the force F that the motor would exert on a mass attached to its shaft at a distance of r. This situation is however quite abstract; in reality, the motor torque sets a load in motion (not necessarily a rotary one) through a mechanical gear. Any difference between the electromagnetic and the mechanical torques results from damping mechanisms, first of all friction. The *damping torque* is proportional to velocity ω_m with some *coefficient of damping* (or *friction*) B.

In general, the motor is loaded with some *working load torque* T_{WL}. According to the first principle of dynamics, at equilibrium, i.e. when the motor's velocity ω_m remains constant, the *equivalent working load torque* $T_{WL(eq)}$ equals the mechanical torque T_m. The *equivalent* load $T_{WL(eq)}$ is proportional to T_{WL} and accounts for the gear. A special case is when the load torque T_{WL} equals 0; it is called the *idling state.*

2.2.c. Output voltage characteristic for the full-bridge DC converter

As demonstrated in Ref. A [see Eq. (7-74)], the average output voltage, or the output voltage DC component V_o, is

$$V_o = (2D - 1)V_i = (2D_1 - 1)V_d \tag{2.4}$$

where $V_i = V_d$ is the input (supply) voltage of the full-bridge and D is the duty cycle of one of the bridge transistors, D_1. This is the basic control characteristic of the full-bridge converter. In order to give it a universal character, it is usually presented in the relative form, related to the input voltage,

$$V_{o(r)} \overset{\Delta}{=} \frac{V_o}{V_i} \tag{2.5}$$

which leads to

$$V_{o(r)} = 2D - 1 \tag{2.6}$$

This relationship has been presented in Fig. 1.

As stated in Ref. A, the voltage control characteristic of an ideal converter is independent of current. However, it is dependent in a real circuit because of non-zero switch resistances. These cause a decrease in the output voltage by the amount of voltage drops across semiconductor switches included in the current conduction loop. As voltage drops are always dependent on current to some extent, the output voltage characteristic of a real converter will also exhibit this dependence.
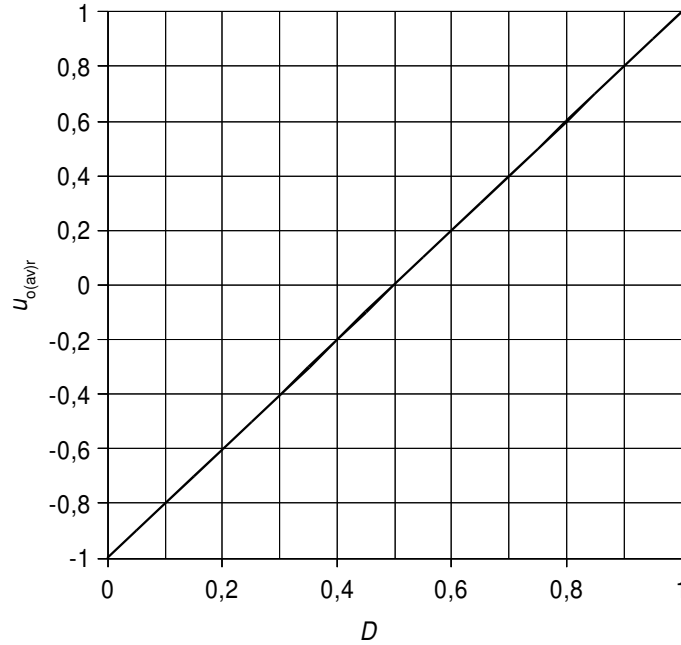
Fig. 1. Output voltage control characteristic of an ideal full-bridge DC/DC converter

2.2.d. Current and power for a full-bridge converter-controlled DC motor

For a general large inductive load, such as a motor's armature, the output current waveform $i_o = i_a$ can be assumed to be triangular (see Fig. 7-28 in Ref. A). Under this assumption, a formula for the average output power can be derived as

$$P_o = \frac{1}{T_s} \int_{t_0}^{t_0+T_s} v_o i_o \mathrm{d}t = V_o I_o = V_t I_a \tag{2.7}$$

where $I_o = I_a$ is the DC component of the converter output current, or the motor armature current.

For an RL load, the Ohm's law applies to average values, so

$$I_o = \frac{V_o}{R_o} \tag{2.8}$$

where R_o is the load resistance. After substituting (2.4) and (2.8) into (2.7), we obtain the following control characteristic of the average output power

$$P_o = \frac{V_o^2}{R_o} = (2D-1)^2 \frac{V_i^2}{R_o} \tag{2.9}$$

To an RLE load such as an electric motor, Eq. (13-12) applies, so

$$I_a = \frac{V_t - E_a}{R_a} = \frac{V_o - E_a}{R_a} \tag{2.10}$$

where E_a is the DC component of the electromotive force e_a produced by a rotating DC motor, proportional to its angular velocity ω_m and to the field winding torque Φ_f according to Eq. (13-11). Substituting this to (2.7), we get

$$P_o = \frac{V_t^2 - V_t E_a}{R_a} \tag{2.11}$$

In order to obtain a characteristic as a function of the duty cycle, we must first relate E_a to V_t through the angular velocity ω_m.

2.2.e. Idling state control characteristics

Equation (13-13) still does not give a clear picture of motor control characteristics using a full-bridge converter, because its right-hand side contains the electromagnetic torque which is linked to the left-hand side, i.e. to the angular velocity. In steady state (ω_m = const, T_{WL} = const), this link is described with Eq. (13-11) whereas from Eq. (13-9), the torque is expressed with

$$T_{em} = B\omega_m + T_{WL} \tag{2.12}$$

Substituting these into (13-13), we have

$$\omega_m = \frac{1}{k_E}V_t - \frac{R_a}{k_E k_T}T_{em} = \frac{1}{k_E}V_t - \frac{R_a}{k_E k_T}\left(B\omega_m + T_{WL}\right) = \frac{1}{k_E}V_t - \frac{R_a B}{k_E k_T}\omega_m - \frac{R_a}{k_E k_T}T_{WL} \tag{2.13}$$

After rearranging,

$$\omega_m = \frac{1}{1 + \dfrac{R_a B}{k_E k_T}} \cdot \left(\frac{V_t}{k_E} - \frac{R_a}{k_E k_T}T_{WL}\right) = \frac{k_E k_T}{k_E k_T + R_a B} \cdot \left(\frac{V_t}{k_E} - \frac{R_a}{k_E k_T}T_{WL}\right) =$$
$$= \frac{k_T}{k_E k_T + R_a B}V_t - \frac{R_a}{k_E k_T + R_a B}T_{WL} = \frac{V_t}{k_E + R_a B/k_T} - \frac{T_{WL}}{k_E k_T/R_a + B} \tag{2.14}$$

In its final form, the result shows that also after the relation of torque to velocity is taken into account, the angular velocity is essentially a linear function of the DC component of the armature voltage V_t, or of the average converter output voltage V_o. Following (13-5), it is also a linear function of the control signal duty cycle. The coefficients of this relationship result from the motor properties described by k_E, k_T and B. However, an empirical law of mechanics says that the coefficient of kinetic friction B is a decreasing function of the relative velocity of the objects that experience this friction. Therefore, in reality, we will observe some divergence from the linear law.

For the idling state, Eq. (2.14) takes a simpler form of

$$\omega_m = \frac{V_t}{k_E + R_a B/k_T} \tag{2.15}$$

whereas for an ideal motor (B = 0) this would become

$$\omega_m = \frac{V_t}{k_E} \tag{2.16}$$

In this case, the relation is not only linear but proportional. Using (2.1), Eq. (2.15) can be re-written for the rotational speed:

$$n_m = \frac{|V_t|}{2\pi(k_E + R_a B/k_T)} \tag{2.17}$$

Substituting (2.15) into (13-11) yields

$$E_a = \frac{k_E V_t}{k_E + R_a B/k_T} = \frac{V_t}{1 + (R_a B)/(k_E k_T)} \tag{2.18}$$

After substituting into (2.11), this in turn permits obtaining the average power control characteristics for the idling state:

$$P_o = \frac{V_t^2 - V_t \cdot \dfrac{1}{1 + (R_a B)/(k_E k_T)} V_t}{R_{arm}} = \frac{V_t^2}{R_a}\left[1 - \frac{1}{1 + (R_a B)/(k_E k_T)}\right] \tag{2.19}$$

which can be rearranged into

$$P_o = \frac{V_t^2}{R_a[1 + (k_E k_T)/(R_a B)]} = \frac{V_t^2}{R_a + k_E k_T / B} \tag{2.20}$$

Considering the universal voltage conversion characteristics (2.4), the idling state characteristics for a motor controlled with a full-bridge converter are expressed as following as functions of the duty cycle:

$$\omega_m = (2D - 1)\frac{V_i}{k_E + R_a B/k_T} \tag{2.21}$$

$$P_o = (2D - 1)^2 \frac{V_i^2}{R_a + k_E k_T / B} \tag{2.22}$$

Based on (2.10), (2.21) and (13-11), the armature current DC component is

$$I_a = \frac{V_t - k_E \omega_m}{R_a} = \frac{V_t - \dfrac{k_E V_t}{k_E + R_a B/k_T}}{R_a} = \frac{V_t}{R_a}\left(1 - \frac{1}{1 + (R_a B)/(k_E k_T)}\right) =$$
$$= \frac{V_t}{R_a + k_E k_T / B} = (2D - 1)\frac{V_i}{R_a + k_E k_T / B} \tag{2.23}$$

Equation (2.21) tells that the idle velocity is approximately (with friction neglected) a linear function of the duty cycle D. As $(2D - 1) \in [-1; 1]$, the result can be either positive or negative. Considering that the angular velocity is a vector, this should be interpreted as rotation in different directions.

