Lecture Book
Drive Systems

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Topics on Electrical Engineering

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Part I.

Laboratory Experiments

Chapter 1

Measurement Board

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Learning Outcomes

- Familiarise yourself with the equipment and software.
- Understanding the relationship between phase-to-phase voltages, phase voltages, and hall effect sensor signals.

Requirements None

1.1. Measurement Boards

As a famous scientist and a Victorian engineer once said,

> *To measure is to know*[1].

[1] *William Thomson, 1st Baron Kelvin*

Following this enlightening idea, we shall look at our equipment and get a good understanding of them prior to our experiments which are covered in Parts 2, 3 and 4, focusing on control methods for BLDC and Permanent Magnet Synchronous Motor (PMSM). To be able to conduct these experiments and retrieve data we can do data manipulations in, you will be provided a measurement kit which will allow you to measure voltage and current values during experiments for the BLDC and PMSM drive systems. There are two (2) circuits to be used in the experiments which are as follows:

1. Motor side measurement board, which can be seen in **Fig.** 1.1a, and

2. Load side measurement board, which is shown in **Fig.** 1.1b.

The former circuit will be connected to the CY8CKIT-037 motor driver board kit[2], and the latter will be connected to the load motor. Both circuits are custom made for this lab for an easier time for measuring currents and voltages from the inverter.

[2] If it is not connect, please let the lab supervisor know.

1.1.1. Motor Side Measurement Board

The circuit used in motor side measurement can be seen in **Fig.** 1.1a.

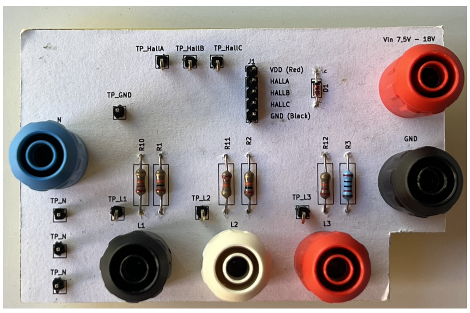
As can be seen, during normal operation, the board is supplied by a voltage source with 5 V. This can be achieved from a standard laboratory Direct Current (DC) power supply or connecting it to the 5 V of the Motor control kit which we will look at in more detail in the next section.

The connector **<J2>** needs to be connected to the inverter side of the Motor control kit, named connector **<J9>**, while **<J3>** allows the connection to the motor terminals.

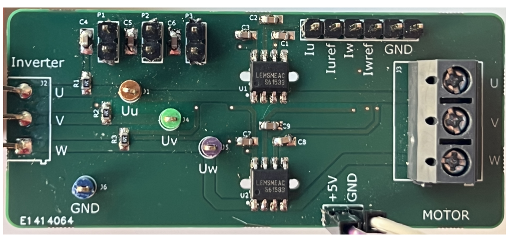
> Please respect the phase sequence as explained in each exercise for correct operation of the motor.

Jumpers **<P1>**, **<P2>**, and **<P3>** will be connected without the need of extra warning. The phase or phase-to-phase voltage measurements are available at connectors **<J1>**, **<J4>**, and **<J5>**, respectively.

> The **GND** of the measurement kit is also the **GND** of the Motor control kit which is connected to the negative terminal of the DC-link.



(a) Load side measurement boards



(b) Motor side measurement boards

Figure 1.1.: Measurement boards for use in the laboratory sessions.

> If jumpers <P1>, <P2>, and <P3> are opened, a RC low-pass filter with a cut-off frequency of 1 kHz is created allowing an easy (even if coarse) representation of the fundamental component of the phase voltages.

For the measurement of rotor position, two (2) Hall-based current sensors, (**U1**, **U2**) of the type GO 10-SME by the company LEM, are provided. Output signals, including bias voltages, are available at P4. The sensors sensitivity is 80 mV A^{-1}. All students are invited to download the data-sheet to understand the working principle.

The measurement boards can be seen in figure X. On the left hand size the board connected to the Driver circuit can be seen. This board is designed to access voltage and signal waveform along with the waveform seen by the Hall sensors[3].

[3]A sensor which produces a voltage proportional to one axial component of the magnetic field vector $\vec{B}$ using the Hall effect

1.1.2. Load Side Measurement Board

The circuit used in load side measurement can be seen in **Fig.** 1.1b. The circuit comprises of a 3-phase input from the load, V_{in} for the Hall-effect sensors to operate, The pin connections (<J1>) to connect the load motor hall effect cables.

1.1.3. Motor-Load System

The drive system investigated as part of this laboratory experiments consists of a motor test bench equipped with two (2) BLDC machines which are connected by their shafts. One of them acts as a motor where the electricity fed to it will make the rotor spin. The second one shall act as a load where the connected shaft will transmit mechanical power from the motor to load. This in turn will start spin the rotor and these rotors with PMs will start inducing electricity in the stator coils[4]. The configuration is seen in **Fig.** 1.2.

[4]As you can see, the second motor will act as a generator.

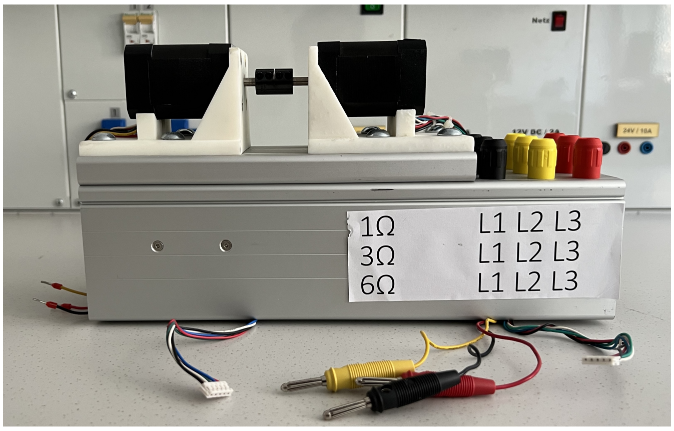


Figure 1.2.: The motor-load configuration with its winding in display. The connection is done in star on the load side for measurement purposes.

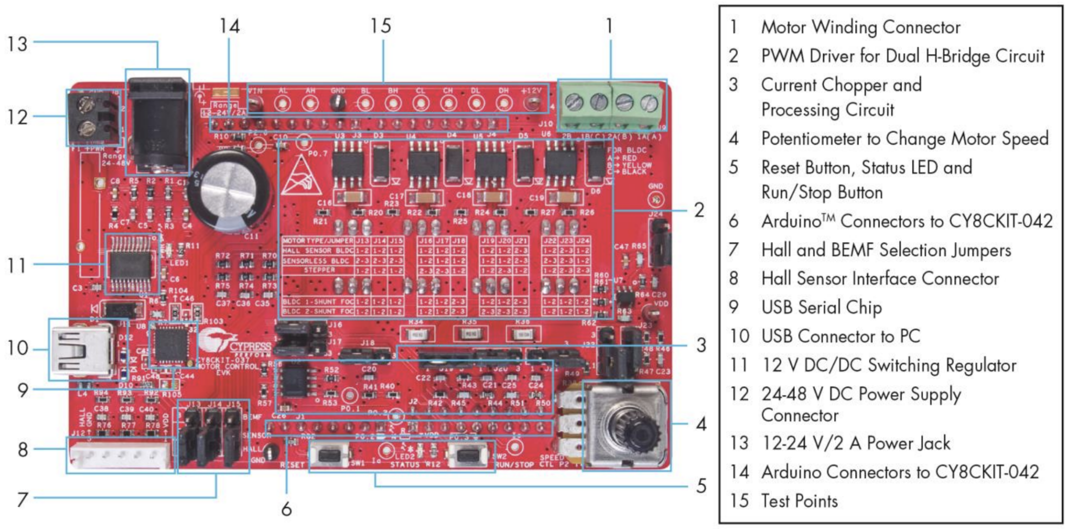


Figure 1.3.: A detailed diagram of the CY8CKIT motor driver board.

The drive which is acting as a motor is driven by the motor control evaluation kit CY8CKIT-037 from Cypress which you can access its documentation web-page from here . Let's look at this board in more detail.

1.2. CY8CKIT-037 Motor Control Evaluation Kit

CY8CKIT is an ARM-Cortex based embedded system on a chip (SoC) device designed for use in motor control of electric machines requiring solid-state commutation[5]. The motor control system can be separated into its two (2) primary parts:

[5] Anything which requires transistor or electronic components to rotate the rotor

1. the driver board, and
2. the controller board.

This device is designed to create control techniques for three (3) motors:

- PMSM motors,
- Stepper motors, and
- BLDC motors.

The board itself and its constituent parts can be seen in **Fig.** 1.3. To describe this board in a bit more detail, The CY8CKIT-037 Motor Control EVK is the driver board, which contains the required physical infrastructure needed to drive a motor such as; DC/DC power circuit, dual H-bridge circuit, motor current and bus voltage sampling and processing circuit, protection circuit, user configuration circuit, and connectors to the controller board.

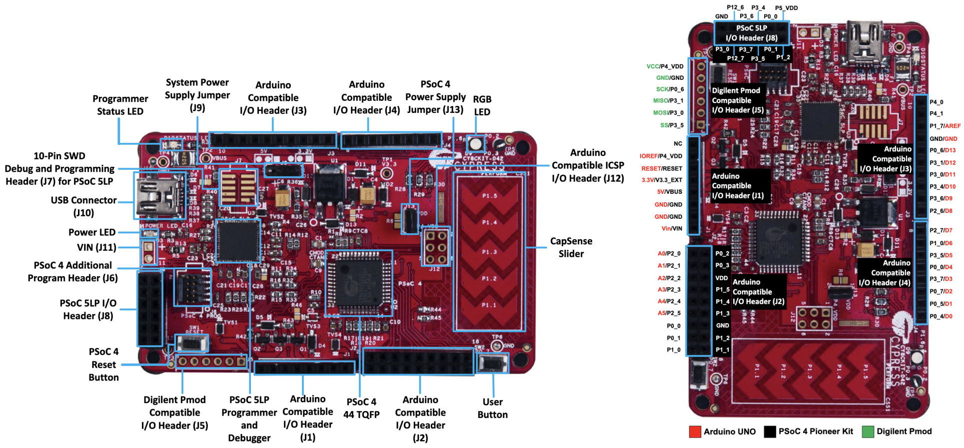


Figure 1.4.: Accessible I/O ports of CY8CKIT-042 board.

The way the board operates can be summarised as follows:

1. the controller board receives the signals,
2. implements the proper algorithm to process the received signals, and
3. generates control signals to the driver board to run the motor.

the EVK board and its general description of all its individual components can be seen in **Fig.** 1.3.

> For more information on this board (you will need it) please click here . The documentation is well done and covers almost all the required information you need to get a good understanding of the equipment.

To be clear, CY8CKIT-037 is the driver board. We also need to have a board to control the driver and that is where CY8CKIT-042 kit comes to play.

1.3. CY8CKIT-042 Pioneer Kit

The PSoC 4 Pioneer Kit consists of the following blocks:

- PSoC 4
- PSoC 5LP
- Power supply system
- Programming interfaces
- Arduino compatible headers
- Digilent Pmod compatible header
- PSoC 5LP GPIO header
- CapSense slider
- Pioneer board LEDs
- Push buttons (Reset and User button

A detailed description of all its headers and ports can be seen in **Fig.** 1.4 To establish a complete motor control system, the programmable system on chip (PSoC) 4 Pioneer Kit CY8CKIT-042 from Cypress needs to be connected. This can be seen in **Fig.** 1.5

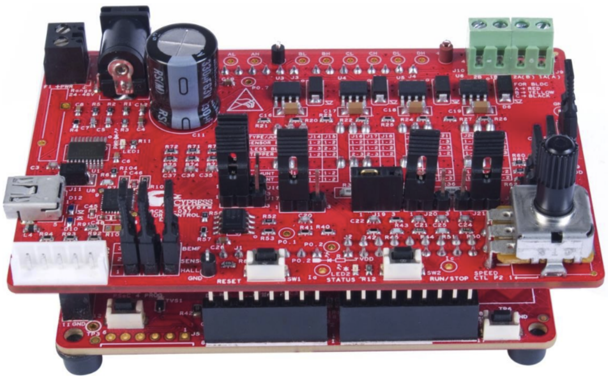


Figure 1.5.: The connected boards of CY8CKIT-037 being on top and CY8CKIT-042 on bottom.

1.4. Preparing the Setup

Prior to attending this lab session it is worthwhile to have a brief look at the datasheet of the motor you will be working with, which you can find it here . The motor you will be working with is a BLDC motor with all the relevant information provided in the datasheet.

> It is important to **NOT** connect the motor phases to the inverter as they shall be connected to the motor side measurement board.

the motor hall effect wires will be connected to the CY8KIT-037 Driver board at port, with a sequence of `<J13>`, `<J14>`, `<J15>`, `<J16>`. To get a better understanding of the board you, please look at the manual here .

The hall sensors shall be connected to connector J12 with proper orientation. Signals of Hall sensors, will be available on headers `<J13>`, `<J14>`, `<J15>`. For further details, see the manuals of the motor and CY8CKIT-037.

1.5. Required Measurements and Assessments

Once the connections have been done, and double checked it is time to do some measurements. Please conduct the following tests on the motor:

1. Measure the phase-to-phase voltage (V_{bc}) which are the yellow, black wires of the motor respectively.

2. Measure the phase-to-neutral voltage V_a. To this purpose use the provided measuring board or realise a three-phase resistive load with 10 kΩ resistors star connected in order to realise the a virtual neutral point

3. Measure the Hall-voltage H_1.

Once the measurements have been concluded, please do some analysis on the data and answer the following question in reasonable detail.

1. What does the phase relationship between V_{bc} and H_1 mean?

2. Which phase relationship has the flux of phase A?

3. Explain the phase relationship between phase voltage V_a and H_1

4. Plot the diagram of the aforementioned signals.

1.6. A Digression: Describing Phases

As we know[6], electricity distribution comes in three (3) phases for commercial applications. The naming of these phases are generally left for the countries and their engineering bodies to standardise. However when it comes to electrical machine design there are two (2) major governing bodies which dictate what standard it should conform to:

[6] hopefully . . .

1. For the European market, the standard **IEC 60034-8 Rotating electrical machines - Part 8: Terminal markings and direction of rotation** [1] is used[7],

2. For the American market, the NEMA standard, **Terminal Markings and Connections Three Phase Motors-single speed** is used.

