

# **Laboratory Book**

## **Drive Systems**

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# Lab Rules and Safety

- No eating or drinking in the laboratory
- Keep walkways clear (of bags, coats, etc)
- Report any accident or breakage to the instructor immediately
- If in doubt about any verbal or written instruction, ask before carrying it out
- Do not wear personal audio devices and turn off cell phones
- Do not leave any objects loose on the equipment, such as screws, nuts, or washers.
- Do not physically interact with rotating object. If the motor needs to be interacted, first make sure the power supply is turned off and the motor is at a standstill.
- Get instructor approval before working on any equipment
- Have the appropriate documentation before troubleshooting electronic equipment.
- Don't rush your work as this increases the risk of problems.
- If any equipment is broken or not working to the level required by the manual/lecture please report it to the supervisor.
- Leave the laboratory as you have found it. Points will be taken from the group/individual who has left their test bench untidy.

If you are unsure about a procedure, ask for help **IF IN DOUBT, DON'T TOUCH/DO IT - ASK FOR HELP**

**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<sup>1</sup>.*

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 calculations in, you will be provided a measurement kit

<sup>1</sup> William Thomson, 1<sup>st</sup> Baron Kelvin

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

The former circuit will be connected to the CY8CKIT-037 motor driver board kit<sup>2</sup>, 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.

<sup>2</sup>If it is NOT connected, 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.

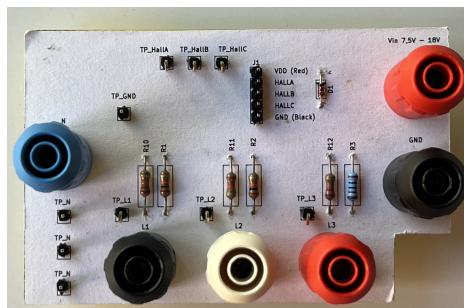
As can be seen, during normal operation, the board is supplied by a voltage source with 5 V. This can be achieved from a standard laboratory Direct Current (DC) power supply or connecting it to the 5 V of the Motor control kit which we will look at in more detail in the next section.

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.

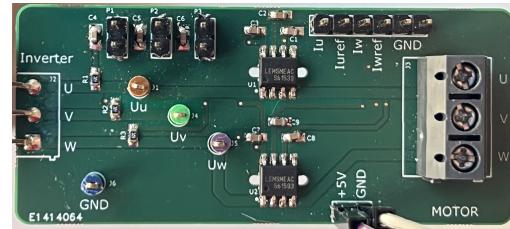
Please respect the phase sequence as described by the data-sheet given [here](#) for correct operation of the motor.

Jumpers **<P1>**, **<P2>**, and **<P3>** will be connected without the need of extra explanation. 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<sup>3</sup> representation of the fundamental component of the phase voltages.

<sup>3</sup>... while sacrificing elegance

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  $80 \text{ mV A}^{-1}$ . Students who are interested in its implementation and the working process can have a look at it [here](#)

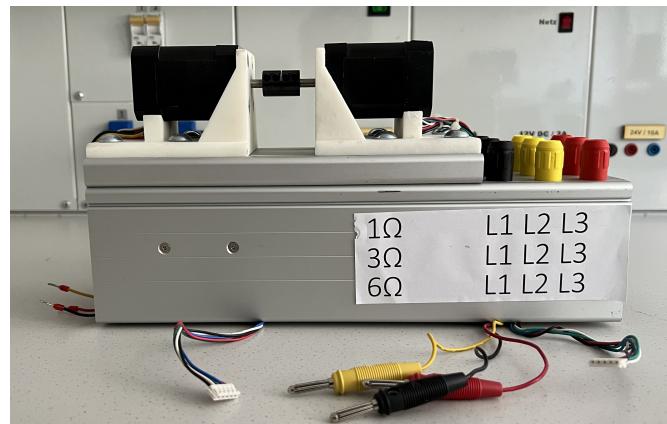
### 1.1.2. Load Side Measurement Board

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 sensor 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<sup>4</sup>. The configuration is seen in **Fig. 1.2**.

<sup>4</sup>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.

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.