Looking at Eq. (2.22), it can be concluded that the average output power for an RLE load in the form of a DC motor is approximately a quadratic function of the duty cycle D. Its precise form will depend on the character of the $B = f(\omega_m)$ relationship for given motor and external mechanical system.

Substituting $B = 0$, it is easy to determine that an idling ideal motor draws zero power and zero current, whereas these quantities increase with increasing B. Considering (2.13), the effect of adding a working load is similar as the corresponding torque T_{WL} adds to the damping torque $B\omega_m$ (except

that the former does not depend on velocity). This is an expected result: the greater the load of the motor's shaft, the greater electric power must be drawn to produce rotation with a given velocity, which in turn means a greater current drawn. Taking $B \to \infty$, it can be determined that with increasing damping torque (or, similarly, working load torque), the power characteristics tends to a limit which appears to be the value obtained for an RL load of an equal resistance ($R_o = R_a$), expressed with Eq. (2.9).

C

Experiment

3. Measurements

3.1. Measurement circuit setup

Circuit description

The electrical schematic of the power sub-circuit of the experimental circuit is shown in Fig. 2. It represents a full-bridge DC/DC converter supplying a permanent-magnet DC motor. The parameters of this motor are as follows: rated voltage $U_r = 24$ V, rated power $P_r = 20$ W, armature inductance $L_{arm} = 1.46$ mH at $f = 1$ kHz, armature resistance $R_{arm} = 1.20\ \Omega$.

Subscripts used in figures have been composed in a unified manner, according to the following scheme:

- L as a first letter – left leg of the bridge,
- R as a first letter – right leg of the bridge,
- L as a second letter – low-side transistor,
- H as a second letter – high-side transistor,
- M as a second letter – middle point of a leg,
- G – a transistor's gate.

The microprocessor-based control sub-circuit is composed of a red development board containing the MSP430G2231 microcontroller and a white interface circuits board. The white board contains an optical isolation circuit for the signal input from the microcontroller, a MOSFET-based inverter and two transistor gate drivers (one for the left and another for the right leg of the bridge). A detailed schematic of the control sub-circuit, including the interface circuits board and the development board resources used is presented in Fig. 3.

By running an appropriate program, the microcontroller generates a pulse wave corresponding (as far as the waveform is concerned) to the $v_{G(RL)}$ waveform, i.e., the drive voltage for the right low-side transistor's gate. On the interface circuits board, it passes through a diode optocoupler U_1 thanks to which the microcontroller is separated from the power circuit and the motor which generate considerable disturbance. The task of the NMOS inverter built upon the Q_1 transistor is first of all to increase the signal amplitude, as the voltage of 5 V, which is the maximum supply value

for the optocoupler, is insufficient for power transistor gate drivers. But the negation function itself is also needed because the optocoupler used is an inverting circuit (applying a high state to the input diode turns on the output transistor which results in a low state at the output). This way, we obtain a waveform of an amplitude equal to the supply voltage $CVCC$ and a shape consistent with the waveform generated by the microcontroller.
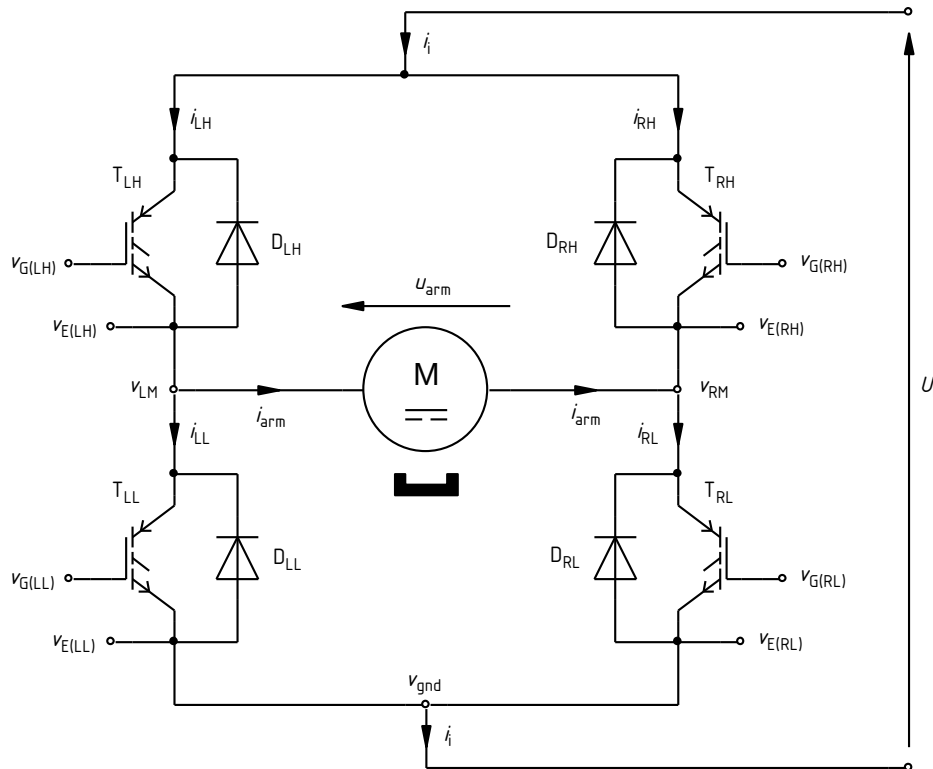

Fig. 2. Power sub-circuit electrical schematic of the experimental circuit

This waveform is then input to the gate driver U$_2$ which generates the true $v_{G(RL)}$ voltage, having the same form and amplitude but providing a current capability necessary for charging a power transistor's gate. The same driver also generates the $v_{G(RH)}$ waveform driving the gate of the right high-side transistor. The other inverter, built upon the Q$_2$ transistor, and the other double gate driver U$_3$ provide the $v_{G(LL)}$ and $v_{G(LH)}$ drive voltages for the transistors in the left leg of the bridge. The right low-side transistor's gate voltage $v_{G(RL)}$ will be considered the basic signal, with respect to which all the other ones are analysed. Its duty cycle will be denoted D_{GRL} which therefore also represents approximately (neglecting any asymmetrical delays in the propagation path) the duty cycle of the signal generated by the microcontroller.

The pulse wave is generated by the microcontroller's hardware, in a dedicated module of the integrated circuit, without constantly and explicitly involving the program. However, this module is software-configurable. In the case of the present exercise, this means the possibility to define the duty cycle through the *TACCR1* register. In order to simplify exercise realisation, this module has been configured so that the contents of this register were numerically equal to the duty cycle D_{GRL} expressed as a percentage, i.e. a number from the range of 0 to 100 (not 0 to 1). The S3 button located on the interface circuits board and connected to pin P1.3 of the microcontroller will be used to activate the generator.

The complete experimental circuit, composed of the power sub-circuit with the motor and the control sub-circuit including two boards, is placed on a main board according to Fig. 4.

Voltages at selected circuit points, as marked in Fig. 2, have been led out to white connector blocks. Emitter nodes, labelled v_E and only used to connect the power circuit to the control circuit, are an exception; their voltages are however identical to the v_{gnd}, v_{LM} and v_{RM} voltages which are accessible through the connector blocks. The arrangement of these connector blocks is presented in

Fig. 4. The same drawing also presents the arrangement of wires led out to enable measuring currents marked in Fig. 2.

Results are recorded using the TDS1002B (Fig. 4a) or the TDS224 (Fig. 4b) oscilloscope. Oscilloscope configuration should be carried out at the time indicated in this manual and according to guidelines given. For current measurements, an autonomous current probe is used (without a separate amplifier). The DC component of the motor current is measured with a multimeter.