[7] As with everything continental, Deutschen Instituts für Normung (DIN) standards were used previously which IEC re-implemented and revised

For example, an electrical machine compliant to the **IEC 60034-8** will ensure clockwise rotation of the drive shaft for positive electrical phase sequence U-V-W.

As an example are the three (3) aforementioned standards. The DIN standard is mentioned as there are still a lot of electrical machines which were designed conforming to DIN.

	DIN	NEMA	IEC
Input Phases	R, S, T	L1, L2, L3	U, V, W
Motor Terminal In	U, V, W	T1, T2, T3	U1, V1, W1
Motor Terminal Out	X, Y, Z	T4, T5, T6	U2, V2, W2

Table 1.1.: Different types of standards used in describing the electric machine terminal and phase connections.

Now the main question to ask.

Which standard do I follow?

Living in an international time requires more attention to certain descriptors as it is not that hard to buy an equipment across the pond and use it here[8]. The important thing to do is always read the data sheet the equipment comes in as there are other things to worry about as well such as:

[8]For completeness sake, the terms (A, B, C) and (R, B, Y) are also used

- Type of connections (wye, delta)
- Operating frequency (i.e., 50 Hz, 60 Hz)
- Rated current, or
- Rated speed.

Chapter 2

BLDC Control with Sensors

Table of Contents

Learning Outcomes

- To develop a working understanding of the block-commutation technique for BLDC motors.
- Block commutation is applied with 120° commutation angle and is also based on the angular position measured by the Hall sensors.

Requirements Review the theory of the block-commutation for BLDC and read **Section 5.3** on the Motor kit user manual which can be found here .

2.1. Preliminary Information

2.1.1. Commutation Technique

Three-phase BLDC motors have become ever more popular as years went on with being used in numerous applications such as power tools, drivers, sanders, grinders and saws [2]. A method which is simple, yet powerful, is block commutation using Hall sensors which has been the dominant control method for three-phase BLDC motors in power tool applications and this lab session[1], you will be experimenting with this technique.

[1]what a coincidence . . .

Block commutation of three-phase BLDC motors is an electronic commutation scheme also known as trapezoidal commutation [3], six-step commutation or 120° commutation. In this control method, each phase conducts for 120°[2] during the positive and negative half of a BEMF cycle, and is **OFF** or un-energised for the remainder of the electrical cycle.

[2]electrical degrees of course

This algorithm requires rotor position information for every 60°, and normally three Hall sensors are used to provide the rotor position feedback. Having six (6) sampling points results in a trapezoidal shape.

2.1.2. Motor Design

A BLDC Motor is a rotating electric motor consisting of stator armature windings and rotor containing permanent magnets. This is in contrast to a conventional brushed DC motor the stator is made up of permanent magnets and rotor consists of armature windings.

The conventional DC motor commutes itself with the use of a mechanical commutator whereas a BLDC motor needs electronic commutation for the direction control of current through the windings. Typically BLDC motors have three (3) phase windings that are wound in either **star** or **delta** fashion and need a 3-phase inverter bridge for the electronic commutation.

In BLDC motors the phase windings are distributed in trapezoidal fashion to generate the trapezoidal BEMF waveform. The commutation technique generally used is trapezoidal or called block commutation where only two (2) phases will be conducting at any given point of time. Their BEMF waveforms can be seen in

Figure 2.1.: A standard out-runner rotor BLDC motor. Here the rotor which contains PM is spinning outside whereas the stator is inside [4].

An alternative way of commutating the motor is called sinusoidal commutation in which all the three phases will be conducting at any given point of time. PMSM motors also interchangeably called as BLDC motors which have the windings distributed in sinusoidal fashion suited for this sinusoidal type of commutation.

The torque generated by PMSM motors is smooth as compared to BLDC motors in which torque will have more ripples. But the peak torque developed by PMSM motors is less as compared to BLDC motors.

The trapezoidal commutation method is the simplest way to control BLDC motors and easy to implement the control aspects of it. For proper commutation and for motor rotation, the rotor position information is paramount. Only with the help of rotor position information, the electronic switches in the inverter bridge will be switched **ON** and **OFF** at the correct order to ensure proper

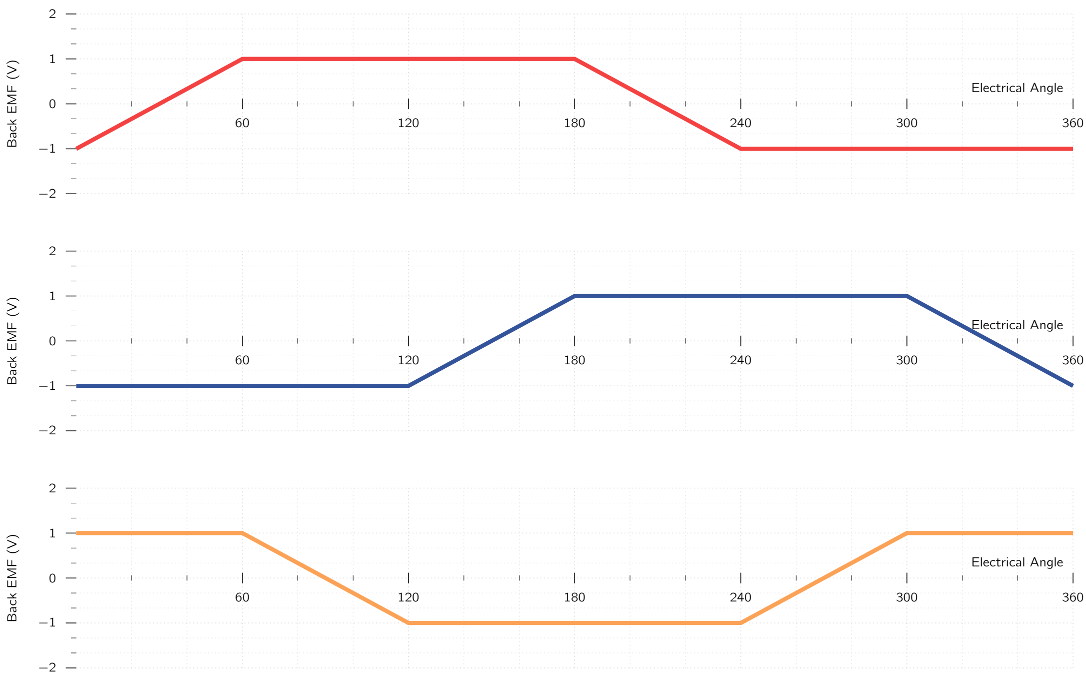


Figure 2.2.: The three-phase BEMF trapezoidal waveforms of a BLDC.

direction of current flow in respective coils.

To achieve the correct detection of rotor position Hall effect sensors are used in general as position sensors for trapezoidal commutation, with an example shown in **Fig.** 2.3. Each hall sensor is typically placed mechanically 120° apart and produces a positive step voltage whenever it faces the North Pole of the rotor.

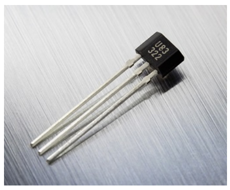


Figure 2.3.: A hall-effect sensor [5].

2.2. The Experiment

2.2.1. Configuration of the Hardware and Software

To get started with the experiment please adjust both CY8CKIT-037 and CY8KIT-042 according to the pictures presented in **Fig.** 4.1b and **Fig.** 4.1a, respectively. Select 5 V as the V_{DD} power at jumper `<J9>` on the CY8KIT-042, and always keep the USB cable connected to CY8KIT-042, as the device does not provide a 5 V converter. It gets the power directly from the USB port of the PC.

> For the CY8CKIT-037 board, please make sure all jumpers are connected correctly as per shown in **Fig.** 4.1b prior to plugging it to a computer or a power outlet.

Once your equipment has been checked and deemed to be in correct form, please connect the motor-load setup with the motor side connecting to the output of the inverter measurement board, and the load side connected to the load measurement board correctly.

> Don't forget to connect the hall-effect sensor output of the motor to CY8CKIT-037. IF you are confused about which alignment it should be on, consult the database of the motor.

Following this step, you can start working on the code.

Start by loading `Sensored BLDC Motor Control.cywrk` project into PSoC Creator IDE workspace.

Once the **Sensored BLDC Motor Control** code example loaded into PSoC Creator IDE, you must firs compile it. You can do this via:

1. Build > Build BLDC Motor Control

   If successful, continue on with,

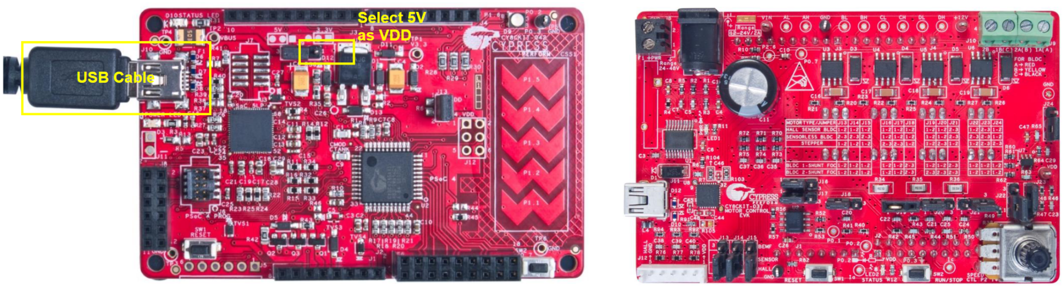
2. Debug > Program

Once the program has been loaded to the device, ensure the USB cable from the CY8CKIT-042 is connected to the PC in this step.

> otherwise, the motor will not rotate.

Press the **SW2** button to start motor rotation. Rotate the potentiometer clockwise to increase the motor speed or vice versa. If the motor does **NOT** rotate and you observe LED2 blinking, it indicates that an error has occurred. If so, ensure that step 1 through step 5 have been executed correctly. Then press the Reset button and press the SW2 button again. If LED2 still blinks, there must be a problem in the hardware or software.

> This problem could like be caused by the wrong jumper configuration of the CY8CKIT-037 which should be revisited.



(a) Configuration for CY8CKIT-042

(b) Configuration for CY8CKIT-037

Figure 2.4.: The boards which will be used in this experiment. Make sure they are connected once the proper configuration has been done on them with CY8CKIT-042 being on the bottom and CY8CKIT-037 being on top.

2.2.2. Embedded Code Configuration

The following is a code example which can be changed to rotate different sensored BLDC motors containing different motor parameters. Some parameters in the project firmware need to be modified according to specific motor characteristics and functional requirements[3]. These parameters are defined as a **struct** in `motor.h`.

[3] This information can be found in the motor datasheet.

C.R. 1

```c
typedefstruct
{
    uint8 Dir;           /* Direction                     */
    uint16 speedRpm;     /* Actural motor speed           */
    uint16 speedRpmRef;  /* motor speed command value     */
    uint16 kp;           /* Proportional coeffient of PID */
    uint16 ki;           /* Integral coeffient of PID     */
    uint16 maxSpeedRpm;  /* Motor parameters              */
    uint16 minSpeedRpm;  /* Motor parameters              */
    uint8 polePairs;     /* Pole Pairs                    */
    uint8 maxCurr;       /* Over current threshold        */
}UI_DATA;
```

The struct variable is in `motor.c` and is initialised in `motor.c` by function `Init_UI_FW`.

C.R. 2

```c
UI_DATA UI_Data;

void Init_UI_FW(void)
{
    /* Setting UI Initial parameter*/
    UI_Data.Dir         = CLOCK_WISE;
    UI_Data.maxSpeedRpm = 4000;
    UI_Data.minSpeedRpm = 500;
    UI_Data.speedRpmRef = 1000;
    UI_Data.polePairs   = 4;
    UI_Data.maxCurr     = MAX_CURR_MEDIUM;
    UI_Data.kp          = 500;
    UI_Data.ki          = 50;
}
```

The `Init_UI_FW` function initialises the parameters before the motor begins its operation, and the initialising value is specific to the motor used in the experiment.

> To use a different motor and have different functional requirements such as RPM or direction, you need to change the initialising value in this function.

2.2.3. Simulation Framework

To aid in your experiment and expand your understanding, MATLAB scripts and a SIMULINK model has been provided to help the analysis of measurement results as well as to be used in the report for comparison purposes.

The following files can be downloaded from GitHub:

`initBCPWM.m` An initialisation file to be run before the SIMULINK model. To do proper comparison, please configure variables as you see necessary. Some examples are:

electrical frequency, commutation strategy and duty cycle of PWM

C.R. 3

matlab

```matlab
% VARIABLES ---------------------------------------------------------------
% Selection of switching commutation strategy 120/180
% Set 1 = 120 degree commutation
% Set 0 = 180 degree commutation
BLDC_120_180   = 1;

% Duty cycle:
% set the PWM duty cycle to control the output voltage/current
duty_cycle     = 0.6;

% Fundamental frequency:
% set the electrical frequency corresponding to measurements
f_fundamental  = 265;           % Electrical frequency          (Hz)
f_pwm          = 20000;         % Sampling/Switching frequency  (Hz)

% Solver step size
sover_max_step = 1e-6;          % Solver step size

Vdc            = 24;            % DC-link voltage               (V)

% MOSFET PARAMETERS -------------------------------------------------------

Ron            = 5e-3;          % MOSFET On-Resistance          (Ohm)
Rd             = 70e-3;         % Revese Diode Resistance       (Ohm)
Vf             = 0.87;          % Reverse Diode forward Voltage (V)

% MOTOR PARAMETERs --------------------------------------------------------
%
% NOTE: Calculated for BLY172S-24V-4000, delta configuration.

p              = 4;             % Pole pairs                    (-)
Rs             = 3/2 * 0.8;     % Serial resistance (Delta)     (Ohm)
Ls             = 3/2 * 1.2e-3;  % Serial inductance (Delta)     (H)

% Back EMF Constant (rad.V/s)
Ke             = sqrt(2) * 3.35e-3 * 60 / 2 / pi / p;

```

C.R. 4 matlab

```matlab
% Based on the Commutation method choose a load angle
if BLDC_120_180 == 1
    load_angle=pi/3;        % for 120
else
    load_angle = pi/6;      % for 180
end
```

`modelBCPWM.slx` A SIMLINK model of motor and inverter implementing two (2) different commutation strategies; namely 120° and 180°. The major system can be seen in **Fig.** 3.2. Details

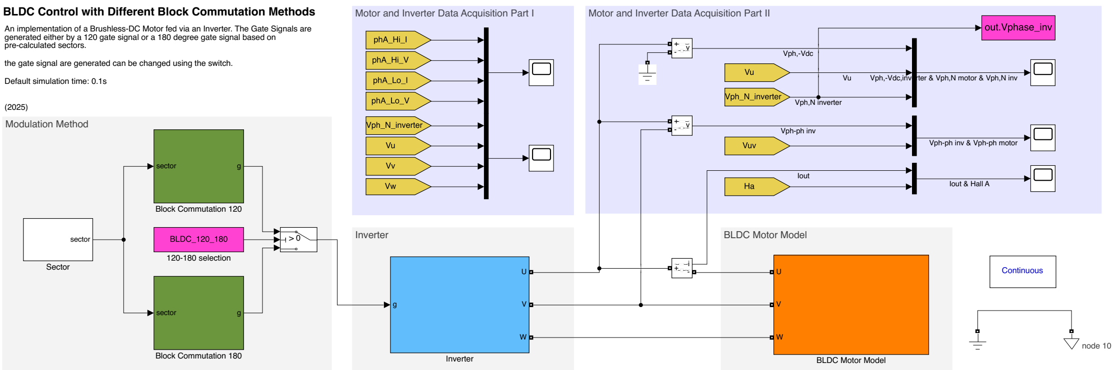


Figure 2.5.: The overview of the simulation of Commutation modulation of BLDC implemented in SIMULINK.

of its subsystem and its inner working can be seen in Appendix.