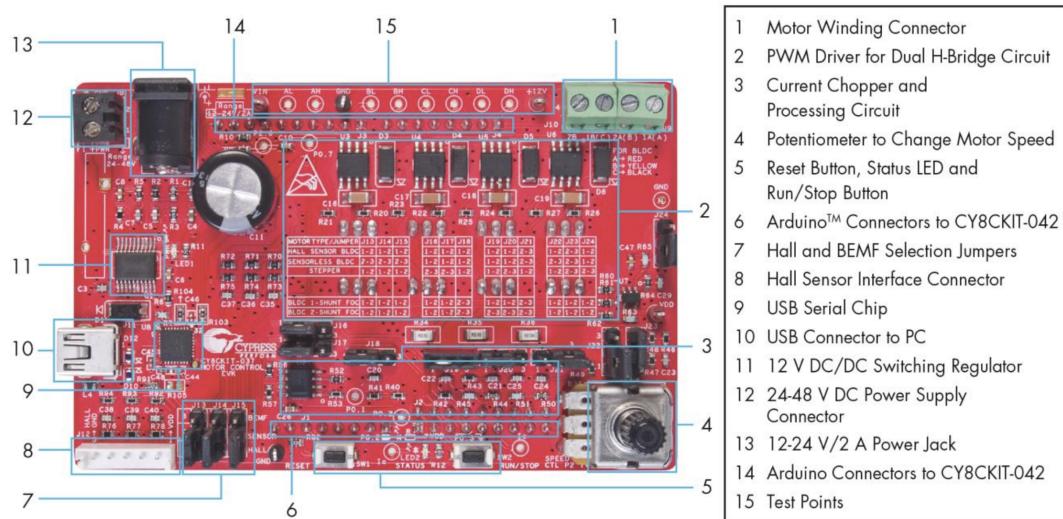


Figure 1.3.: A detailed diagram of the CY8CKIT motor driver board.

## 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<sup>5</sup>. The motor control system can be separated into its two (2) primary parts:

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

<sup>5</sup>Anything which requires transistor or electronic components to rotate the rotor

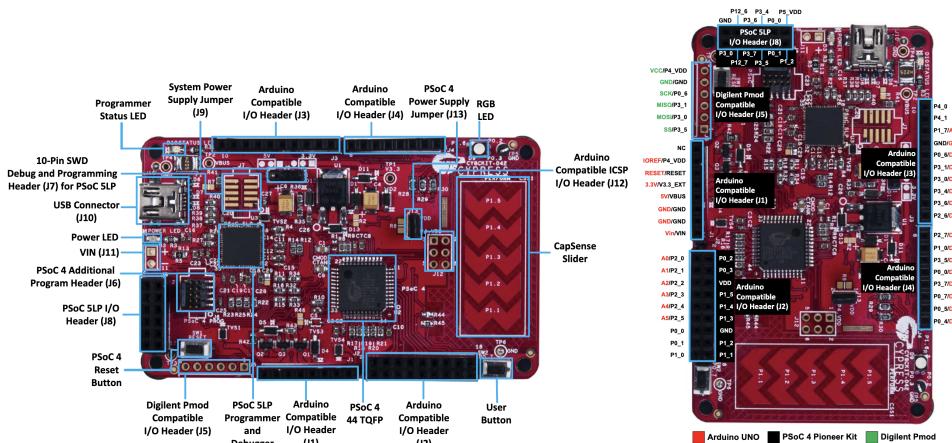
This device is designed to create control techniques for three (3) motors:

- 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.

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



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

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 repeat it again, 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**.

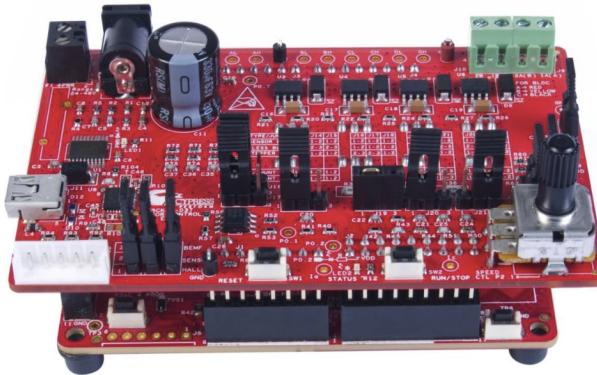


Figure 1.5.: The connected boards of CY8CKIT-037 being on top and CY8CKIT-042 on bottom.