Rotational speed measurement

On the white board, the rotational speed measurement circuit has been placed, too. It is composed of an emitting diode D_2, supplied together with the rest of the interface circuits, and a receiver phototransistor Q_3, supplied from the microcontroller board and connected with the microcontroller (via the interface circuits board where the R_7 resistor has been mounted), both operating in the infrared range. These components have been mounted close to the motor axis, opposite to one another.
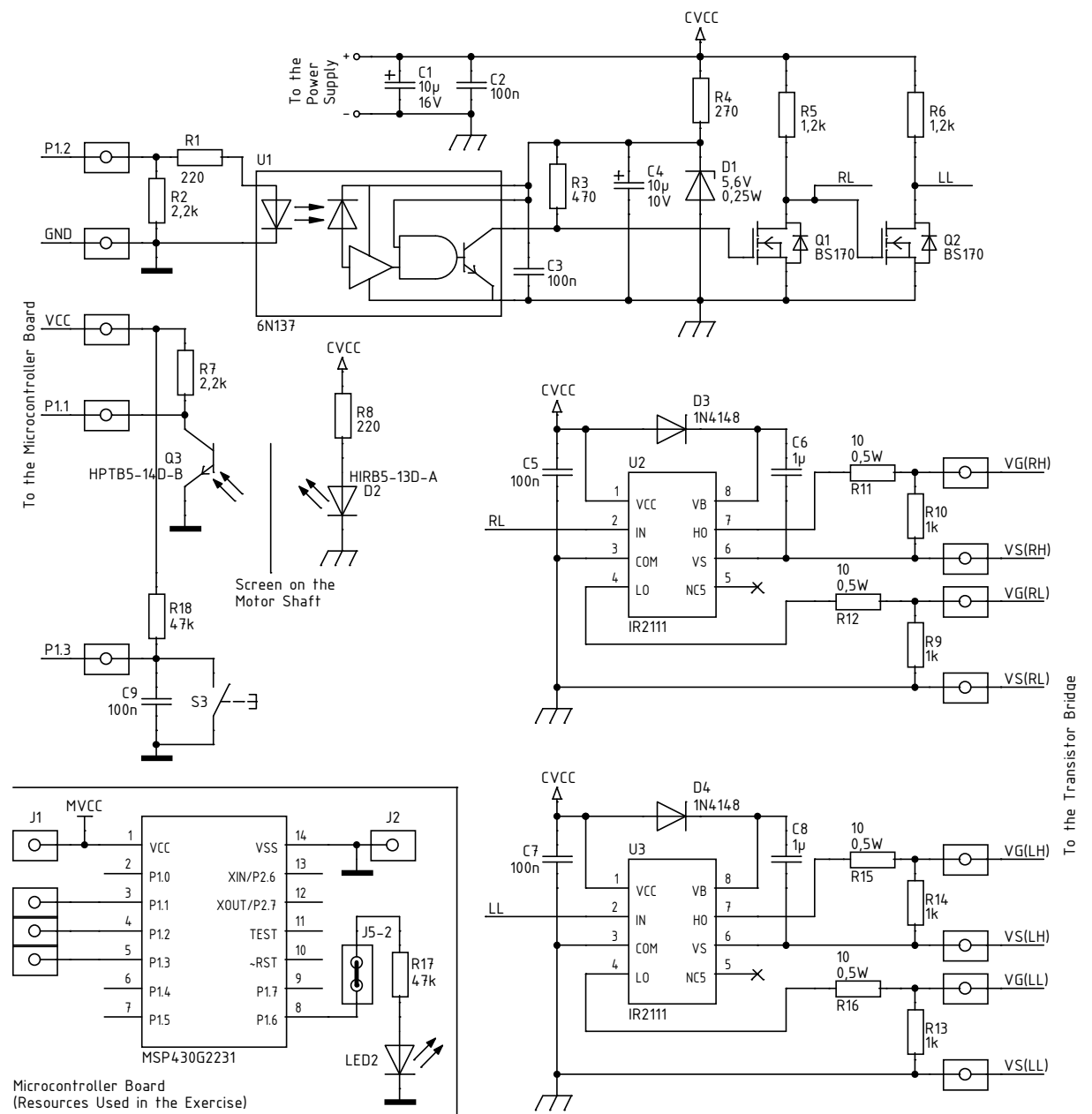

Fig. 3. Electrical schematic of the control sub-circuit of the experimental circuit

When the motor rotates, a screen installed on its shaft in the form of a two-blade "propeller" periodically interrupts the infrared light beam illuminating the phototransistor, which results in its being turned off. At these moments, a high voltage level (the microcontroller supply voltage *VCC*) appears at the collector of this transistor, while a low level (zero voltage) is present there for the remaining time, when the transistor is driven by the light beam.

The signal obtained in the above way, which takes the form of a pulse train, is input to the pin P1.1 of the microcontroller. This pin is configured as an input issuing interrupt requests upon detection of a rising edge. A variable named *pwm_periods_counter* is used in the microcontroller's program, in which subsequent periods of the transistor bridge control signal are counted. In the interrupt service routine for the P1.1 input, the current value of this variable is copied to the *periods_per_halfrev* variable whereas the value of *pwm_periods_counter* itself is cleared and counting starts back from zero.

(a)
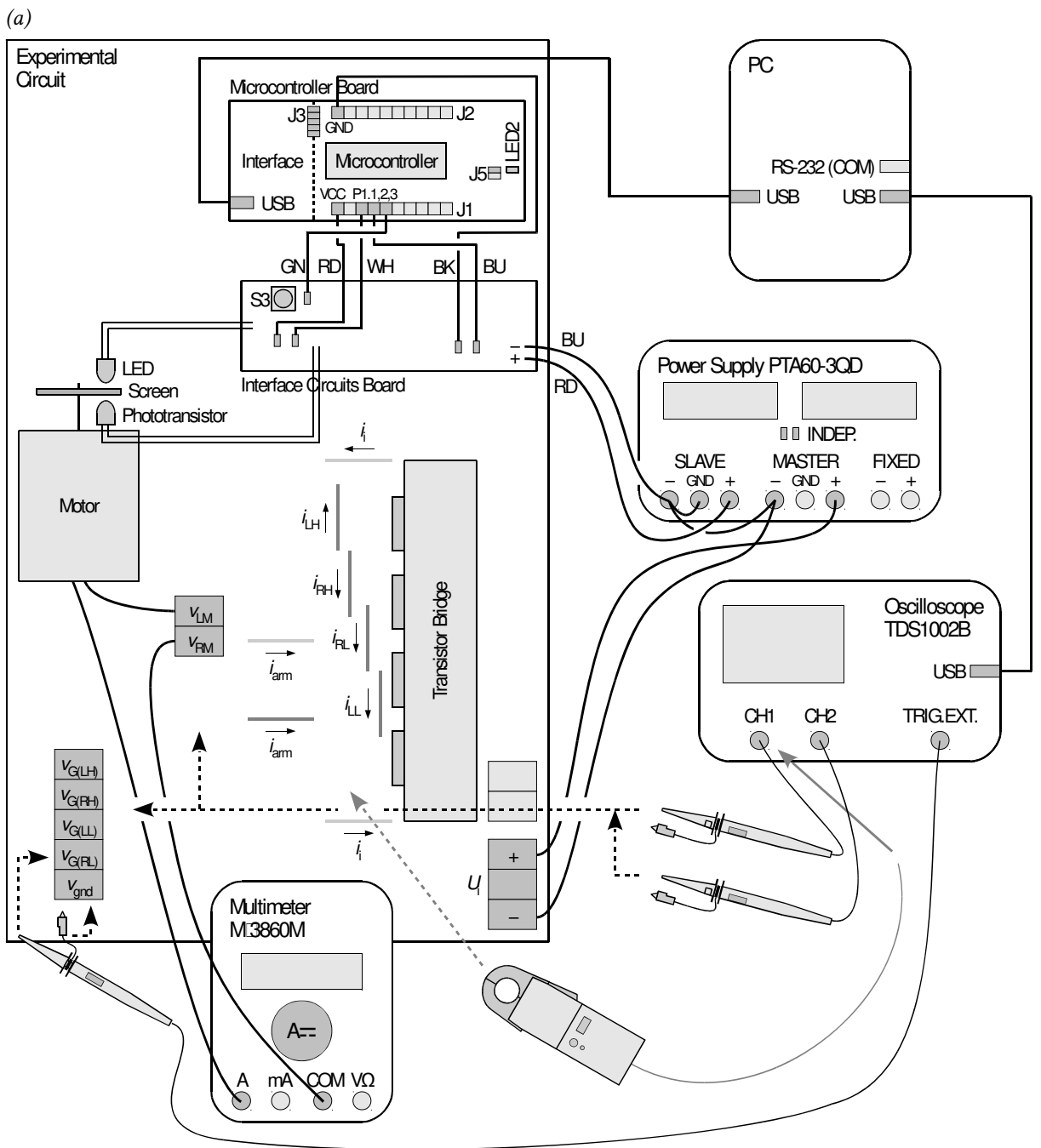
Fig. 4. Measurement set-up diagram showing component layout on the experimental circuit board (including connectors and wires providing access to voltages and currents): (a) with the TDS1002B oscilloscope; (b) with the TDS224 oscilloscope