`do_sig_analysis.m` basic script to perform FFTs and low-pass filter of signals from simulations or oscilloscope measurements. The full code can be seen in Appendix.

`do_filter.m` low-pass filter function. Pass and stop band can be defined depending on needs. The full code can be seen in Appendix.

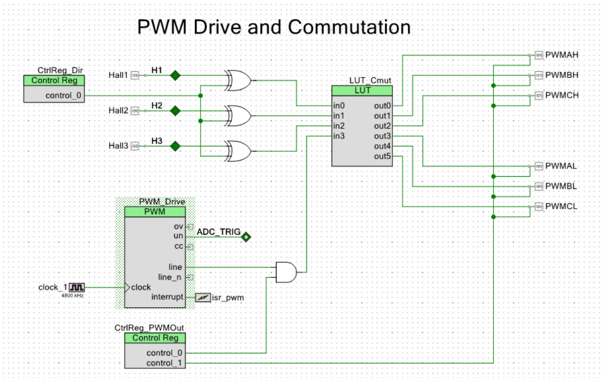
`importAgilentBin.m` function provided by Keysight to import data saved from DSOX oscilloscope series in binary (`.bin`) format. The full code can be seen in Appendix.

2.3. Required Measurements and Assessments

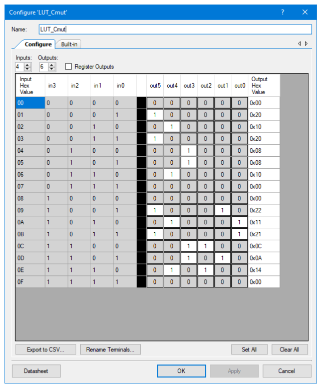
In this final part of the lab exercise, you will perform the following measurements and comparison with simulations:

1. Measure the high and low side gate signals of phase A (`<AH>` and `<AL>`) available at the test points on top side of CY8CKIT-037, under different speed conditions.

2. Measure `<AH>` and `<H1>` and `<H2>` Hall-sensor signals and comment on their phase relationship and calculate the angle difference.



(a) The top design of the Sensored BLDC control exercise.



(b) CY8CKIT-037 PSoC™ 4 Motor Control Evaluation Kit

Figure 2.6.: Development board for use in the experiment.

3. Analyse the look up table (LUT) in `TopDesign.cysch` (**Fig.** 2.6a) and shown in **Fig.** 2.6b which implements the 120° with PWM commutation strategy. Observe in particular the actuation of the high side switch.

4. Generate the time diagram explaining the commutation strategy and its implementation.

5. Compare the achieved results with the implementation in the simulation done in SIMULINK.

6. Measure the phase A voltage with respect to $-V_{dc}$. In this case $-V_{dc}$ is also connected to GND.

7. Measure the phase A current (i_a) using the provided measurement board on the motor side.

8. Measure the phase-to-phase BC voltage (v_{bc}) using either the math channel of the oscilloscope or post processing in MATLAB.

9. Calculate the FFTs and THD of the three (3) aforementioned points and compare them and discuss the results.

10. Repeat the measurements for at least three (3) different speeds:

    - 100 rpm,
    - 2000 rpm,
    - 4000 rpm.

11. Compare the results with the simulations in similar conditions and elaborate on the results.

12. Run further simulations in the following two (2) conditions:

    a) 120° with a duty-cycle of 1,

    b) 120° with a duty-cycle of 1.

13. Calculate FFTs and THD of phase and phase-to-phase voltages in the above simulation conditions and elaborate on their results.

A Detailed instruction on what is required for the report is given in Part 5.

Chapter 3

Sensorless BLDC Control

Table of Contents

Learning Outcomes

- To develop a working understanding of the block-commutation technique for BLDC motors.
- Work with sensorless control methods for BLDC motors and analyse its performance.

Requirements Review the theory for the technique for BLDC and read **Section 5.3** on the Motor kit user manual which can be found here .

3.1. Preliminary Information

3.1.1. Sensorless BLDC Control

There are different methods which we can use to control the BLDC motor. The simplest way is to use Hall position sensors. However, sensors increase cost and add reliability problems in motors operating in harsh environments where demands for sensor robustness are high. The increasing power of embedded computing, coupled with lower prices for power semiconductors and micro-controllers, has allowed more sophisticated methods of motor control. One popular technique is to use a BEMF signal, which is induced by revolving the rotor permanent magnet around the drive coils.

Most BLDC motors have a three-phase winding topology with a star connection. It is driven by energizing two phases simultaneously, while the other phase is kept afloat. The key to BLDC commutation is to sense the rotor position and then energize the phases that produce the maximum amount of torque. The rotor travels 60 electrical degrees at every commutation step. The appropriate stator current path is activated when the rotor is 120 degrees away from alignment with the corresponding stator magnetic field. It is then deactivated when the rotor is 60 degrees from alignment. The next circuit is activated and the process repeats.

The voltage polarity of BEMF crosses from positive to negative or from negative to positive (zero-crossing) between two commutations. Ideally, the zero-crossing of BEMF occurs at 30 electrical degrees after the last commutation and 30 electrical degrees prior to the next commutation. By measuring the zero-crossing of BEMF and the 30-degree time interval, the controller can perform the commutation without a position sensor.

3.2. The Experiment

3.2.1. Configuration of the Hardware and Software

To get started with the experiment please adjust both CY8CKIT-037 and CY8KIT-042 according to the pictures presented in **Fig.** 4.1b and **Fig.** 4.1a, respectively. Select 5 V as the V_{DD} power at jumper `<J9>` on the CY8KIT-042, and always keep the USB cable connected to CY8KIT-042, as the device does not provide a 5 V converter. It gets the power directly from the USB port of the PC.

> For the CY8CKIT-037 board, please make sure all jumpers are connected correctly as per shown in **Fig.** 4.1b prior to plugging it to a computer or a power outlet.

Once your equipment has been checked and deemed to be in correct form, please connect the motor-load setup with the motor side connecting to the output of the inverter measurement board, and the load side connected to the load measurement board correctly.

> Don't forget to connect the hall-effect sensor output of the motor to CY8CKIT-037. IF you are confused about which alignment it should be on, consult the database of the motor.

Following this step, you can start working on the code.

Start by loading `Sensored BLDC Motor Control.cywrk` project into PSoC Creator IDE workspace.

Once the **Sensored BLDC Motor Control** code example loaded into PSoC Creator IDE, you must firs compile it. You can do this via:

1. Build > Build BLDC Motor Control

   If successful, continue on with,

2. Debug > Program

Once the program has been loaded to the device, ensure the USB cable from the CY8CKIT-042 is connected to the PC in this step.

> otherwise, the motor will not rotate.

Press the **SW2** button to start motor rotation. Rotate the potentiometer clockwise to increase the motor speed or vice versa. If the motor does **NOT** rotate and you observe LED2 blinking, it indicates that an error has occurred. If so, ensure that step 1 through step 5 have been executed correctly. Then press the Reset button and press the SW2 button again. If LED2 still blinks, there must be a problem in the hardware or software.

> This problem could like be caused by the wrong jumper configuration of the CY8CKIT-037 which should be revisited.

3.2.2. Simulation Framework

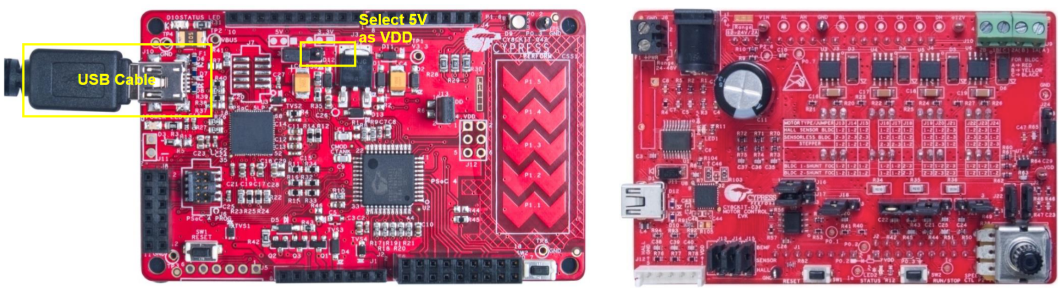
To aid in your experiment and expand your understanding, MATLAB scripts and a SIMULINK model has been provided to help the analysis of measurement results as well as to be used in the report for comparison purposes.

`initBCPWM.m` An initialisation file to be run before the SIMULINK model. To do proper comparison, please configure variables as you see necessary. Some examples are:

electrical frequency, commutation strategy and duty cycle of PWM

C.R. 1 matlab

```matlab
% VARIABLES -----------------------------------------------------------------
% Selection of switching commutation strategy 120/180
% Set 1 = 120 degree commutation
% Set 0 = 180 degree commutation
BLDC_120_180    = 1;
```



(a) Configuration for CY8CKIT-042

(b) Configuration for CY8CKIT-037

Figure 3.1.: The boards which will be used in this experiment. Make sure they are connected once the proper configuration has been done on them with CY8CKIT-042 being on the bottom and CY8CKIT-037 being on top.

C.R. 2

matlab

```matlab

% Duty cycle:
% set the PWM duty cycle to control the output voltage/current
duty_cycle     = 0.6;

% Fundamental frequency:
% set the electrical frequency corresponding to measurements
f_fundamental  = 265;           % Electrical frequency          (Hz)
f_pwm          = 20000;         % Sampling/Switching frequency  (Hz)

% Solver step size
sover_max_step = 1e-6;          % Solver step size

Vdc            = 24;            % DC-link voltage               (V)

% MOSFET PARAMETERS -------------------------------------------------------

Ron            = 5e-3;          % MOSFET On-Resistance          (Ohm)
Rd             = 70e-3;         % Revese Diode Resistance       (Ohm)
Vf             = 0.87;          % Reverse Diode forward Voltage (V)

% MOTOR PARAMETERs --------------------------------------------------------
%
% NOTE: Calculated for BLY172S-24V-4000, delta configuration.

p              = 4;             % Pole pairs                    (-)
Rs             = 3/2 * 0.8;     % Serial resistance (Delta)     (Ohm)
Ls             = 3/2 * 1.2e-3;  % Serial inductance (Delta)     (H)

% Back EMF Constant (rad.V/s)
Ke             = sqrt(2) * 3.35e-3 * 60 / 2 / pi / p;

% Based on the Commutation method choose a load angle
if BLDC_120_180 == 1
    load_angle=pi/3;        % for 120
else
    load_angle = pi/6;      % for 180
end
```

`modelBCPWM.slx` A SIMLINK model of motor and inverter implementing two (2) different commutation strategies; namely 120° and 180°. The major system can be seen in **Fig.** 3.2. Details of its subsystem and its inner working can be seen in Appendix.

`do_sig_analysis.m` basic script to perform FFTs and low-pass filter of signals from simulations or oscilloscope measurements. The full code can be seen in Appendix.

`do_filter.m` low-pass filter function. Pass and stop band can be defined depending on needs. The full code can be seen in Appendix.

`importAgilentBin.m` function provided by Keysight to import data saved from DSOX oscilloscope series in binary (`.bin`) format. The full code can be seen in Appendix.

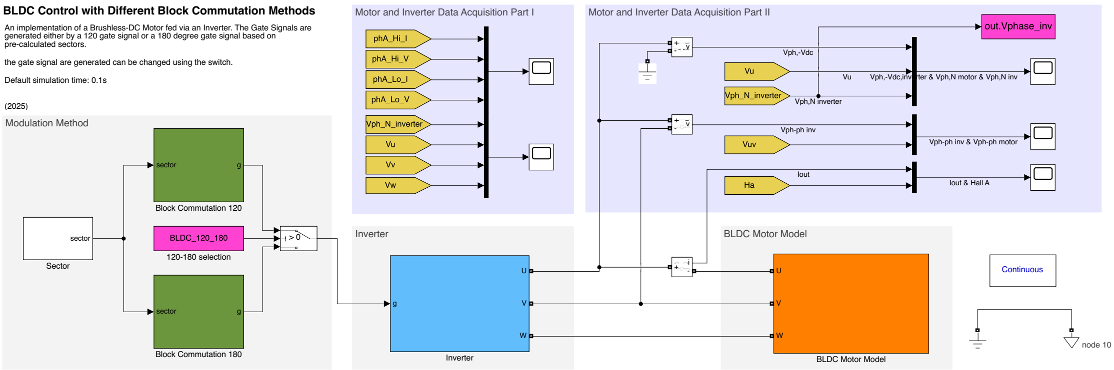


Figure 3.2.: The overview of the simulation of Commutation modulation of BLDC implemented in SIMULINK.