## 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 its manual [here](#).

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

## Installing the Software

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 March 11, 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.

Once you have your account and installed the software you need to have some example code to work with. If it is **NOT** installed within the PSoC Creator, you can download it [here](#).

## 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  $10\text{ k}\Omega$  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<sup>6</sup>, 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:

1. For the European market, the standard **IEC 60034-8 Rotating electrical machines - Part 8: Terminal markings and direction of rotation** [1] is used<sup>7</sup>,
2. For the American market, the NEMA standard, **Terminal Markings and Connections Three Phase Motors-single speed** is used.

<sup>6</sup>hopefully ...

<sup>7</sup>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.

Now the main question to ask is this:

	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.

*“Which standard do I follow?...”*

Living in an international world requires more attention to certain descriptors, quirks, and misdemeanours, as it is not that hard to buy an equipment across the pond and use it in the continent<sup>8</sup>. 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:

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

<sup>8</sup>For completeness sake, the terms (A, B, C) and (R, B, Y) are also used

# Chapter 2

## BLDC Control with Sensors

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#### Learning Outcomes

- To develop a working understanding of the block-commutation technique for BLDC motors.
- Working with MATLAB and SIMULINK to assess and assimilate the theoretical and practical knowledge.

**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<sup>1</sup>, you will be experimenting with this technique.

<sup>1</sup>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  $120^\circ$  commutation. In this control method, each phase conducts for  $120^\circ$ <sup>2</sup> during the positive and negative half of a BEMF cycle, and is **OFF** or un-energised for the remainder of the electrical cycle.

<sup>2</sup>electrical degrees of course

This algorithm requires rotor position information for every  $60^\circ$ , 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 **Fig. 2.2.**

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.



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].

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

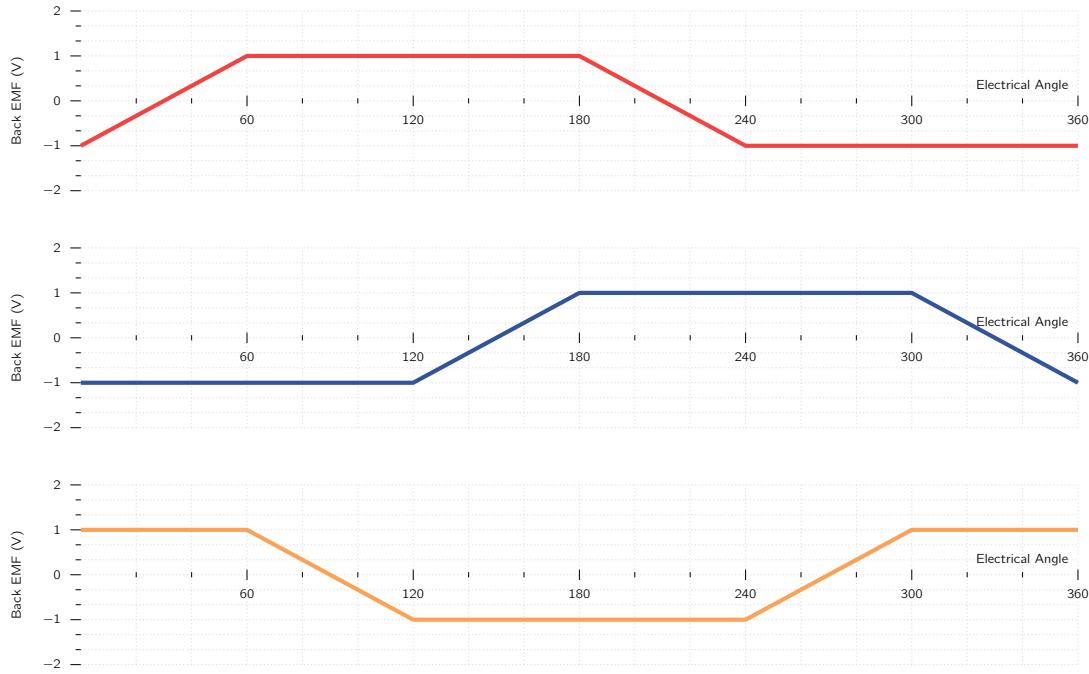


Figure 2.2.: The three-phase BEMF trapezoidal waveforms of a BLDC.