(b)
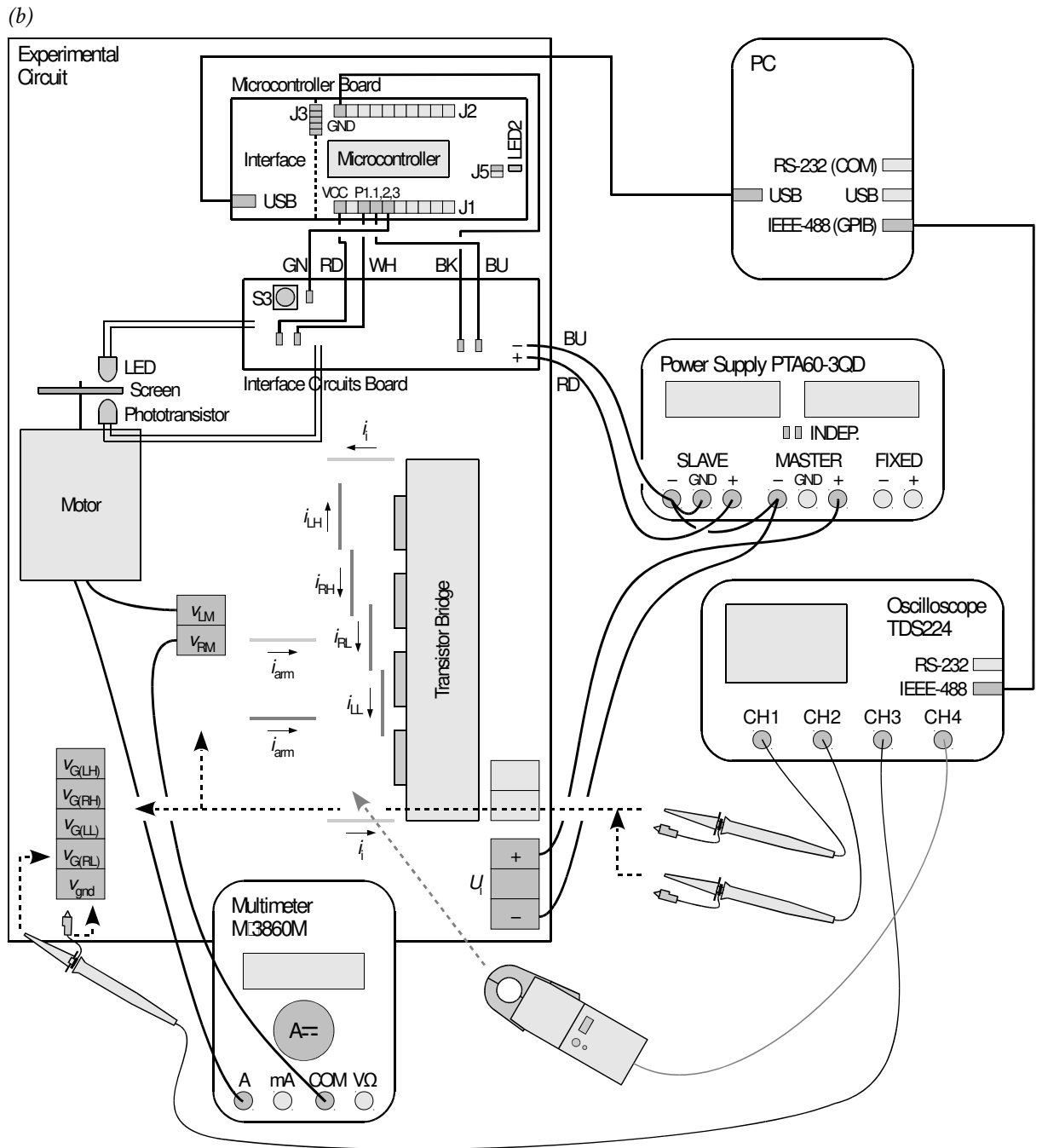
Fig. 4. (cont.)

Thus, the *periods_per_halfrev* variable contains the number of control waveform periods that have passed between subsequent interrupts, or between subsequent pulses coming from the phototransistor. It is therefore the number of periods that corresponds to one half-revolution of the motor, as the two-blade screen masks the phototransistor every half-revolution. The value of this variable, N_{hrev}, can be read on the computer on an ongoing basis.

If, in addition, the frequency of the bridge control signal f_s is known, then the rotational speed n of the motor can be calculated in a simple way. In each one-second interval, there are f_s periods of the control waveform. On the other hand, the duration of the motor's one half-revolution is N_{href} times longer than one such period, so one full revolution is $2N_{hrev}$ times longer. The number of revolutions in each one-second interval is therefore $2N_{hrev}$ times lower than the number of control waveform periods (in each one-second interval); but this latter number of periods is nothing else but the f_s frequency. This can be expressed mathematically with the formula:

$$n = \frac{f_s}{2N_{hrev}}$$

(3.1)

Circuit configuration

Fig. 4 also shows a block diagram of the complete measurement set-up taking into account the two possible laboratory stands. It should be assembled in the way described below, following the order of actions given. If an oscilloscope model designation is given at a given point, this means that this point only applies to this given oscilloscope model while it should not be performed when another oscilloscope model is used.

In order not to waste time, following steps should be carried out in parallel with step 1.

1. Turn on the PC. Turn on the oscilloscope and configure the connection to the PC strictly according to the procedure described in the manual available at the laboratory stand.

2. On a power supply with two adjustable sections, while keeping it <u>turned off</u>:
   - select the *Independent* mode of operation (two buttons in the middle of the front panel whose setting explanation can be found on the panel above them),
   - connect the "–" terminals of both adjustable sections one with another,
   - connect the "–" terminal of one of the adjustable sections to the supply network protective earth terminal of the power supply (GND);
   - turn all the knobs to zero (extreme counterclockwise position).

3. Bring power to the interface circuits board: using wires with insulated alligator clips, connect the adjustable section of the power supply which has its "–" terminal grounded to the two wires leading out of the board, of which the red one is the positive end and the blue one is the negative end.

4. Bring the converter input voltage U_i (see Fig. 4) from the other adjustable section of the power supply.

5. Insert a multimeter operating as an ammeter in series with the motor, in the following way:
   (a) using a screwdriver, disconnect the motor from the v_{RM} socket (<u>not any other</u>) on the circuit board;
   (b) connect the v_{RM} socket to the COM input (<u>not any other</u>) of the multimeter;

   Only in the above conditions will the current sign displayed by the multimeter conform to its direction as marked in Fig. 2.

   (c) connect the released wire from the motor to the <u>current</u> input of the multimeter of an <u>appropriate maximum load</u>, using an alligator clip attached to a banana plug;
   (d) set the multimeter into the DC current mode of 1 A at least;
   (e) leave the multimeter switched off.

6. Connect (or verify existing connections) the interface circuits board to the microcontroller board (J1 and J2 pin headers) through pin connectors, in the following order starting from the one located closest to the power supply wires (those used in step 3, see Fig. 4):
   - blue wire, to pin P1.2,
   - black wire, to pin GND,
   - green wire, to pin P1.3,
   - white wire, to pin P1.1,
   - red wire, to pin VCC.

7. Make sure that:
   (a) on the microcontroller board, using jumpers, connected are (see Fig. 4):
   - the LED2 indicator to pin 1.6 (pin 2 of the J5 pin header),

- the TEST, RST, RXD, TXD signals and the VCC supply voltage from the programming and debugging interface block to the microcontroller block (all the pins of the J3 pin header);

(b) no accidental shorts of neighbouring component leads are present on the interface circuits board.

Before proceeding with the following step, connections must be checked by the teacher. This step must be first read <u>in its entirety</u> and only then one should proceed with its execution.

Under normal operating conditions, during and after execution of the following step, the current drawn indicated on the power supply ammeter should not exceed 0.15 A. If, <u>while setting voltage or later</u>, anything else is observed, immediately turn off the power supply and ask the teacher to check the circuit once again.

8. Turn on the power supply. Slightly increase the current limit (*Current* knob) of the section which <u>supplies the control circuit</u> (the interface circuits board) until red current limiting indicator (*C.C.*) goes out. In this section, set the voltage (*Voltage* knob) to 10 V. If the current limiting mode is activated in the course of setting (the red indicator lights up), <u>first decrease the voltage</u> (turn the *Voltage* knob counterclockwise) so as the red indicator extinguishes, next increase the current limit and only after that try to set the desired voltage again.

9. Connect the microcontroller board to the computer through a USB A/Mini-B cable long enough (do not use any extension cable as this would degrade transmission quality to an extent disabling communication). In the case a hardware installation window appears, do not close it, instead ask the teacher to introduce the password in order to complete the installation. The green PWR LED should light up on the microcontroller board.