> The sensorless angle calculation algorithm is however not implemented and is left for the curious

3.3. Required Measurements and Assessments

In this final part of the lab exercise, you will perform the following measurements and comparison with simulations:

1. Measure the phase A voltage with respect to Udc, H1 Hall-sensor signal and current of phase A. Comment the phase relationship between these quantities. What conclusion can be drawn on the performance of the sen- sorless algorithm?
2. Generate time diagram explaining the commutation strategy and its im- plementation with particular regard to the back-EMF measurement time intervals
3. Compare the achieved results with the implementation in the simulation.
4. Measure the phase A voltage with respect to $-V_{\mathrm{dc}}$. In this case $-V_{\mathrm{dc}}$ is also connected to GND.
5. Measure the phase A current using the provided measurement board.
6. Measure the phase-to-phase BC voltage using the math channel of the oscilloscope (or post processing in MATLAB).
7. Calculate the FFTs and THD of phase A voltage, phase A current, phase-to-phase BC voltage and compare them
8. Repeat the measurements for at least three (3) different speeds:

- 100 rpm,
- 2000 rpm,
- 4000 rpm.

9. Compare the results with the simulations in similar conditions.

Chapter 4

Sensorless FOC of PMSM

Table of Contents

Learning Outcomes

- To develop a working understanding of the FOC method used in PMSM motors.

Requirements A review the basics of the FOC and have read the Section 5.5 in the manual shown here .

4.1. Preliminary Information

4.1.1. Field Oriented Control

The correct starting a PMSM correctly is one of the primary tasks in modern control systems. For us to be able to achieve this, we need to know the **exact position** of the rotor.

> If we don't know the rotor position, then we don't know which coils to activate. Without this information, it impossible to operate the motor.

For the case with **no absolute position** sensor, the simplest solution is to apply voltage to one of the phases and wait until the rotor is oriented along the field. However, in the event the position of the rotor poles does not coincide with this phase, the rotor can make an uncontrolled backward movement, and if the rotor has only one pair of poles[1] and not take the required position at all.

[1] these are most often used on high-speed electric motors as lower pole number means higher speed

At the initial time of the stand-still, the rotor of an electric machine at the initial moment is in a stationary state, it does not create a back-EMF[2], which makes it possible to determine its position, therefore all methods for determining the initial position of the rotor is using:

[2] The electromotive force (EMF) manifesting as a voltage that opposes the change in current which induced it.

a. a special test signal fed to the stator of the motor, and

b. a special algorithm for analysing the response to it.

There are the following methods of sensorless determination of the initial position of the rotor:

1. carrier signal injection;
2. PWM method;
3. current impulse method [2]

Given only the 3rd method allows determining the position of the rotor and distinguishing the north pole from the south pole, it is optimal for solving the problem of sensorless start.

The approach is based on the study of changes in the inductance of the stator coils depending on the position of the rotor. It involves applying the correct sequence of voltage pulses applied to the stator coils and measuring the peak value of the currents received to estimate the position of the rotor.

The time to determine the initial position without a sensor takes less than 15 ms.

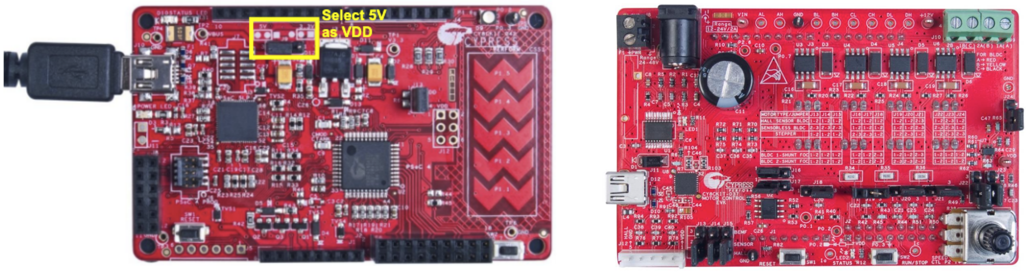
> To improve the accuracy of the method, the control system is calibrated the first time the motor is connected.

4.1.2. Sensorless Motor Control

At Low Speeds

At low speed (0-10% of rated speed), the back EMF generated by the motor is insufficient to determine the position of the rotating rotor. Therefore, information about the position of the rotor is obtained due to the difference between the inductances along the **d** and **q** axes, which is available in the PMSM with a salient pole rotor. For this, a high-frequency component is superimposed on the main control signal[3]. After that, a high-frequency component is allocated, from which information about the position of the rotor and the speed of rotation of the electric motor is extracted.

[3] The signal is modulated



(a) Configuration for CY8CKIT-042

(b) Configuration for CY8CKIT-037

Figure 4.1.: The boards which will be used in this experiment. Make sure they are connected once the proper configuration has been done on them with CY8CKIT-042 being on the bottom and CY8CKIT-037 being on top.

At Working Speeds

When the speed reaches a certain range (10% — 100% of the rated rotation speed), it is sufficient for the BEMF to be used in calculating the rotor position with acceptable accuracy. To calculate the angle, a state observer is used, which implements the calculation of all the variables and parameters of the permanent magnet motor required to implement the adaptive vector control algorithm, based on information about two stator phase currents (taken from current sensors) and two specified phase voltages.

4.2. The Experiment

In this laboratory session we will focus on the FOC, an industry wide technique used in many types of machines. So let's get started.

4.2.1. Configuration of the Hardware and Software

To get started with the experiment please adjust both CY8CKIT-037 and CY8KIT-042 according to the pictures presented in **Fig.** 4.1b and **Fig.** 4.1a, respectively. Select 5 V as the V_{DD} power at jumper <J9> on the CY8KIT-042, and always keep the USB cable connected to CY8KIT-042, as the device does not provide a 5 V converter. It gets the power directly from the USB port of the PC.

> For the CY8CKIT-037 board, please make sure all jumpers are connected correctly as per shown in **Fig.** 4.1b prior to plugging it to a computer or a power outlet.

Once your equipment has been checked and deemed to be in correct form, please connect the motor-load setup with the motor side connecting to the output of the inverter measurement board, and the load side connected to the load measurement board correctly.

> Don't forget to connect the hall-effect sensor output of the motor to CY8CKIT-037. IF you are confused about which alignment it should be on, consult the database of the motor.

Following this step, you can start working on the code.

Start by loading `Sensorless \gls{foc} Motor Control.cywrk` project into PSoC Creator IDE workspace.

Once the **Sensorless FOC Motor Control** code example loaded into PSoC Creator IDE, you must firs compile it. You can do this via:

1. Build > Sensorless FOC Motor Control

   If successful, continue on with,

2. Debug > Program

Once the program has been loaded to the device, ensure the USB cable from the CY8CKIT-042 is connected to the PC in this step.

> otherwise, the motor will not rotate.

Press the **SW2** button to start motor rotation. Rotate the potentiometer clockwise to increase the motor speed or vice versa. If the motor does **NOT** rotate and you observe LED2 blinking, it indicates that an error has occurred. If so, ensure that step 1 through step 5 have been executed correctly. Then press the Reset button and press the SW2 button again. If LED2 still blinks, there must be a problem in the hardware or software.

> This problem could like be caused by the wrong jumper configuration of the CY8CKIT-037 which should be revisited.

For a proper operation of the experiment, the user is required to install the following software:

PSOC™ Creator an integrated development environment (IDE) provided by infineon, to allow a tight integration of hardware and firmware of the embedded device. Current version as of February 25, 2025 is 4.4.

The software can be downloaded from their official website here.

> To be able to download this software, the user needs to create a free account with infineon.

4.2.2. Simulation Framework

To aid in your experiment and expand your understanding, MATLAB scripts and a SIMULINK model has been provided to help the analysis of measurement results as well as to be used in the report for comparison purposes.

The following files can be downloaded from GitHub:

`initSVPWM.m` An initialisation file to be run before the SIMULINK model[4]. Configure in this file the electrical frequency, activation of FOC, setpoint of the current or of the voltage (the first will be used if FOC is active. Further clarifications will be given in class by the lecturer)

[4] As the name implies, it is an init file and SIMUNLINK cannot run anything without initialisation.

C.R. 1

matlab

```
% VARIABLES ---------------------------------------------------------------

% Setup for FOC
% Set 1 = FOC
% Set 0 = Free Angle
FOC = 1;

Isetpoint = 5;                  % used if FOC = 1
Vsetpoint = 5;                  % used if FOC = 0

% Fundamental frequency:
% set the electrical frequency corresponding to measurements
f_fundamental  = 100;           % Electrical frequency          (Hz)
f_pwm          = 20000;         % Sampling/Switching frequency  (Hz)

% Solver step size
sover_max_step = 1e-6;          % Solver step size

Vdc            = 24;            % DC-link voltage               (V)

% MOSFET PARAMETERS -------------------------------------------------------

Ron            = 5e-3;          % MOSFET On-Resistance          (Ohm)
Rd             = 70e-3;         % Revese Diode Resistance       (Ohm)
Vf             = 0.87;          % Reverse Diode forward Voltage (V)

% MOTOR PARAMETERs --------------------------------------------------------
%
% NOTE: Calculated for BLY172S-24V-4000, delta configuration.

p              = 4;             % Pole pairs                    (-)
Rs             = 3/2 * 0.8;     % Serial resistance (Delta)     (Ohm)
Ls             = 3/2 * 1.2e-3;  % Serial inductance (Delta)     (H)

% Back EMF Constant (rad.V/s)
Ke             = sqrt(2) * 3.35e-3 * 60 / 2 / pi / p;

load_angle_offset = 120/180*pi;
```

C.R. 2 matlab

```matlab

% Additional calculations for FOC
if FOC == 1
    Iref            = Isetpoint;
    E               = Ke * 2 * pi * f_fundamental / sqrt(3);
    Vd              = E + 1/3 * Rs * Iref;
    Vq              = 2 * pi * f_fundamental * Ls * 1/3 * Iref;
    V_uvw           = sqrt(Vd^2 + Vq^2);
    voltage_angle   = atan2(Vq,Vd);
else
    V_uvw = Vsetpoint;
end

%voltage_angle = 0;

load_angle = load_angle_offset - voltage_angle;
```

`modelSVPWM.slx` The main SIMULINK model of motor and inverter implementing two (2) different commutation strategies:

- Space Vector Pulse Width Modulation (SVPWM),
- Sinusoidal Pulse Width Modulation (SPWM).

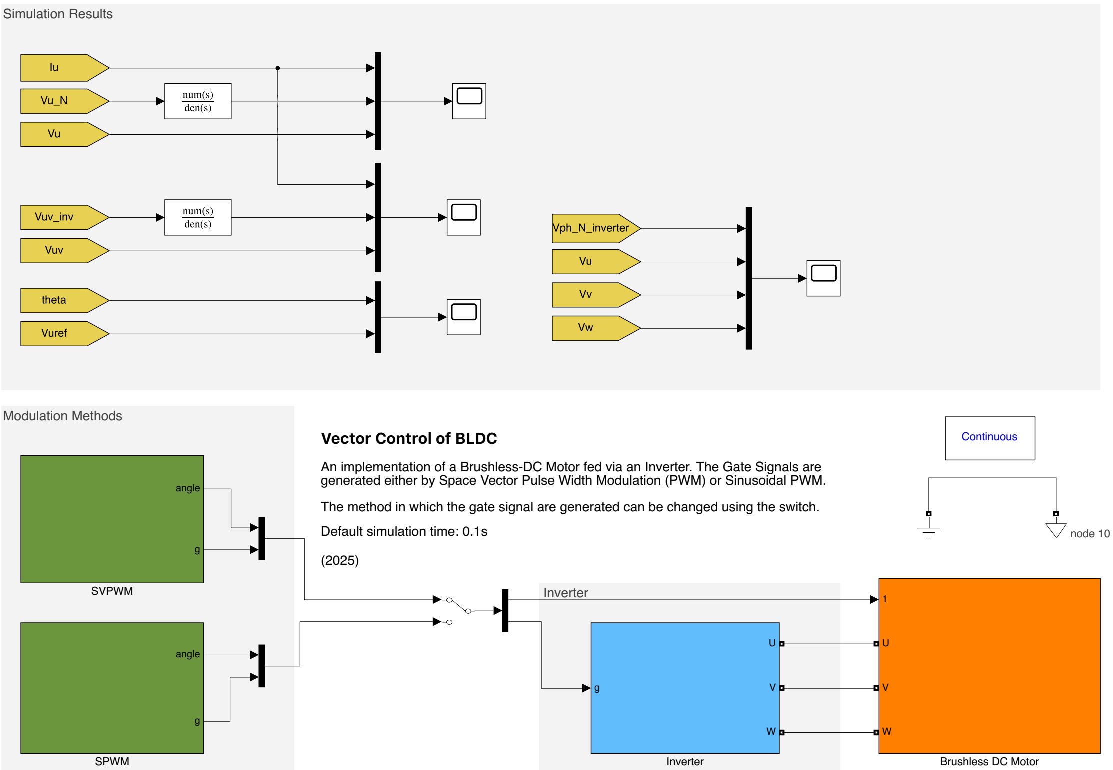


Figure 4.2.: The SIMULINK model you have been given for this experiment.

Details of its subsystem and its inner working can be seen in Appendix.

`do_sig_analysis.m` basic script to perform FFTs and low-pass filter of signals from simulations or oscilloscope measurements. The full code can be seen in Appendix.

`do_filter.m` low-pass filter function. Pass and stop band can be defined depending on needs. The full code can be seen in Appendix.

`importAgilentBin.m` function provided by Keysight to import data saved from DSOX oscilloscope series in binary (`.bin`) format. The full code can be seen in Appendix.

4.3. Required Measurements and Assessments

In this final part of the lab exercise, you will perform the following measurements and comparison with simulations:

1. Measure the phase-a voltage with respect to $-V_{\mathrm{dc}}$, H_1 Hall-sensor signal and current of phase-a. Comment the phase relationship between these quantities. What conclusion can be drawn on the performance of the sensorless algorithm?

2. Measure a phase-to-phase and phase voltage voltage. Apply the provided low-pass filter with adequate cut-off frequency. Compare and comment the achieved results.

3. Generate time diagram explaining the commutation strategy. Use the Hall-sensors as references to correctly determine the relationship with the phase voltages. Make use of the provided simulations as an aid to this process.

4. Measure the phase A voltage with respect to $-V_{\mathrm{dc}}$. In this case $+V_{\mathrm{dc}}$ is also connected to `<GND>`.