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. 2.4b** and **Fig. 2.4a**, 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. 2.4b** 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 first compile it. You can do this via:

1. Build > Build BLDC Motor Control

If successful, continue on with,

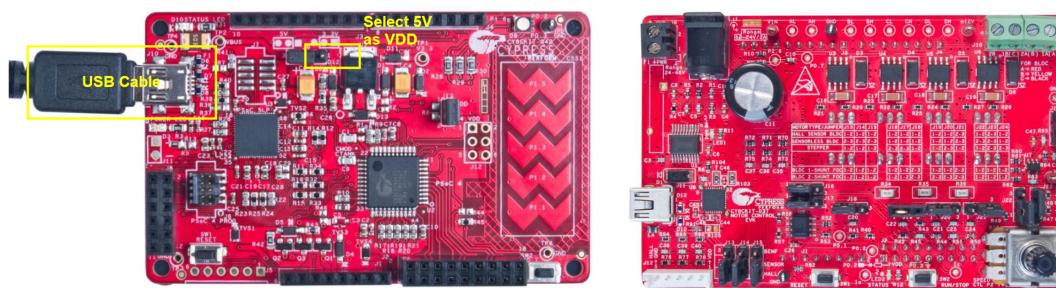
2. Debug > Program

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 likely be caused by the wrong jumper configuration of the CY8CKIT-037 which should be revisited.



**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<sup>3</sup>. These parameters are defined as a **struct** in [motor.h](#).

```

1 typedef struct
2 {
3     uint8 Dir;          /* Direction */
4     uint16 speedRpm;   /* Actual motor speed */
5     uint16 speedRpmRef; /* Motor speed command value */
6     uint16 kp;          /* Proportional coefficient of PID */
7     uint16 ki;          /* Integral coefficient of PID */
8     uint16 maxSpeedRpm; /* Motor parameters */
9     uint16 minSpeedRpm; /* Motor parameters */
10    uint8 polePairs;   /* Pole Pairs */
11    uint8 maxCurr;     /* Over current threshold */
12 }UI_DATA;

```

C.R. 1

c

<sup>3</sup>This information can be found in the motor datasheet.

The struct variable is in [motor.c](#) and is initialised in [motor.c](#) by function [Init\\_UI\\_FW](#).

```

1 UI_DATA UI_Data;
2
3 void Init_UI_FW(void)
4 {
5     /* Setting UI Initial parameter*/
6     UI_Data.Dir      = CLOCK_WISE;
7     UI_Data.maxSpeedRpm = 4000;
8     UI_Data.minSpeedRpm = 500;
9     UI_Data.speedRpmRef = 1000;
10    UI_Data.polePairs = 4;
11    UI_Data.maxCurr = MAX_CURR_MEDIUM;
12    UI_Data.kp = 500;
13    UI_Data.ki = 50;
14 }

```

C.R. 2

c

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

```

1 % VARIABLES -----
2 % Selection of switching commutation strategy 120/180
3 % Set 1 = 120 degree commutation
4 % Set 0 = 180 degree commutation
5 BLDC_120_180 = 1;
6
7 % Duty cycle:
8 % set the PWM duty cycle to control the output voltage/current
9 duty_cycle = 0.6;
10
11 % Fundamental frequency:
12 % set the electrical frequency corresponding to measurements
13 f_fundamental = 265; % Electrical frequency (Hz)
14 f_pwm = 20000; % Sampling/Switching frequency (Hz)
15
16 % Solver step size
17 sover_max_step = 1e-6; % Solver step size
18
19 Vdc = 24; % DC-link voltage (V)
20
21 % MOSFET PARAMETERS -----
22
23 Ron = 5e-3; % MOSFET On-Resistance (Ohm)
24 Rd = 70e-3; % Reverse Diode Resistance (Ohm)
25 Vf = 0.87; % Reverse Diode forward Voltage (V)
26
27 % MOTOR PARAMETERS -----
28 %
29 % NOTE: Calculated for BLY172S-24V-4000, delta configuration.
30
31 p = 4; % Pole pairs (-)
32 Rs = 3/2 * 0.8; % Serial resistance (Delta) (Ohm)
33 Ls = 3/2 * 1.2e-3; % Serial inductance (Delta) (H)
34
35 % Back EMF Constant (rad.V/s)
36 Ke = sqrt(2) * 3.35e-3 * 60 / 2 / pi / p;
37