Microcontroller configuration

10. From the Start Menu, run the Texas Instruments Code Composer Studio environment, while:

    (a) during its start:

    - in the *Workspace Launcher* dialog, enter *H:\workspace* as the path and check *Use this as the default and do not ask again*,
    - accept any possible further suggestions;

    (b) after it starts:

    - in the *CCS App Center – Pending Installation* dialog, click *No*;
    - in the *Getting started* window, select *Yes* for *Would you like to use CCS in 'Simple' mode.*

11. Create a new project: choose *File ▸ New ▸ CCS Project* and in the dialog displayed:

    - choose Target: *MSP430G2231*;
    - give the project a name, e.g., *motor*, check *Use default location*;
    - on the *Project templates and examples list* choose *Empty Grace (MSP430) Project*;
    - click *Finish*; after the dialog closes, <u>wait</u> for the project configuration process to terminate, which will be indicated by displaying a *Grace (MSP430) – Welcome* page.

12. Replace project sources with the bridge converter controller program:

    (a) close the file *main.cfg* and do not open any other project files for now;

    (b) delete the files *main.c* and *main.cfg* as presently found in the project folder located in *H:\workspace*;

    (c) copy the files *main(en).c* and *main.cfg* found in the laboratory folder to the project folder;

    (d) rename the file *main(en).c* found <u>in the project folder</u> to *main.c*;

    (e) in the programming environment, from the *Project Explorer* pane found in the left side panel, open the file *main.c.*

13. Compile the program, generate the machine code and run it in debug mode by clicking the *Debug main.c* icon (a green one) in the toolbar. In the *ULP Advisor* dialog, check *Do not show this message again* and click *Proceed.*

Oscilloscope configuration

14. Using a voltage probe, connect the $v_{G(RL)}$ voltage to the oscilloscope, using:
   - [TDS1002B]   synchronisation input (EXT TRIG),
   - [TDS224]   channel 3 input (CH3).

   In this exercise, ground terminals of <u>all</u> probes should be connected to the v_{gnd} node, which is connected both to the ground of the control sub-circuit and to the negative terminal of the power sub-circuit supply.

   [TDS1002B]   Using the switch found on the probe holder body, set the attenuation to 10x.

   Any other ground connection for any probe will cause a short circuit through the oscilloscope, which can damage its input circuitry!

15. Using a separate voltage probe, connect the same voltage $v_{G(RL)}$ to the oscilloscope's channel 1 input. Using a voltage probe, connect the voltage $v_{G(LL)}$ to the oscilloscope's channel 2 input.

   [TDS1002B]   Using switches found on probe holder bodies, set the attenuation to 10x.

16. Using the oscilloscope communication software, upload initial settings to the oscilloscope:

   [TDS1002B]
   - go to the *Get & Send Settings* tab;
   - press *Open* and read the *4b_tds1002b_napięcia.set* file;
   - press *Send Settings*;
   - return to the *Screen Capture* tab.

   [TDS224]
   - from the menu, choose *File ▸ Open* and open the file *ustawienia_4b_tds224_hz56.sht*; choose *Offline* in the dialog that appears;
   - on the list displayed in the left panel, unfold the installed oscilloscope ▸ *Data ▸ Settings*;
   - in the settings file window, select its entire contents and drag them to the *Full Setup* item in the left side panel using the mouse;
   - wait for the introduction of settings on the oscilloscope to complete, which process is indicated by changes of elements on the screen (letters, numbers, curves).

Operation test

17. Run the program:

   (a) check if, after the executable has been built, the debugger has been launched and has stopped at the first line of the *main()* function; in case it has not:
   - if compilation errors have been shown, this indicates that steps 10—12 have been carried out incorrectly or incompletely; in order not to waste time on searching for the exact cause, these steps should be now repeated while creating a new project under a new name,
   - if the *Debug* window is missing, try to display it from the menu *Window ▸ Show View ▸ Other...*,
   - if the debugger has not stopped in the line given above, double click the "main(...)() at main.c" item in the *Debug* pane;

   An appropriate of the above actions should be also performed if later on the debugger does not start correctly after compilation is finished.

(b) launch program execution by clicking the *Resume* button in the toolbar.

18. Push the S3 button on the interface circuits board, which should start the generation of the bridge transistors control waveform, indicated by the LED2 lighting up.

19. Looking at the oscilloscope image:

   ▪ make sure that both 1 and 2 channel waveforms are displayed on the screen;

   When a channel waveform is displayed, this is indicated with an arrow with this channel's number appearing left of the graticule as well as this channel's symbol appearing below the graticule together with its current gain setting. In the case of the Math waveform that is created as a result of a mathematical operation, the symbol is (will be) the M letter.

   Pressing the *Menu* button of a given channel alternatively displays and hides the corresponding waveform.

   ▪ state whether the waveforms have a rectangular form and are visible within a time window corresponding to their 3 to 6 periods; adjust the time base (*Sec/Dev* knob) if needed;

   ▪ ensure that the gain is set to 10 V/div in both channels; this setting is appropriate for every voltage measurement and it should not be modified for the entire course of the exercise;

   ▪ state whether the amplitude of the waveforms is clearly visible and whether they can be distinguished one from another; if needed, adjust the zero levels of the waveforms displayed (*Vertical Position* knobs).

   Aligning zero levels of every waveform investigated in this exercise with the "large" graticule will make result analysis easier (the precise setting is displayed below the graticule during adjustment).

20. Verify the power circuit operation:

   (a) stop control waveform generation by pushing the S3 button again (successfully stopping the generation must be indicated by the LED2 diode going out);

   Under normal operating conditions, during execution of the following step, the current indicated by the ammeter of the power supply section that supplies the power circuit should not exceed 0.1 A and it should return to zero after carrying out that step. If anything else is observed, immediately turn off the power supply and ask the teacher to check the circuit once again.

   (b) on the power supply, using the *Current* knob, for the section supplying the power circuit, set current limit to its maximum (extreme clockwise position);

   (c) with the *Voltage* knob of the section mentioned above, set the voltage to 24 V;

   After the motor is started, the power supply voltmeters can indicate voltages higher than set above. Such indications are false and result from disturbances generated by the bridge with the motor. Therefore, do not take any action related to this fact; in particular, do not change the settings of the *Voltage* knobs which should remained unchanged until the end of the exercise.

   (d) activate control waveform generation using the S3 button on the microcontroller board. The motor should start rotating, driving a current of about 0.3 A from the power supply. If anything else is observed, turn off the power supply and ask the teacher to check the setup once again.

   Later on, the current drawn from the power supply may be higher than the one given above.

3.2.   Transistor drive

1.   Stop the motor by pushing the S3 button.

2.   From the web page, obtain the initial duty cycle value $D_{GRL(1)}$. In the *main.c* code window, replace the current duty cycle D_{GRL} value being written to the *TACCR1* register (see the description in Section 3.1) with $D_{GRL(1)}$.

     Stopping the debugger is not necessary to make changes in the code.

3.   Generate the machine code and run the program, then activate the controller (see steps 3.1/13 and 17−18).

     Saving the source code before generating the machine code is not necessary; this will be suggested automatically. If the debugger is active, the environment is in its *Debug* mode, then launching the *Build All* (*Ctrl+B*) or *Build 'Debug' for project ...* (a toolbar icon) will automatically save the source code and restart debugging after the machine code is generated. The *Resume* command can be equally (apart from using the icon) launched by pressing *F8*.

4.   Based on the waveforms displayed by the oscilloscope, determine if the v_{GRL} signal indeed exhibits the duty cycle determined above (with an accuracy that can be achieved based on the present oscilloscope image, without modifying any of its settings). Go back to step 1 otherwise.

5.   Using the oscilloscope communication application, download and save the oscilloscope image of the $v_{G(RL)}$ and $v_{G(LL)}$ voltages:

     [TDS1002B] in the application, press *Get Screen* and then *Save As* (confirm with the mouse as using the Enter key will cause the dialog box to reopen).

     [TDS224] create a new *LibreOffice Writer* document, then from the left side panel of the application, drag the *Display ▸ Screen Copy* item to the file created; right-click on the inserted picture and choose *Anchor ▸ As character* from the context menu.

     As already stated, in order to facilitate further data analysis, the gain of 10 V/div in channels used for voltage measurements should be kept unchanged throughout in the entire course of the exercise.

6.   Reapply the channel 2 probe so that it measures the $v_{G(RH)}$ voltage (still displaying the $v_{G(RL)}$ voltage). If needed, adjust waveforms position (*Vertical Position*) so that they can be distinguished one from another, but without changing channel gains. Download and save the oscilloscope image.

7.   Repeat step 6 with respect to the $v_{G(LH)}$ potential.

3.3. Characteristics of the full-bridge converter with the motor

Motor voltage waveforms

1. Record the waveforms of potentials at the two terminals of the motor:

    (a) reapply the appropriate probe so that to measure:

    - the v_{LM} potential in channel 1,
    - the v_{RM} potential in channel 2;

    (b) if needed, adjust zero levels so that the waveforms can be distinguished one from another;

    (c) download and save the oscilloscope image.