5. Measure the phase A current using the provided measurement board

6. Measure the phase-to-phase BC voltage using the math channel of the oscilloscope (or post processing in MATLAB)

7. Calculate the FFTs and THD of phase A voltage, phase A current, phase-to-phase BC voltage and compare them

8. Repeat the measurements for at least three (3) different speeds:

   - 100 rpm
   - 2000 rpm
   - 4000 rpm

9. Compare the results with the simulations in similar conditions.

Chapter 5

Lab Report Requirements

Table of Contents

5.1. Introduction

This section describes a general format for lab reports which you can adapt as needed. Lab reports are the most frequent kind of document written in the engineering discipline and can count for as much as 25% of a course yet little time or attention is devoted to how to write them well which this section hopes to improve and to that end this part has been written to be as topic agnostic as possible. It can also become a friction when each lecturer wants/require something a little different. Regardless of variations, however, the goal of lab reports remains the same:

> *. . . to document your findings and communicate their significance.*

Keeping this in mind, we can describe the report's format and basic components. Knowing the pieces and purpose, we can then adapt to the particular needs of a course.

A good lab report does more than present data [6, 7, 8];

> It demonstrates the writer's comprehension of the concepts behind the data

Merely recording the expected and observed results is **NOT** sufficient to get a good grade as you should also identify how and why differences occurred, explain how they affected your experiment, and show your understanding of the principles the experiment was designed to examine.

> A format, however helpful, cannot replace clear thinking and organised writing.

You still need to organize your ideas carefully and express them coherently. This report structure follows the University of Oxford Style guide [9] which can be found here

5.2. A Good Lab Report Structure

A good lab report usually requires a structure as such given below[1]:

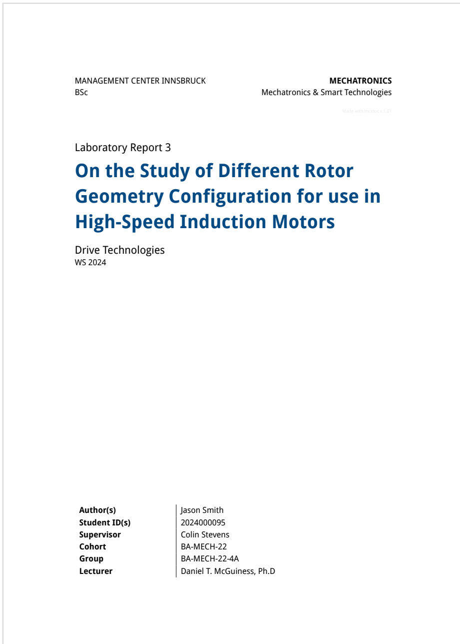
1. Title Page,
2. Abstract
3. Introduction
4. Methods and Materials
5. Experimental Procedure
6. Results
7. Discussion
8. Conclusion
9. References
10. Appendices
11. Further Reading (if applicable)

[1] Of course this is a template as every course might require slight adjustments.

To have a good report for your experiments, you should be clear and concise while giving all the relevant information as possible. Therefore a good report, with all of its Appendices and images provided, including cover page, should not pass over twenty (20) pages. Let's look at these items in detail and elaborate on them, and of course show examples as well.

Title Page

The title page needs to contain the name of the experiment or assignment, the names of lab partners or group members, and the date. Titles should be straightforward, informative, and should **NOT** be unreasonably wrong (i.e., Not Lab #4 but Laboratory Report 3: Sample Analysis using the Debye-Sherrer Method).



MANAGEMENT CENTER INNSBRUCK
BSc

MECHATRONICS
Mechatronics & Smart Technologies

Laboratory Report 3

On the Study of Different Rotor Geometry Configuration for use in High-Speed Induction Motors

Drive Technologies
WS 2024

Author(s)	Jason Smith
Student ID(s)	2024000095
Supervisor	Colin Stevens
Cohort	BA-MECH-22
Group	BA-MECH-22-4A
Lecturer	Daniel T. McGuiness, Ph.D

Figure 5.1.: An example of a good title page for a report or an assignment. This title page was created using the `mcidoc` document class which can be found here .

The language will also play a role as the header and title format needs to be adjusted based on the language being used in teaching the said course. Therefore make sure the title page is formatted in german for german courses and english for the english courses.

Title page should also contain additional information, relevant to the lecture such as:

> the degree, the program, cohort, group (if applicable), lecturer, lab supervisor.

Abstract

An abstract in any research paper or experimental work summarises four (4) essential aspects:

1. The purpose of the experiment[2]
2. Describing the key findings of the experiment,
3. Their significance, and
4. Major conclusions.

[2] sometimes expressed as the purpose of the report.

The abstract often also includes a brief reference to theory or methodology. The information should clearly enable readers to decide whether they need to read your whole report. The abstract should be one paragraph of 100–200 words.

The following example is 191 words [10].

Abstract

This experiment examined the effect of line orientation and arrowhead angle on a subjects ability to perceive line length, thereby testing the Müller-Lyer illusion. The Müller-Lyer illusion is the classic visual illustration of the effect of the surrounding on the perceived length of a line. The test was to determine the point of subjective equality by having subjects adjust line segments to equal the length of a standard line. Twenty-three subjects were tested in a repeated measures design with four different arrowhead angles and four line orientations. Each condition was tested in six randomised trials. The lines to be adjusted were tipped with outward pointing arrows of varying degrees of pointedness, whereas the standard lines had inward pointing arrows of the same degree. Results showed that line lengths were overestimated in all cases. The size of error increased with decreasing arrowhead angles. For line orientation, overestimation was greatest when the lines were horizontal. This last is contrary to our expectations. Further, the two factors functioned independently in their effects on subjects point of subjective equality. These results have important implications for human factors design applications such as graphical display interfaces.

> As stated, the goal of an abstract is for reader to quickly assess your report and understand the overview of your work without reading the work itself. So think of this as a scientific elevator pitch. You need to sell your work to the reader in under 200 words.

Introduction

Once the abstract has sold your work to the reader, the next comes is the introduction. The introduction is more narrowly focused than the abstract. It states the objective of the experiment and provides the reader with background to the experiment[3]. State the topic of your report clearly and concisely, in one or two sentences. As an example please look below [10]:

[3] This is generally known as the *literature review* within the academic circle.

> The purpose of this experiment was to identify the specific element in a metal powder sample by determining its crystal structure and atomic radius. These were determined using the Debye-Sherrer (powder camera) method of X-ray diffraction.

A good introduction is not just a sentence or two as its primary goal is to get the now interested reader up to speed with your work. To that end you should provides all the necessary background theory, previous research, or formulas the reader needs to know.

> Please do not repeat the lab manual, but to show your own understanding of the problem and all the relevant information surrounding it.

For example, the introduction following the aforementioned example might describe the Debye-Sherrer method [11], and explain that from the diffraction angles the crystal structure can be found by applying Braggs law [10, 12].

> If the amount of introductory material seems to be a lot, consider adding subheadings such as: Theoretical Principles or Background.

Digression: A Note on Using the Verb Tense

Introductions often create difficulties as it is the place where careful attention must be made for using the correct tense. Below are two (2) points which should help you navigate the introduction:

- The experiment is already finished. Use the **past tense** when talking about the experiment.

  "The objective of the experiment was . . . "

- The report, the theory, and permanent equipment still exist. It is important for these statement to be written in **present tense**:

  "The purpose of this report is . . . "

  "Braggs Law for diffraction is . . . "

  "The scanning electron microscope produces micro-graphs . . . "

Methods and Materials

This can usually be a simple list, or a table but make sure it is accurate and complete. An example is shown in **Table** 5.1.

In some cases, you can simply direct the reader to a laboratory manual, standard procedure or technical documentation. As an example:

Manufacturer	Model	Description
Anaheeim Automation	BLY172S-24V-4000	Brushless DC Motor [24 V, 53 W]
Cypress	CY8CKIT-037	PSoC 4 Motor Control Evaluation Kit
Cypress	CY8CKIT-042	PSoC 4 Pioneer Kit
Keysight	DSOX1102A	Oscilloscope, 70 MHz, 2 GS0a s

Table 5.1.: The part list used in the experiment A

> *"Equipment was set up as in IEC 360004:08 manual . . . "*

Experimental Procedure

This section describes the process in chronological order. Using clear paragraph structure, explain all steps **in the order they actually happened**, not as they were supposed to happen.

If the lab supervisor says you can simply state that you followed the procedure in the manual, be sure you still document occasions when you did not follow that exactly [10].

> *"At step 4 we performed four repetitions instead of three, and ignored the data from the second repetition . . . "*

> The goal here is to make your work reproducible. Another researcher should be able to duplicate your experiment.

Results

This section is usually dominated by calculations, tables, figures, codes, and algorithms. Regardless, you still need to state all significant results explicitly in verbal form. As an example [10]:

> *"Using the calculated lattice parameter gives, then, $R = 0.1244$ nm . . . "*

Graphics need to be clear, easily read, and must be labelled[4]. It is also worth mentioning that a good scientific report uses as much vector graphics as possible for their plots.

[4] e.g., **Figure 1.1:** Input Frequency and Capacitor Value

As an example, it is **NOT** a good practice to take a photo of the oscilloscope and put it into the report. You should interface with the Oscilloscope to retrieve the data and use your plot software of choice[5] to produce publishing quality plots. If the image cannot be produced in a vector format, it needs to have a minimum of 300 DPI as per publishing standard of IEEE.

[5] MATLAB, gnuplot, pstricks, pgfplots, . . .

An important strategy for making your results effective is to draw the readers attention to them with a sentence or two, so the reader has a focus when reading the graph.

> Regarding figures, avoid figures which are not mentioned in the report. If it is **NOT** mentioned in the report perhaps it is not vital.

In most cases, providing a sample calculation is sufficient in the report. Leave the remainder in an Appendix. Likewise, your raw data can be placed in an appendix as well with any major code you have used in your work no matter how trivial. Refer to Appendices as need arises, pointing out trends and identifying special features.

Discussion

This is the most important part of your report, as you show that you understand the experiment beyond the simple level of completing it.

Explain — **Analyse** — **Interpret**.

Some people like to think of this as the subjective part of the report. By that, they mean this is what is not readily observable. This part of the lab focuses on a question of understanding

> *"What is the significance or meaning of the results? "*

To answer this question, use both aspects of discussion:

Notice that, after the material is identified in the example above, the writer provides a justification. We know it is nickel because of its structure and size. This makes a sound and sufficient conclusion. Generally, this is enough; however, the conclusion might also be a place to discuss weaknesses of experimental design, what future work needs to be done to extend your conclusions, or what the implications of your conclusion are.

References

References include your lab manual and any outside reading you have done. As this is a mechatronics lab, your reference formatting should conform to IEEE citation standard. The citation standard can be seen here or you can look at the end of this lab report to see the standard as well.

Appendices

This section is usually reserved for content which does not particularly fit to any other section. Typically includes such elements as raw data, calculations, graphs pictures or tables that have not been included in the report itself. Each kind of item should be contained in a separate appendix. Make sure you refer to each appendix at least once in your report. For example, the results section might begin by noting [10]:

> *"Micro-graphs printed from the Scanning Electron Microscope are contained in Appendix A . . . "*

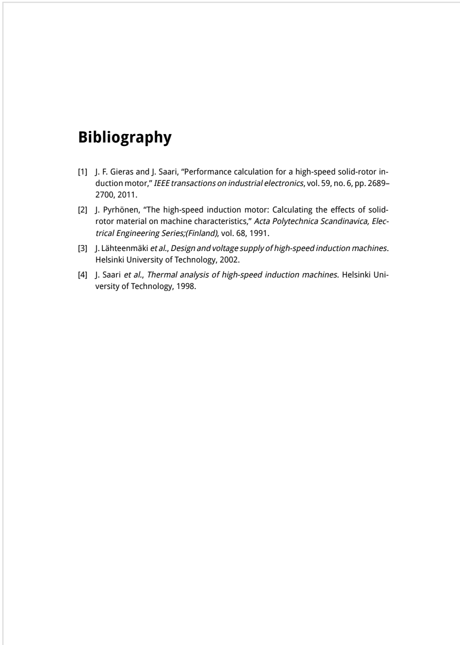
5.3. Documentation Standard

The document should ideally be made in LaTeX. For those who don't know, it is a type-setting language which allows you to create beautiful documents [13]. There are great resources to learn how to write a document in LaTeX such as Overleaf or the TeX stack-exchange and of course the following books would give you more information than you could possibly need[6]:

- The LaTeX Companion (3rd Edition)
- The LaTeX Graphics Companion (2nd Edition)

The author of this section has also authored a LaTeX document class conforming to the MCI requirements for laboratory or assignment documentation which can be found here . The class also includes a semi-detailed README to get you started.

The report must also follow the MCI standards, if you are going to use formatting that is not `mcidoc`.



Bibliography

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Figure 5.2.: An example of a bibliograpy using BibTex and IEEE citation standard. This bibliograpy entry was created using the `mcidoc` document class which can be found here .

[6] Of course these are recommendations for people who want to understand LaTeX as a programming language rather than just a template.

Part II.

Appendix

Appendix A

Simulink Schematics

Table of Contents

This chapter gives a detailed printing of all the systems and subsystems used in the lab manual. All these SIMULINK models have been provided to you via GitHub. The two (2) models are as follows:

modelSVPWM The model which implements two (2) types of modulation techniques (SVPWM, SPWM) to drive a BLDC using an inverter

modelBCPWM The SIMULINK model of the motor which implements two (2) types of commutation techniques which are 120° 180°.

The following pages contains the models.