2. Record the waveform of the voltage across the motor as the difference of voltages at its terminals:

    (a) [TDS224] set zero levels of both channels 1 and 2 in the middle of the screen;

    (b) activate mathematical functions by pressing *Math Menu*; an additional *Math* waveform should show up on the screen, whose zero level is marked by an arrow with the M letter appearing left of the graticule;

    (c) ensure that in the menu that displays, the subtraction operation *CH1–CH2* is selected, which gives the armature voltage $u_{arm} = v_{LM} - v_{RM}$ (see Fig. 2);

    (d) [TDS1002B] in the menu displayed, for the *Math* waveform:

    - set the vertical scale to 10 V/div by selecting *Vertical Scale* and using the large knob in the top left corner of the oscilloscope panel,
    - move the zero level to the middle of the screen by selecting *Position* and using the large knob as above;

    (e) hide channel 1 and 2 waveforms (only the difference waveform M displayed),

    (f) download and save the oscilloscope image.

Setting up characteristics measurement

3. On the oscilloscope:

    (a) in order to obtain stable results, activate the averaging mode by pressing the *Acquire* button and choosing *Average* from the screen menu;

    (b) [TDS224] show channel 1 and 2 waveforms;

    (c) activate the measurement functions with the *Measure* button; in the consecutive fields (from top to bottom), the following measurements should be selected:

    [TDS1002B]

    - in the first field, the mean value (*Mean*) of the armature voltage $u_{arm(av)}$ (i.e. of the subtraction result *Math*),
    - in the third field, the armature voltage (*Math*) frequency (*Freq*).

    [TDS224]

    - in the first and the second fields, the mean values (*Mean*) of bridge leg middle points $v_{LM(av)}$ and $v_{RM(av)}$ (i.e. of channel 1 and 2 waveforms *Ch1* and *Ch2*),
    - in the third field, the left leg middle point voltage (*Ch1*) frequency (*Freq*).

4. Reconfigure the programming environment so that to enable rotational speed measurement:

    (a) in order to speed up measurements, in the program code *main.c*, modify the line above the *TACCR1* value assignment so that the motor starts automatically after running the program, by changing the argument of the *EnablePWM()* function from 0 to 1;

    (b) in the program code *main.c*, find and highlight (with mouse or keyboard) the name of the variable *periods_per_halfrev*, right-click and select *Add Watch Expression* to add it to the watch list.

    (c) generate the machine code and run the program again.

5. Switch on the multimeter.

If the battery discharge indicator (a battery symbol) shows up on the meter's display, do not continue measurements but ask the teacher to replace the battery. Otherwise meter indications may become erroneous.

6. Set the initial value of the duty cycle:

    (a) in the program code, change the duty cycle value (see step 3.2/2) to $D_{\mathrm{GRL(2)}}$ which should be obtained from the web page;

    (b) stop the motor using the S3 button;

    (c) re-generate the machine code and run the program again;

    (d) watching the ammeter (multimeter) indication, wait until this readout stops varying considerably with time (this concerns a noticeable change in one direction, not omnipresent random variations in random direction). This may require a few minutes of operation.

The characteristics of the motor under investigation (such as coefficient of friction or armature resistance) change considerably with temperature. It is therefore important to carry out the measurements on a warm motor, because then characteristics will not vary in time.

In order not to waste time, while the motor is heating up, execute step 7, read steps 8—10 and determine the resulting (<u>from both step 8 and steps 9—10</u>) set of measurement points (e.g. D_{GRL} values) for which control characteristics will be measured. In the case of a delay in exercise realisation, skip further waiting for the motor to heat up after the abovementioned set of measurement points is determined.

Control characteristics measurement

7. Read out and write down the exact values of:

    (a) converter input voltage U_{i}, as indicated by the appropriate power supply section voltmeter;

    (b) bridge switching frequency f_{s}, as indicated on the oscilloscope [see step 3(c)].

Before starting the execution of the following step, it should be first read <u>in its entirety</u>, e.g up to the location where the next step begins.

8. For 5—8 measurement points defined by the duty cycle values D_{GRL} changed in the range between its current value and 50%, perform measurements, reading out and writing down:

    (a) from the multimeter, the DC component of the armature current $I_{\mathrm{arm(0)}}$ (including its sign);

    (b) from the oscilloscope, the average value (*Mean* indication including its sign) of:

       ▪ [TDS1002B] the armature voltage $u_{\mathrm{atm(av)}}$;

       ▪ [TDS224] the left and right leg middle point voltages $v_{\mathrm{LM(av)}}$ and $v_{\mathrm{RM(av)}}$;

    (c) from the programming environment:

       ▪ the duty cycle D_{GRL} of the $v_{\mathrm{G(RL)}}$ waveform (*TACCR1* register content which is a percentage value),

       ▪ the number of control waveform periods per motor half-revolution N_{hrev}, which is the value of the *periods_per_halfrev* variable, <u>whose present value must be read before from the microcontroller</u> by pausing the debugger with the yellow *Suspend* button in the toolbar;

    (d) rotation direction (clockwise or counterclockwise as seen from the front of the motor body, i.e. from the shaft side), by visual observation for these duty cycles for which the motor rotates sufficiently slow.

The set of measurement points <u>must</u> contain <u>among others</u> the following D_{GRL} values:

- $D_{GRL(2)}$ ($D_{GRL(3)}$ when repeating measurements according to step 10),
- 50%,
- $D_{GRL(1)}$ <u>if</u> it is contained between the two above.

Changes to the duty cycle D_{GRL} should be made in analogy to steps 6(a)–(c), i.e. for its each consecutive value, it is necessary to:

- <u>stop the motor beforehand</u> using the S3 button,
- change the duty cycle value in the program,
- generate the machine code and run the program again.

9. Repeat step 6 but this time applying the initial value of $D_{GRL(3)}$ instead of $D_{GRL(2)}$.

10. Repeat step 8 starting from $D_{GRL(3)}$, but skipping the measurement for D_{GRL} = 50%.

3.4. Power circuit voltage and current waveforms

Motor voltage

1. For 2 (*3) different values of the D_{GRL} duty cycle:

   (a) $D_{GRL(1)}$;

   (b) such that the motor is rotating with a rotational speed [corresponding to the value of the variable *periods_per_halfrev* which is to be read out as in step 3.3/8(c)] similar (do not put effort in obtaining it equal) as for $D_{GRL(1)}$ but in the opposite direction [an appropriate value can be predicted base on Eqs. (2.17) and (2.4)];

   (c) * such that the motor is rotating in the same direction as for $D_{GRL(1)}$ but with a significantly different rotational speed;

   carry out the following:

   [TDS1002B]

   - download and save the oscilloscope image of the armature voltage u_{arm};
   - if for a given D_{GRL} value there are no results from Section 3.3, read out and write down:
       - the number of control waveform periods per motor half-revolution N_{hrev} (the value of the variable *periods_per_halfrev* from the programming environment),
       - the average value of the armature voltage $u_{arm(av)}$ (the *Mean* indication on the oscilloscope).

   [TDS224]

   - if channel 1 and 2 waveforms are displayed on the oscilloscope, hide them;
   - download and save the oscilloscope image of the armature voltage u_{arm};
   - if for a given D_{GRL} value there are no results from Section 3.3:
       - read out and write down the number of control waveform periods per motor half-revolution N_{hrev} (the value of the variable *periods_per_halfrev* from the programming environment),
       - show channel 1 and 2 waveforms on the oscilloscope,
       - press the *Measure* button,
       - read out and write down the average values of the bridge middle point voltages $v_{LM(av)}$ and $v_{RM(av)}$ (the *Mean* indications on the oscilloscope).

Motor current

2. [TDS1002B] Disconnect the channel 1 and 2 voltage probes from the circuit and from the oscilloscope (leave the probe that is connected to the trigger input).

3. Re-configure the oscilloscope:

   [TDS1002B]

   - proceeding as in step 3.1/16, upload oscilloscope settings from the file *4b_tds1002b_prąd_hz56.set*.

   [TDS224]

   - turn off waveform averaging by pushing *Acquire* and choosing *Sample* from the screen menu;
   - hide all the waveforms presently displayed (the subtraction result *Math* and, possibly, channel 1 and 2 waveforms);
   - show the channel 4 waveform.

4. Connect the current probe to the channel 1 ([TDS224] channel 4) of the oscilloscope. Switch it on and calibrate according to the procedure described in the operating manual available at the laboratory stand (skip oscilloscope configuration).

5. Clamp the current probe around the wire leading the armature current i_{arm} so that the arrow on the probe body, which indicates the current direction taken as positive, is in conformance with the arrow in Fig. 4.

6. For <u>the same</u> 2 (*3) duty cycle values as in step 1:

   ▪ download and save the oscilloscope image of the armature current i_{arm};

   ▪ if for a given D_{GRL} value there are no results from Section 3.3, write down the DC component of the armature current $I_{arm(0)}$ (the indication of the multimeter).