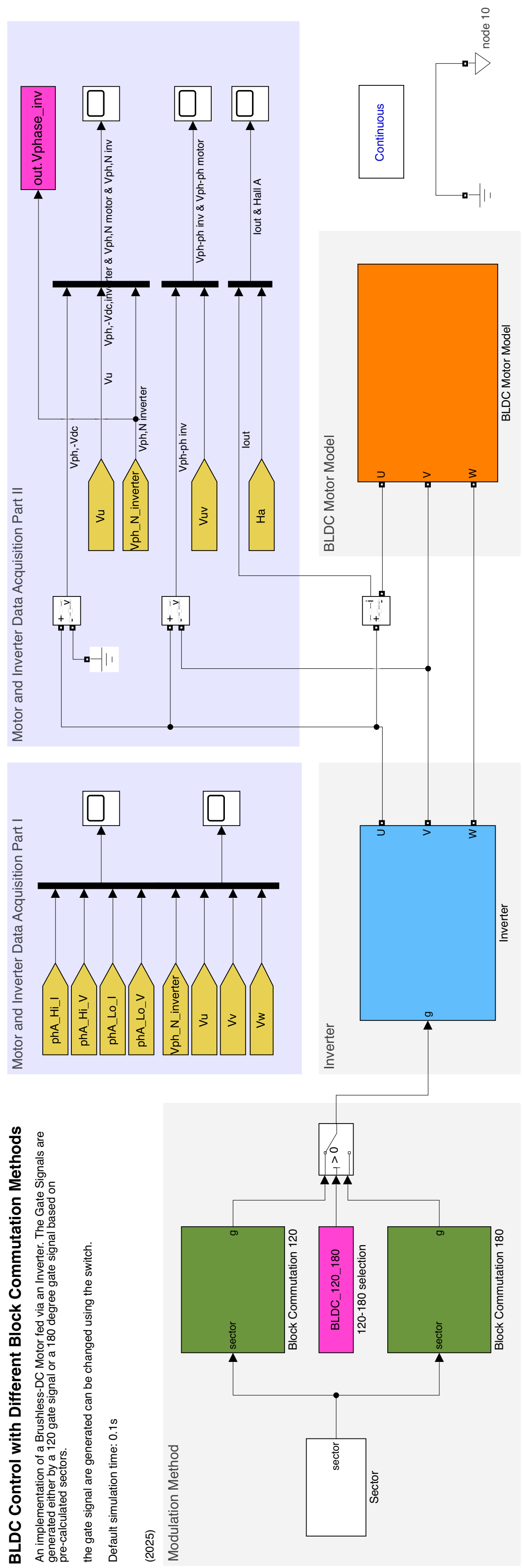

Figure A.1.: All the SIMULINK schematics for Sensor and sensor-less BLDC Control.

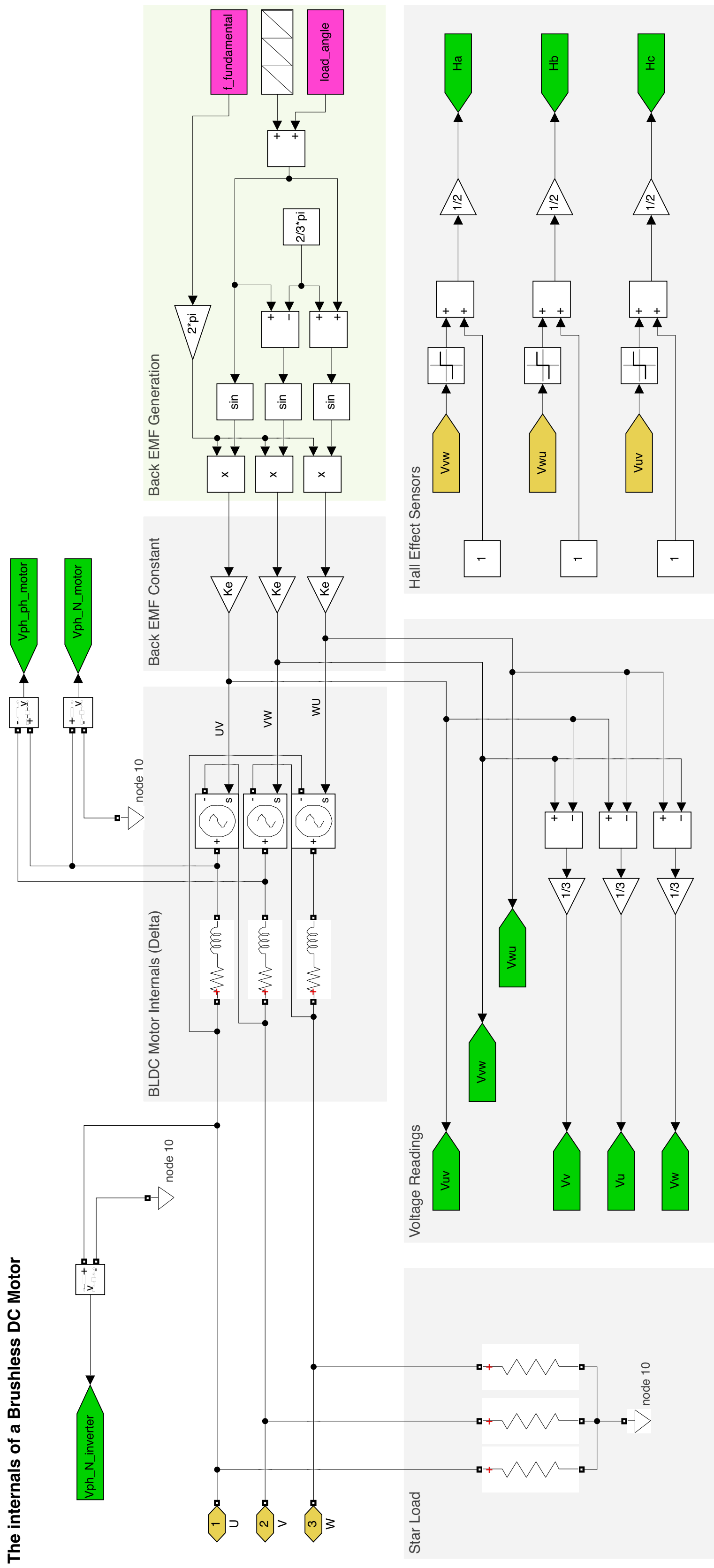

Figure A.2.: All the SIMULINK schematics for Sensor and sensor-less BLDC Control.

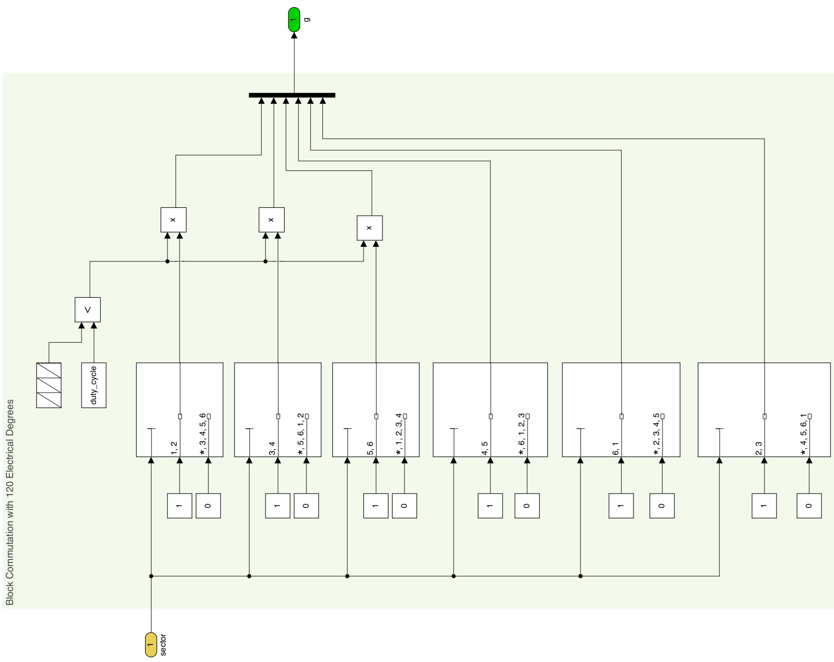

Figure A.3.: All the SIMULINK schematics for Sensor and sensor-less BLDC Control.

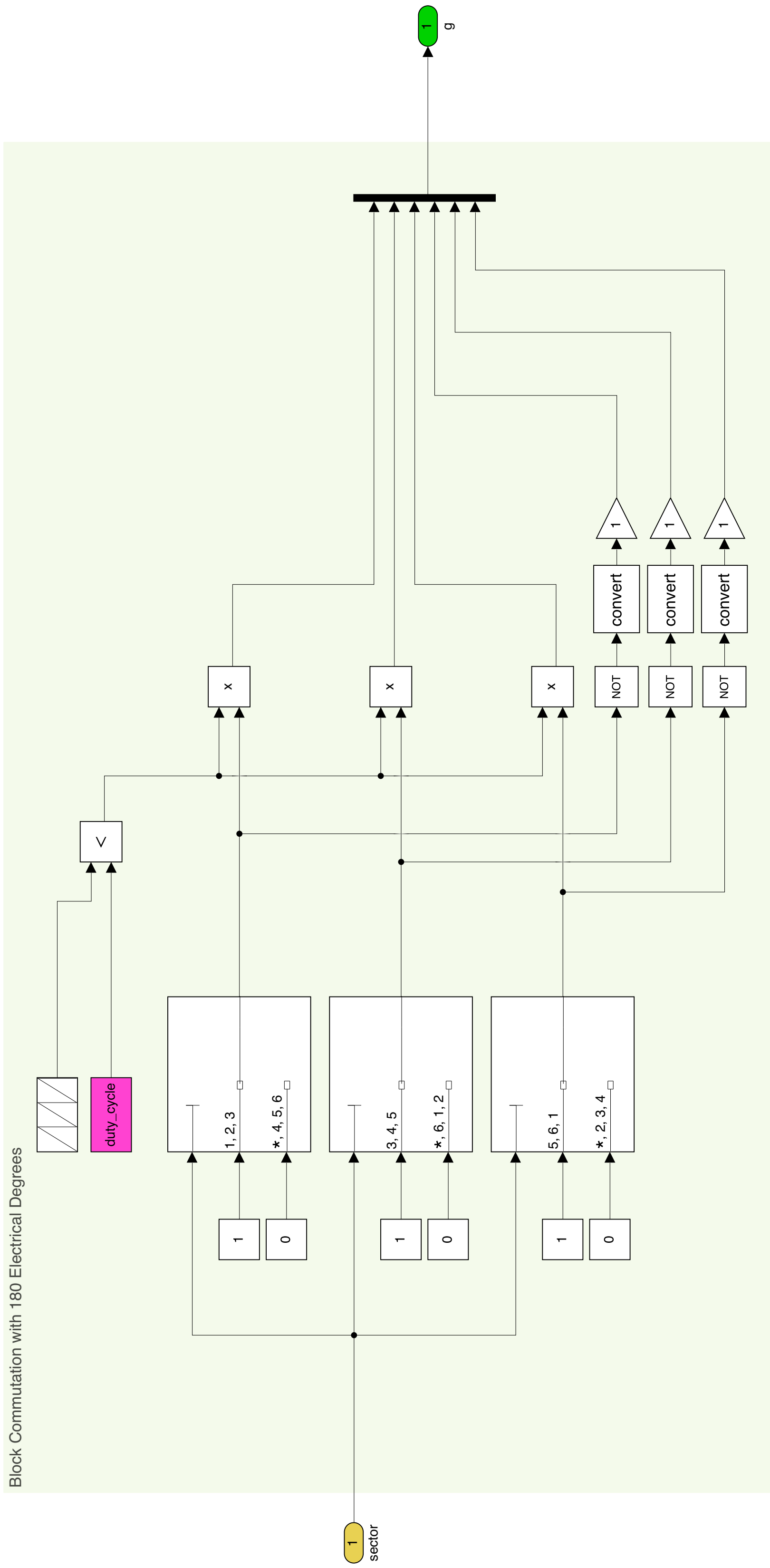

Figure A.4.: All the SIMULINK schematics for Sensor and sensor-less BLDC Control.

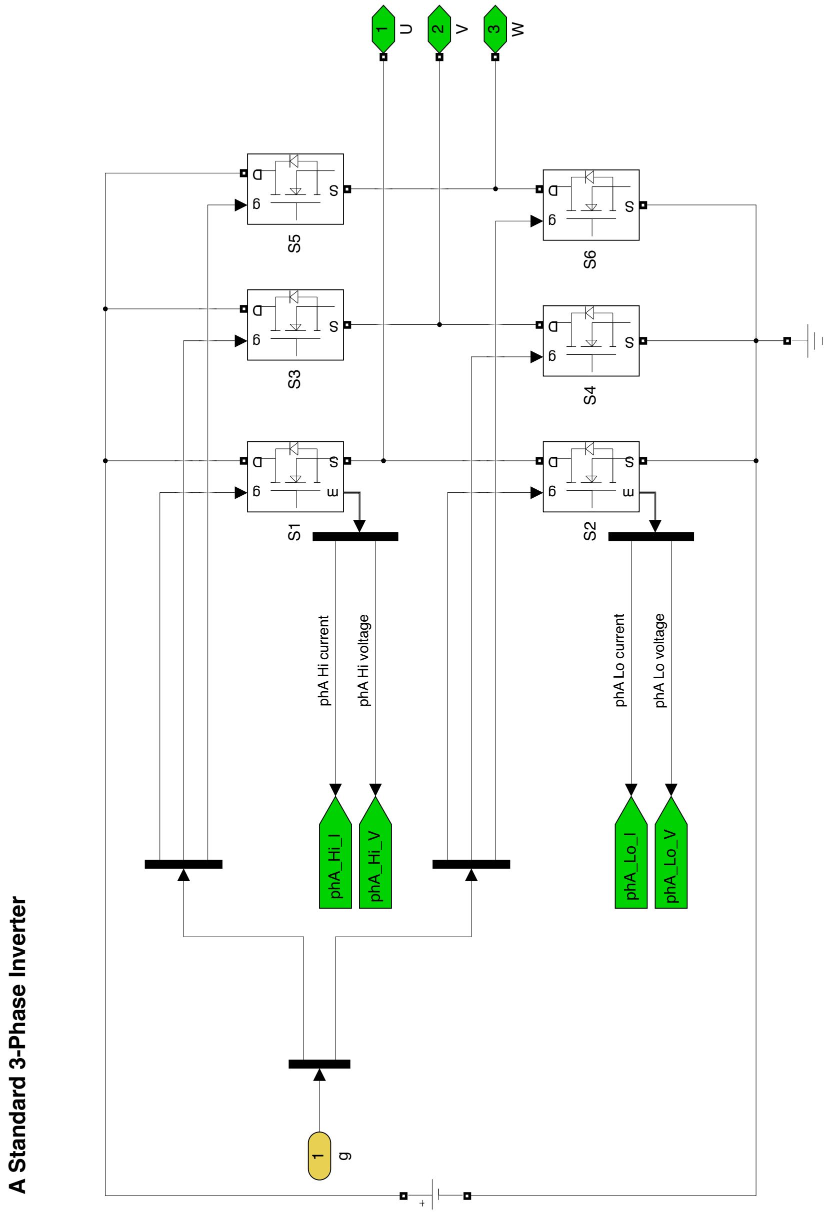

Figure A.5.: All the SIMULINK schematics for Sensor and sensor-less BLDC Control.