Transistor switch currents

7. * By clamping the current probe around appropriate wires, without changing any settings, for the duty cycle of $D_{GRL(1)}$, record the waveforms of all the four switch currents: i_{RL}, i_{RH}, i_{LL}, i_{LH}, paying attention to their directions (see Fig. 4).

Measurement termination

8. Stop the motor using the S3 button.

9. Bring down to zero the power circuit supply voltage and <u>next</u>, the control circuit supply voltage.

10. Close the programming environment and unplug the USB cable from the socket on the microcontroller board.

11. Disconnect the current probe from the circuit and turn it off with the button on its body.

12. Turn off the multimeter and disconnect it from the circuit. Connect the released motor wire back to the v_{RM} socket and tighten the screw.

13. Remove all remaining connections.

4. Result Elaboration and Analysis

4.1. Full-bridge converter

For consistency with the Polish version, throughout this chapter, armature will be denoted with the subscript "arm," whereas in the references and in Sub-chapter 2.2, it is denoted "a" and the armature voltage is denoted v_t. Average values and DC components will be denoted with subscripts "av" and "0," respectively, whereas they are marked with capital letters in the references and in Sub-chapter 2.2.

Control voltages

1. On a single page, collect the oscilloscope images of voltages recorded at the duty cycle of $D_{GRL} = D_{GRL,ini}$:

    - $v_{G(RL)}$ and $v_{G(LL)}$ (step 3.2/5);
    - $v_{G(RL)}$ and $v_{G(RH)}$ (step 3.2/6);
    - $v_{G(RL)}$ and $v_{G(LH)}$ (step 3.2/7).

2. Based on the oscilloscope images of gate voltages for the four transistors of the bridge, determine what switch control scheme was used in the investigated full bridge circuit (see Ref. A, Sections 7-7, 7-7-1 and 7-7-2).

3. * Based on the oscilloscope images from point 1, analyse the waveforms in terms of voltage levels:

    (a) using the graticule, read out the approximate value of the gate voltage v_G of each of the four transistors which was applied to turn on a particular transistor;

    (b) which of the two voltages can be directly linked to the supply voltage of the gate drivers (see Fig. 3 and step 3.1/8)?

    (c) justify the values of the other two voltages considering:

    - what exactly is the controlling quantity for an IGBT (leaving aside the issue of charge, see report on Ex. 4[A] or e.g. Manual 4[A], Ref. A, Fig. 8.43),

- voltage waveforms of bridge middle points recorded in step 3.3/1: $v_{LM} = v_{E(LH)}$ and $v_{RM} = v_{E(RH)}$;

(d) considering your conclusions from point (c), is the role of the gate drivers U_2 and U_3 only to repeat pulse waves fed to their inputs (see Section 3.1, Circuit description), or do they also have any other task to fulfil?

Power circuit

4. Analyse the output voltage waveform of the full-bridge DC/DC converter at the duty cycle of $D_{GRL} = D_{GRL,ini}$:

   (a) gather the oscilloscope images:

   - of the middle point voltages v_{LM} and v_{RM}, registered in step 3.3/1,

   - of the output (motor armature) voltage u_{arm}, registered in step 3.3/2;

   (b) from the oscilloscope images, read out the values of the high and the low levels of each of the above waveforms and on this basis, calculate the amplitude (peak-to-peak value) of each of them, $v_{LM(pp)}$, $v_{RM(pp)}$ and $u_{arm(pp)}$;

   (c) link the output voltage value u_{arm} in each of the two subintervals of circuit operation to the voltages v_{LM} and v_{RM}.

5. * Analyse current waveforms of the bridge switches:

   (a) on a single page, gather the current waveforms recorded at $D_{GRL} = D_{GRL,ini}$:

   - the output current i_{arm} <u>for the above duty ratio</u>, recorded in step 3.4/6,

   - currents of the four switches of the bridge i_{RL}, i_{RH}, i_{LL} and i_{LH}, recorded in step 3.4/7;

   (b) justify the waveforms of the i_{RL}, i_{RH}, i_{LL} and i_{LH} currents referring to the i_{arm} waveform as well as to the control voltage waveforms analysed in point 2;

   (c) considering current directions in Fig. 2, justify the direction (sign) of each of the currents as observed in the corresponding oscilloscope image;

   (d) which semiconductor devices are involved in the conduction of the output current i_{arm} in the case under investigation (see Ref. A, Sections 7-7 and 7-7-1)? in the oscilloscope image of current i_{arm}, mark the different time intervals and label them with symbols of conducting devices according to Fig. 2.

6. * Verify the matching between the converter and the motor:

   (a) based on the switching frequency f_s written down in step 3.3/7(b) and the parameters of the motor used as given in Section 3.1, determine the ratio of τ_o/T_s, where τ_o is the armature time constant (considering the armature as an RL load) and T_s is the converter switching period;

   (b) state whether the converter meets the matching condition with respect to the motor, i.e. its switching period is much less than the time in which an RL load current would reach a steady state:

$$T_s \ll 5\tau_o \tag{4.1}$$

   (c) how, if at all, is the conclusion from point (b) confirmed by the waveforms of the output current i_{arm}?

Conversion characteristic

7. In a table, collect measurement results obtained for different values of the duty cycle (steps 3.3/8 and 10): D_{GRL}, $I_{arm(0)}$, $u_{arm(av)}$ or $v_{LM(av)}$ and $v_{RM(av)}$, N_{hrev} and the direction of rotation (using symbols ↻/↺ or acronyms CW/CCW to denote "clockwise" or "counterclockwise," respectively). For the direction of rotation, observations for low speeds should be extended to the other measurement points coming from step 3.3/8 or from step 3.3/10, respectively.

8. [TDS224]   Based on measured average values of the voltages $v_{LM(av)}$ and $v_{RM(av)}$, calculate for each measurement point the average value of the armature voltage $u_{arm(av)}$ in accordance with Fig. 2, i.e. including <u>accordance with this voltage direction</u> in this figure.

9. Based on measurement results, using the value of the input voltage U_i written down in step 3.3/7 (include its value in the report), for each value of the duty cycle D_{GRL}, calculate and add to the table:

   (a) the relative average output voltage $u_{o(av)r}$, from its definition (2.5);

   (b) the relative average output voltage for an ideal converter $u_{o(av)r,id}$, from Eq. (2.6).

10. Analyse the conversion characteristic of the converter:

   (a) plot <u>in one graph</u> the voltage conversion characteristics: the one determined experimentally for the investigated converter $u_{o(av)r} = f(D_{GRL})$ and the theoretical one for an ideal converter $u_{o(av)r,id} = f(D_{GRL})$;

   (b) what is the nature of the experimental and the theoretical relationships?

   (c) how, if at all, do these two characteristics differ quantitatively (in terms of the values exhibited)? is this in line with expectations (see Section 2.2.c)?

4.2.   Armature control of a DC motor

Elaboration of measurement results

1. Based on measurement results, for each value of the duty cycle D_{GRL}, calculate and add to the table:

    (a) motor rotational speed n, based on Eq. (3.1), using the switching frequency value written down in step 3.3/7, except that if the controller program indicated $N_{hrev} = 0$, then this means $n = 0$;

    (b) motor angular velocity ω, based on Eq. (2.1), taking into account that this is a vector quantity, so its value has a sign corresponding to the direction of rotation; assume that the z axis points towards the observer and therefore, assign the "+" sign to the counterclockwise direction;

    (c) armature average electromotive force $e_{arm(av)}$, based on Eq. (13-12) and using the motor data given in Section 3.1;

    (d) converter average output power P_o, assuming a triangular current waveform and therefore using Eq. (2.7);

    (e) * (average) internal mechanical power of the motor $P'_{mec(av)}$, using Eqs. (13-4) and (13-6), assuming that $\omega = $ const and $e_{arm} = $ const $ = e_{arm(av)}$, resulting in

    $$P'_{mec(av)} = P_{el} = (e_{arm} i_{arm})_{av} = e_{arm(av)} \cdot (i_{arm})_{av} = e_{arm(av)} \cdot I_{arm(0)} \tag{4.2}$$

    (f) * (DC component of) electromagnetic torque of the motor $T_{em(0)}$, based on Eq. (13-5) (this is of course impossible for $\omega = 0$, so such points are to be skipped);

    (g) * total equivalent coefficient of friction B_{eq}, based on Eq. (2.12) re-written for idling, as the engine was not loaded with any external torque, i.e. $T_{WL} = 0$.

Rotational speed control

2. Analyse the regulation characteristic of the motor under investigation:

    (a) plot the regulation characteristic of idle speed with armature control, i.e. $n = f(u_{arm(av)})$ at Φ_f = const (since a permanent magnet motor was used) and $T_{WL} = $ const $ = 0$ (since the engine was not loaded), while placing characteristics for both directions of rotation in one graph, but as two separate curves;

    (b) what is the nature of the relationship plotted? does it agree with theoretical predictions (see Section 2.2.e)?

3. Analyse the armature voltage and current waveforms for different control conditions:

    (a) on a single page, gather oscilloscope images of armature voltage u_{arm} and current i_{arm} recorded in steps 3.4/1 and 6 (place each current image next to the corresponding voltage one):

        ▪ for the initial duty cycle $D_{GRL,ini}$,

        ▪ for a similar rotational speed in the opposite direction,

        ▪ * for a different rotational speed in the same direction.

    (b) link the average values of the output voltage $u_{arm(av)}$ to the respective waveforms (see Ref. A, Sections 7-7 and 7-7-1);

    (c) in what way had the armature voltage waveform u_{arm} to be changed in order to obtain motor rotation at the same speed in the opposite direction? how did this change affect the DC component of the armature current $I_{arm(0)}$ (link numerical data to I_{arm} current waveforms) and is this consistent with theoretical predictions (see Section 2.2.d)?

(d) based on the steady state torque equation (2.12) and a suitable relationship linking torque with current (see Ref. B, Section 13-3), justify why it was the very change in the current observed in point (c) that was required to reverse the direction of rotation (and thus the sign of the angular velocity);

(e) * re-apply the reasoning of points (c)—(d) to the case where the rotational speed of the motor was changed without changing the direction of rotation.

Motor constants

4. Determine the relation of electromotive force to angular velocity:

   (a) plot armature electromotive force e_{arm} as a function of motor angular velocity ω (a single curve for both directions of rotation);

   (b) determine the nature of this relationship and state whether it agrees with theoretical predictions (see Ref. B, Section 13-3);

   (c) on the graph, using an appropriate spreadsheet function, display the linear regression line for the measured relationship together with its equation (LibreOffice: double-click the graph to enter the editing mode, then select *Insert ▸ Trend Lines* from the menu, choose *Linear* as the type and check *Show equation*); change the number format of the displayed regression line coefficients to get an accuracy of three significant digits (LibreOffice: select the equation by clicking on it, press the *Format Selection* (Calc) button in the toolbar and go to the *Numbers* tab);

   (d) assuming that relationship (13-11) holds, from the regression line equation shown, read out the value of the voltage constant k_E of the motor under investigation.

5. * Determine the relation of torque to armature current:

   (a) plot the DC component of the electromagnetic torque $T_{em(0)}$ as a function of the DC component of the armature current $I_{arm(0)}$ (one curve for both directions of rotation);

   (b) determine the nature of relationships and state whether it agrees with theoretical predictions (see Ref. B, Section 13-3);

   (c) on the graph, using an appropriate spreadsheet function, display the linear regression line for the measured relationship together with its equation as in point 4(c); it may be necessary to remove points from the graph that correspond to very low speeds if they are clearly located far from a straight line;

   (d) assuming that relationship (13-10) holds, from the regression line equation shown, read out the value of the torque constant k_T;

   (e) is it possible (bearing measurement uncertainty in mind) to state that experimental results confirm the relationship (13-7)?

Power conversion

6. * Analyse the coefficient of friction:

   (a) plot the equivalent coefficient of friction B_{eq} as a function of angular velocity ω (two separate curves in one drawing for the two directions of rotation);

   (b) describe the observed relationship;

   (c) from the graph, read out the approximate value of $B_{eq(min)}$ which the coefficient of friction tends to.

7. * Obtain theoretical control characteristics of average power:

   The calculations should be performed for each measurement point and, if necessary, also for additional duty cycle values so that in step 8(a), a smooth curve is obtained in the full duty cycle range from 0 to 1.

(a) calculate the theoretical average output power $P_{o(theo,RL)}$ for an ideal (lossless) converter with an RL load, based on Eq. (2.9) and considering that motor armature is the receiver, hence $R_o = R_{arm}$;

(b) calculate the theoretical average output power $P_{(theo,RLE)}$ for an ideal converter with a real RLE load representing an idling DC motor, based on Eq. (2.22) and using the values of k_E, k_T and $B_{eq(min)}$ determined so far and the motor data given in Section 3.1.

Collect your results in a new table or add them to the one created previously.

8. Analyse the idling state control characteristic of average power:

(a) plot (* in a single graph, adjusting its scale to the range of values of P_o and $P_{o(theo,RLE)}$ and not that of $P_{o(theo,RL)}$) the control characteristics of average power:

- the one determined experimentally $P_o = f(D_{GRL})$,

- * the theoretical one for an RL load $P_{o(theo,RL)} = f(D_{GRL})$,

- * the theoretical one for an RLE load $P_{o(theo,RLE)} = f(D_{GRL})$;

(b) describe the nature of the relationship obtained experimentally;

(c) state whether this character is consistent with the one predicted with the analysis carried out in Section 2.2.e;

(d) * compare the characteristic determined experimentally to the theoretical ones:

- does the idling engine actually draw a power lower than could be delivered to an RL receiver with the same resistance (see Section 2.2.e)?

- considering Eq. (2.22), which has been applied, and motor parameter values substituted thereto [see point 7(b)], what may be the main reason for discrepancies between the experimental characteristic and the theoretical one for an RLE receiver (see Section 2.2.e)?

5. Expected Report Contents

Bridge converter operation

1. Oscilloscope images of gate potentials, clearly labelled, as well as their analysis in respect of the switch control scheme applied, according to steps 4.1/1—3
(i.e., 3 oscilloscope images of paired v_G potentials)

2. Oscilloscope images of quantities related to the output diagonal of the bridge, levels read out from them and links established between them, according to step 4.1/4
(i.e., v_{LM}, v_{RM} and u_{arm} waveforms)

3. * Oscilloscope images of armature current and switch currents at the same duty cycle as well as their analysis in respect of waveform shape, direction and flow loop, according to step 4.1/5
(i.e., i_{arm}, i_{RL}, i_{RH}, i_{LL} and i_{LH} waveforms recorded for $D_{GRL} = D_{GRL,ini}$)

4. * Analysis of bridge switching frequency selection in respect of coupling with the motor used, according to step 4.1/6

5. Table containing measurement and calculation results, citing the formulae used, as well as the input voltage value measured, according to steps 4.1/7—8

6. Voltage control characteristic, the experimental one and the theoretical one for the ideal converter, with comparative analysis, according to step 4.1/9
[i.e., $u_{o(av)r} = f(D_{GRL})$ and $u_{o(av)r,id} = f(D)$ curves in one plot]

Armature control of a DC motor

7. Result additions to the table, citing the formulae used, according to step 4.2/1

8. Idle state armature control characteristic of rotational speed and its analysis, according to step 4.2/2
[i.e., $n = f(u_{arm(av)})$ plot]

9. Oscilloscope images of armature voltage and current for different control conditions and an analysis of differences between these cases, according to step 4.2/3

[i.e., u_arm and i_arm waveforms for $D_\text{GRL} = D_\text{GRL,ini}$ and the same rotational speed in the opposite direction (* and for a different rotational speed in the same direction)]

10. Graphical presentation and analysis of relationships between electrical and mechanical quantities, according to step 4.2/4 (* and 5)
{i.e., $e_\text{arm} = f(\omega)$ [* and $T_\text{em(0)} = f(I_\text{arm(0)})$] plot(s), each with a linear regression curve displayed, its equation shown and the obtained value of the respective motor constant}

11. * Coefficient of friction characteristic and its analysis, according to step 4.2/6
[i.e., $B_\text{eq} = f(\omega)$ plot and the value of $B_\text{eq(min)}$ read out from it]

12. * Table (or addition to the one created earlier) containing the theoretical average output power for two load types, according to step 4.2/7
(i.e., a set of values of $P_\text{o(theo,RL)}$ and $P_\text{o(theo,RLE)}$ for varying D)

13. Idling state control characteristic of average power, an experimental one (* and theoretical ones for an ideal converter with an RL load and with a DC motor as an RLE load) with an analysis in respect of accordance with theoretical predictions, according to step 4.2/8
[i.e., $P_\text{o} = f(D_\text{GRL})$ relationship plot (* three curves in a single graph)]

6. Required Knowledge

6.1. Prerequisites

- Full-bridge DC/DC converter: electrical schematic, bipolar switch control scheme, devices conducting in different sub-periods of operation
  (see Ref. A)

6.2. Test scope

1. Full-bridge DC/DC converter: electrical schematic, bipolar switch control scheme. Devices conducting in different sub-periods of operation at different average output current levels. Waveforms of middle point potentials and output voltage. Average output voltage and its characteristic as a function of the duty cycle (formula, plot).
   (see Ref. A; Sub-chapter 2.2)

2. Control of a permanent-magnet DC motor with a full-bridge DC/DC converter: average output power characteristic as a function of the duty cycle (without formulae), rotational speed characteristic as a function of average armature voltage (including the theoretical formula), direction of rotation.
   (see Sub-chapter 2.2, report)

7. References

[1]   <u>Mo</u>han N., Undeland T. M., Robbins W. P.: *Power Electronics: Converters, Applications, and Design.* 3rd Ed. Wiley, 2003. ISBN 0-471-22693-9.