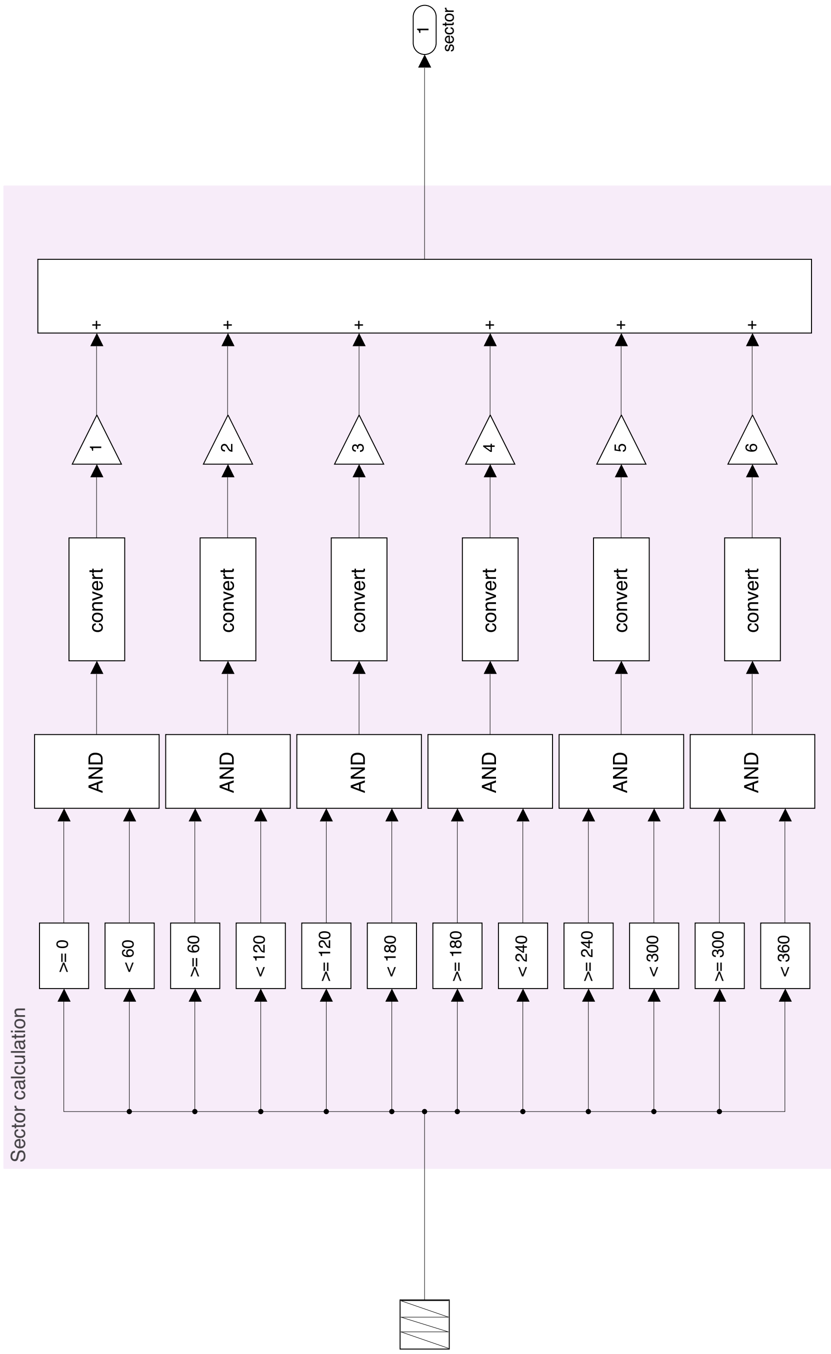

Figure A.6.: All the SIMULINK schematics for Sensor and sensor-less BLDC Control.

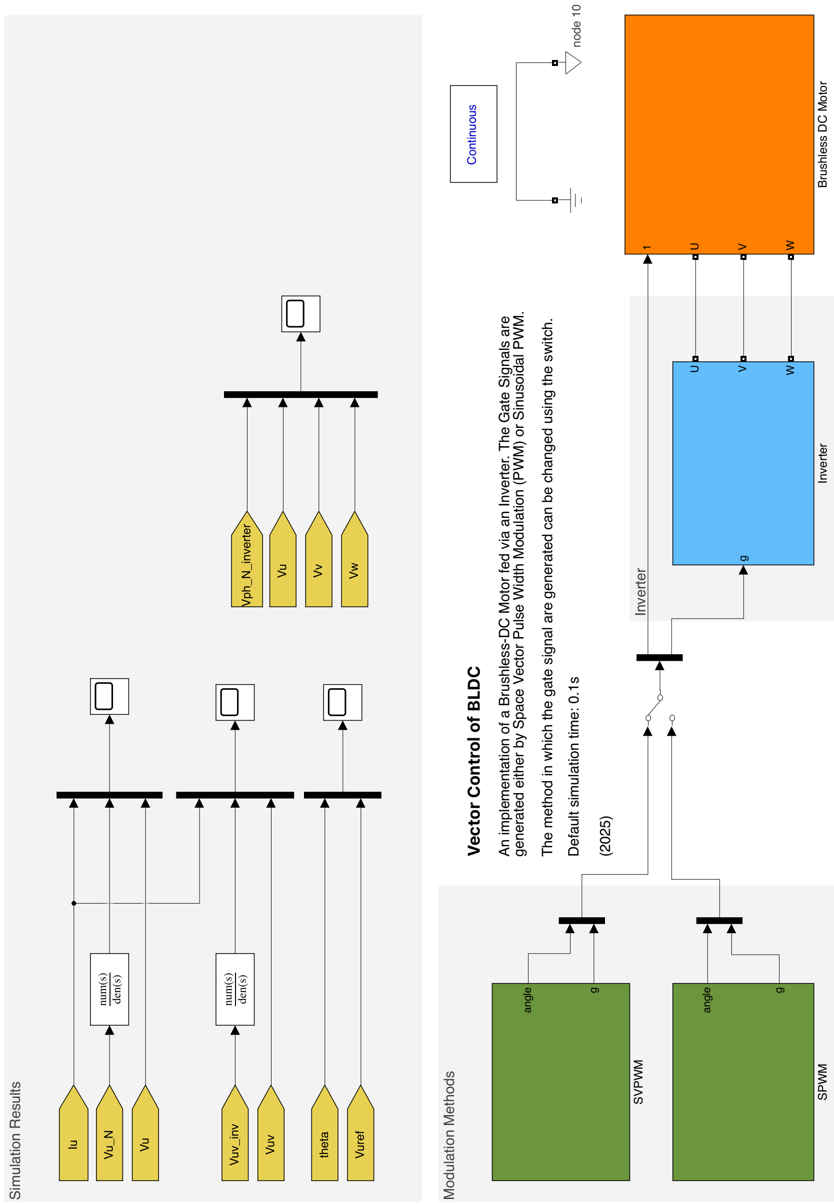

Figure A.7.: Schematic of a BLDC control with FOC.

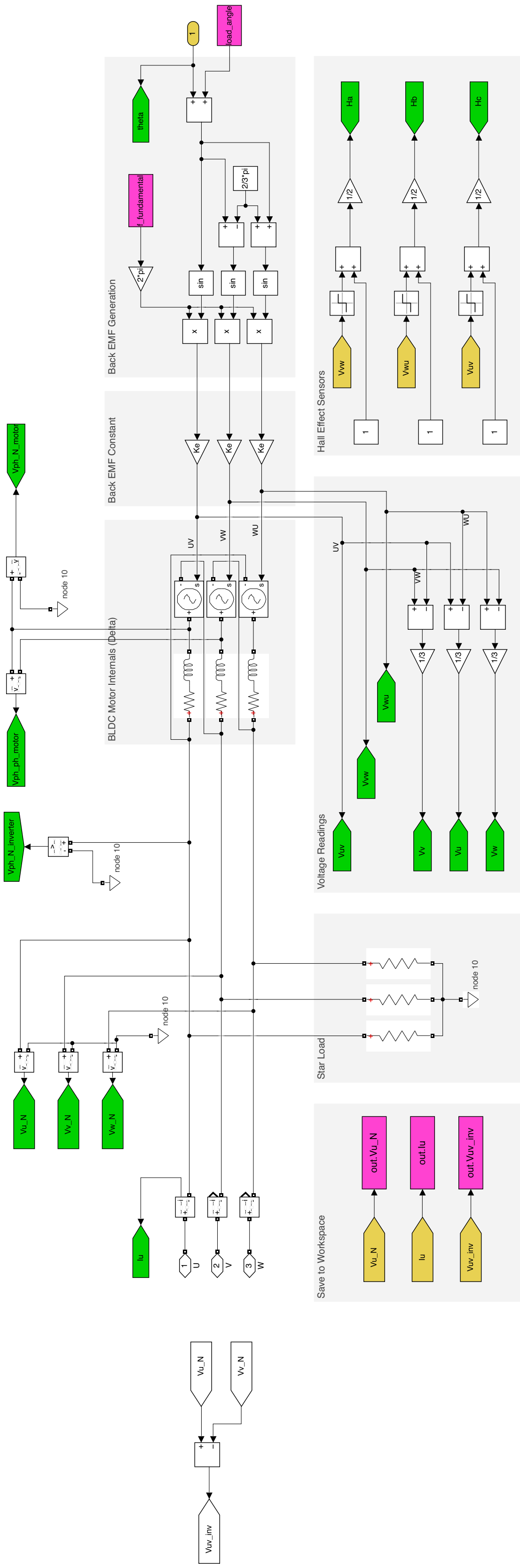

Figure A.8.: Schematic of a BLDC control with FOC.

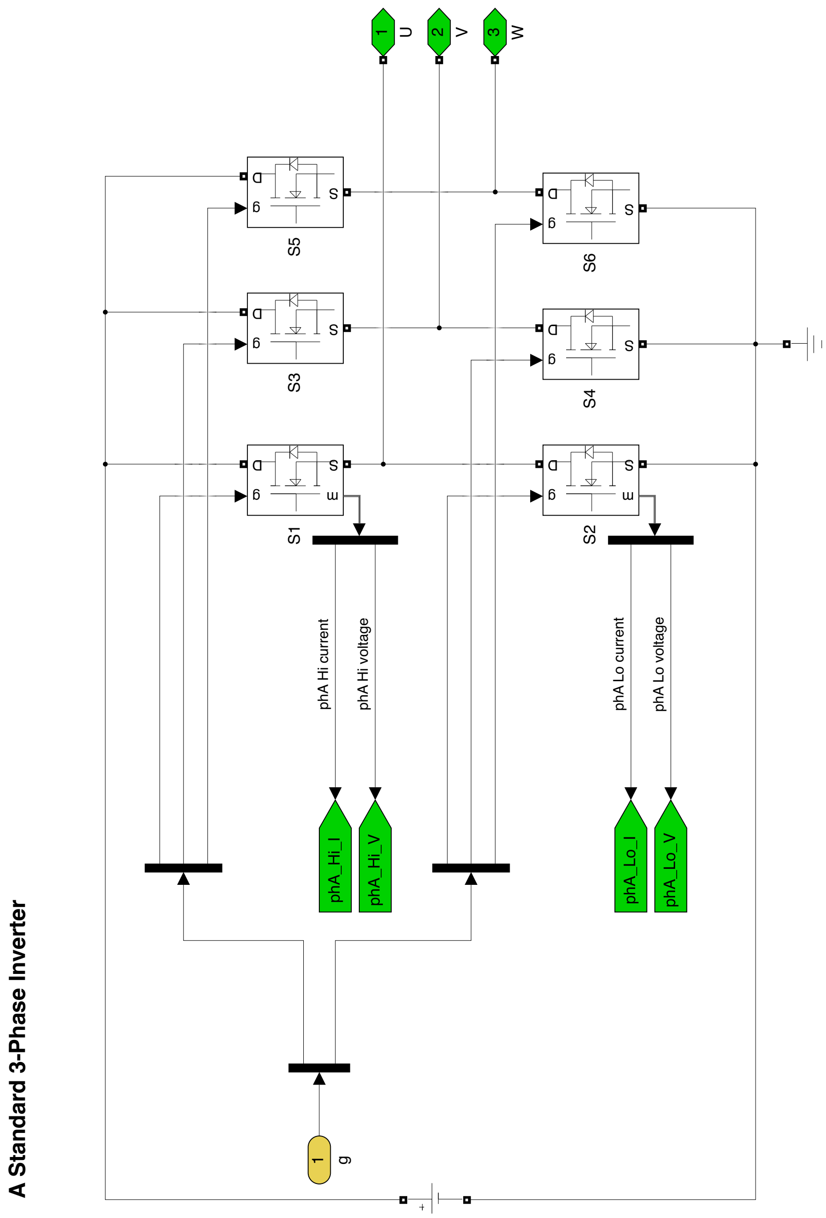

Figure A.9.: Schematic of a BLDC control with FOC.

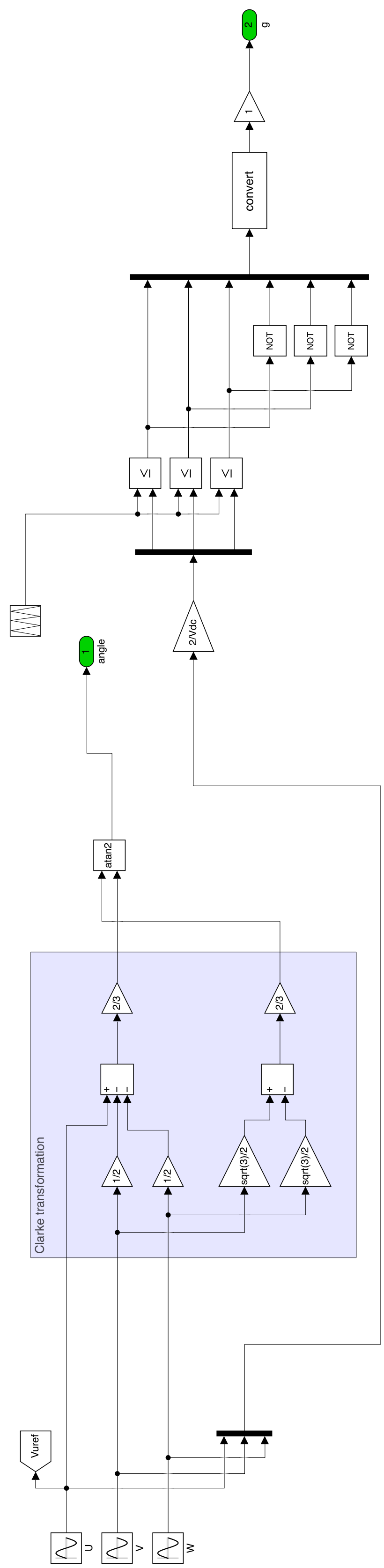

Figure A.10.: Schematic of a BLDC control with FOC.

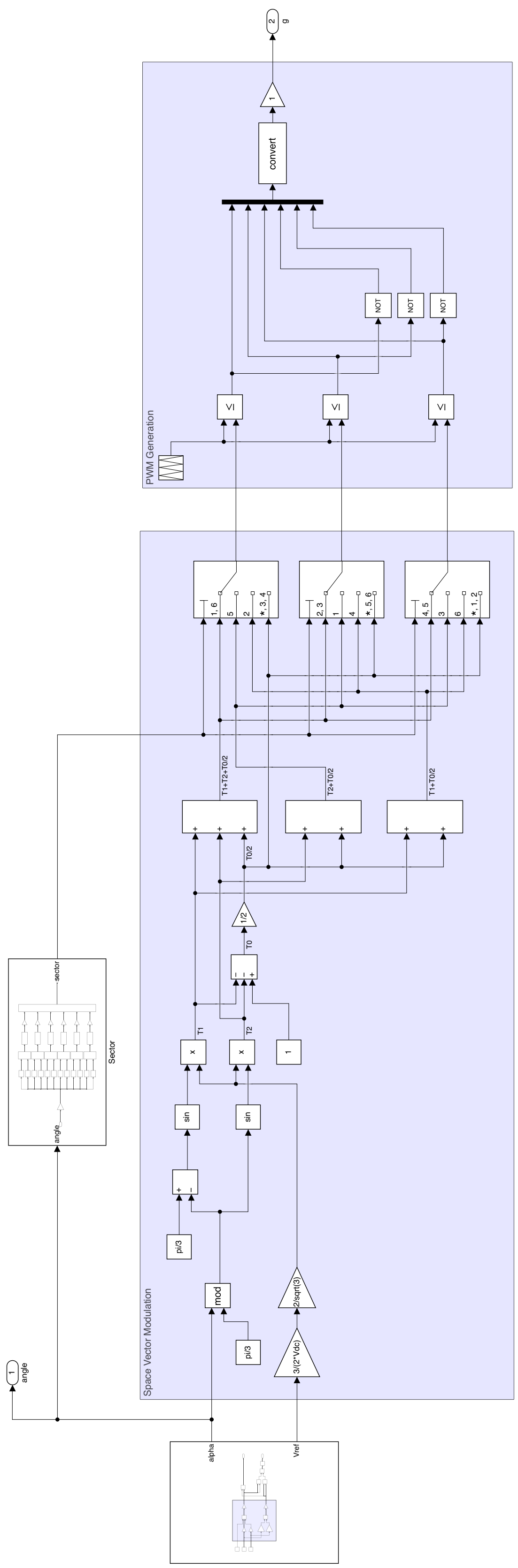

Figure A.11.: Schematic of a BLDC control with FOC.

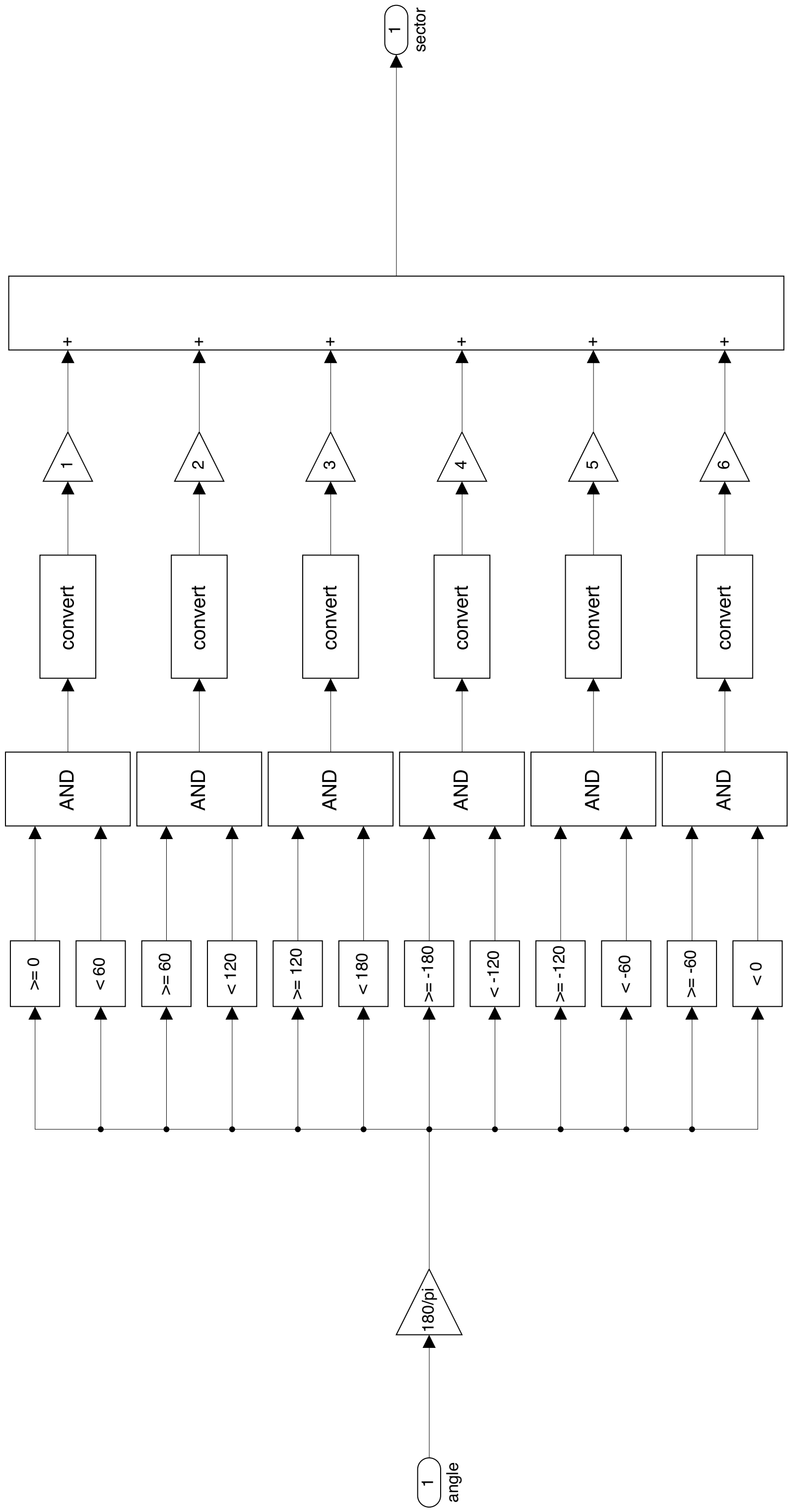

Figure A.12.: Schematic of a BLDC control with FOC.

Appendix B

MATLAB Codes

Table of Contents

C.R. 1

matlab

```
%{
****************************************************************************
*    Initialisation script for use in Block Commutation Simulation of a   *
*    Brushless DC Motor using SIMULINK. Please run this script PRIOR to   *
*    running the SIMULINK model.                                          *
*                                                                         *
*    (2025)                                                               *
****************************************************************************
%}

% CLEANING OUT THE HOUSE -------------------------------------------------
% Clear the workspace from all previous statements/values
clc;
clear;
close all;

% VARIABLES --------------------------------------------------------------
% Selection of switching commutation strategy 120/180
% Set 1 = 120 degree commutation
% Set 0 = 180 degree commutation
BLDC_120_180    = 1;

% Duty cycle:
% set the PWM duty cycle to control the output voltage/current
duty_cycle      = 0.6;

% Fundamental frequency:
% set the electrical frequency corresponding to measurements
f_fundamental   = 265;          % Electrical frequency          (Hz)
```

```
f_pwm          = 20000;         % Sampling/Switching frequency  (Hz)

% Solver step size
sover_max_step = 1e-6;          % Solver step size

Vdc            = 24;            % DC-link voltage               (V)

% MOSFET PARAMETERS -------------------------------------------------------

Ron            = 5e-3;          % MOSFET On-Resistance          (Ohm)
Rd             = 70e-3;         % Revese Diode Resistance       (Ohm)
Vf             = 0.87;          % Reverse Diode forward Voltage (V)

% MOTOR PARAMETERs --------------------------------------------------------
%
% NOTE: Calculated for BLY172S-24V-4000, delta configuration.

p              = 4;             % Pole pairs                    (-)
Rs             = 3/2 * 0.8;     % Serial resistance (Delta)     (Ohm)
Ls             = 3/2 * 1.2e-3;  % Serial inductance (Delta)     (H)

% Back EMF Constant (rad.V/s)
Ke             = sqrt(2) * 3.35e-3 * 60 / 2 / pi / p;

% Based on the Commutation method choose a load angle
if BLDC_120_180 == 1
    load_angle=pi/3;        % for 120
else
    load_angle = pi/6;      % for 180
end

% END OF CODE -------------------------------------------------------------
```

C.R. 2 matlab

```
%{
***************************************************************************
*    Initialisation script for use in Space Vector modulation of a        *
*    Brushless DC Motor using SIMULINK. Please run this script PRIOR to   *
*    running the SIMULINK model.                                          *
*                                                                         *
*    (2025)                                                               *
***************************************************************************
%}

% CLEANING OUT THE HOUSE --------------------------------------------------
% Clear the workspace from all previous statements/values
clc;
clear;
close all;

% VARIABLES ---------------------------------------------------------------

```

C.R. 3 matlab

C.R. 4

matlab

```matlab
% Setup for FOC
% Set 1 = FOC
% Set 0 = Free Angle
FOC = 1;

Isetpoint = 5;                  % used if FOC = 1
Vsetpoint = 5;                  % used if FOC = 0

% Fundamental frequency:
% set the electrical frequency corresponding to measurements
f_fundamental  = 100;           % Electrical frequency          (Hz)
f_pwm          = 20000;         % Sampling/Switching frequency  (Hz)

% Solver step size
sover_max_step = 1e-6;          % Solver step size

Vdc            = 24;            % DC-link voltage               (V)

% MOSFET PARAMETERS -------------------------------------------------------

Ron            = 5e-3;          % MOSFET On-Resistance          (Ohm)
Rd             = 70e-3;         % Revese Diode Resistance       (Ohm)
Vf             = 0.87;          % Reverse Diode forward Voltage (V)

% MOTOR PARAMETERs --------------------------------------------------------
%
% NOTE: Calculated for BLY172S-24V-4000, delta configuration.

p              = 4;             % Pole pairs                    (-)
Rs             = 3/2 * 0.8;     % Serial resistance (Delta)     (Ohm)
Ls             = 3/2 * 1.2e-3;  % Serial inductance (Delta)     (H)

% Back EMF Constant (rad.V/s)
Ke             = sqrt(2) * 3.35e-3 * 60 / 2 / pi / p;

load_angle_offset = 120/180*pi;

% Additional calculations for FOC
if FOC == 1
    Iref           = Isetpoint;
    E              = Ke * 2 * pi * f_fundamental / sqrt(3);
    Vd             = E + 1/3 * Rs * Iref;
    Vq             = 2 * pi * f_fundamental * Ls * 1/3 * Iref;
    V_uvw          = sqrt(Vd^2 + Vq^2);
    voltage_angle  = atan2(Vq,Vd);
else
    V_uvw = Vsetpoint;
end

%voltage_angle = 0;

load_angle = load_angle_offset - voltage_angle;
```

C.R. 5

matlab

```matlab
% END OF CODE -------------------------------------------------------------
```

C.R. 6

matlab

```matlab
function y = doFilter(x,yFs)
%DOFILTER Filters input x and returns output y.

% MATLAB Code
% Generated by MATLAB(R) 9.8 and DSP System Toolbox 9.10.
% Generated on: 30-Mar-2022 16:01:35

persistent Hd;

if isempty(Hd)

    Fpass = 1000;     % Passband Frequency
    Fstop = 5000;     % Stopband Frequency
    Apass = 1;        % Passband Ripple (dB)
    Astop = 40;       % Stopband Attenuation (dB)
    Fs    = yFs;  % Sampling Frequency

    h = fdesign.lowpass('fp,fst,ap,ast', Fpass, Fstop, Apass, Astop, Fs);

    Hd = design(h, 'equiripple', ...
        'MinOrder', 'any', ...
        'StopbandShape', 'flat');



    set(Hd,'PersistentMemory',true);

end

y = filter(Hd,x);

```

C.R. 7

matlab

```matlab
function [f,P1,timeVector,voltageVector_LP]=do_sig_analysis(timeVector,voltageVector)

Fs=1/mean(diff(timeVector));
T = 1/Fs;             % Sampling period
L = length(voltageVector);             % Length of signal
t = (0:L-1)*T;        % Time vector

voltageVector_LP = doFilter(voltageVector,Fs);
%plot(timeVector,voltageVector,timeVector,voltageVector_LP);

X=voltageVector;
Y = fft(X);
P2 = abs(Y/L);
P1 = P2(1:L/2+1);
P1(2:end-1) = 2*P1(2:end-1);
```

C.R. 8

matlab

```
f = Fs*(0:(L/2))/L;
%figure
%plot(f,P1)
end
```

Glossary

BEMF Back Electro-motive Force. 4, 17, 18, 33

BLDC Brushless DC. viii–xiii, 4, 5, 8–11, 13, 16–20, 23, 25, 26

DC Direct Current. 9, 11, 17

DIN Deutschen Instituts für Normung. 14

FOC Field Oriented Control. viii–xiii, 5, 31, 33, 34

PM Permanent Magnet. 4, 17

PMSM Permanent Magnet Synchronous Motor. 8, 9, 11, 17, 31

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