```

```

38 % Based on the Commutation method choose a load angle
39 if BLDC_120_180 == 1
40     load_angle=pi/3;           % for 120
41 else
42     load_angle = pi/6;        % for 180
43 end

```

C.R. 4  
matlab

**modelBCPWM.slx** A SIMLINK model of motor and inverter implementing two (2) different commutation strategies; namely  $120^\circ$  and  $180^\circ$ . The major system can be seen in **Fig. 2.5.** Details

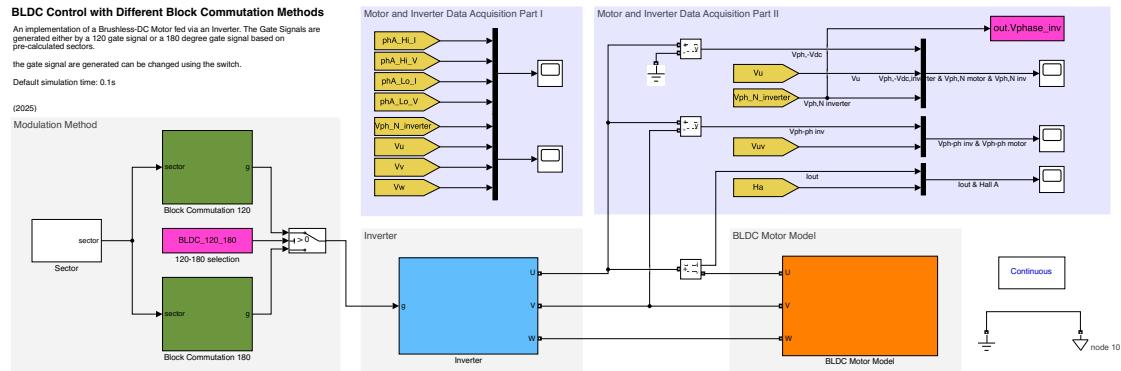


Figure 2.5.: The overview of the simulation of Commutation modulation of BLDC implemented in SIMULINK.

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

**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 B.

**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 B.

**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 B.

## 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.

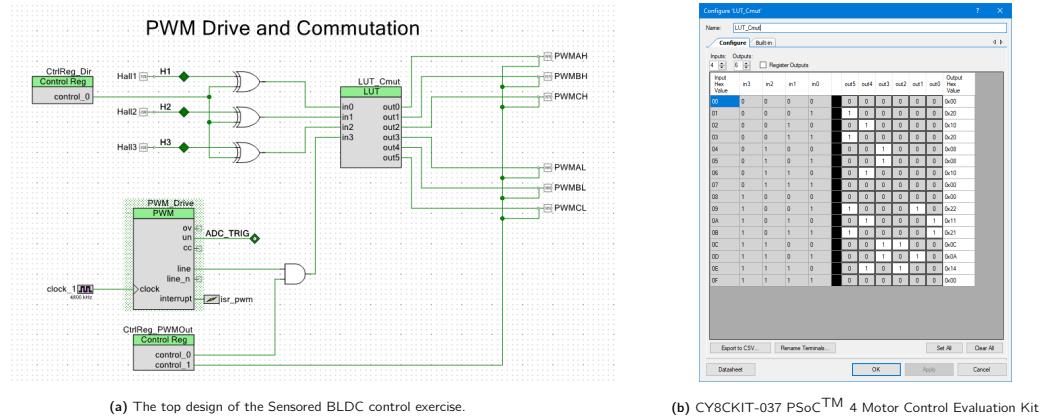


Figure 2.6.: Development board for use in the experiment.

3. Analyse the look up table (LUT) in `TopDesign.cysch` (**Fig. 2.6a**) shown in **Fig. 2.6b** which implements the  $120^\circ$  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)  $120^\circ$  with a duty-cycle of 1,
  - b)  $120^\circ$  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 along with how it should be formatted is given in Part 5.

# Chapter 3

## Sensorless BLDC Control

### Table of Contents

3.1. Preliminary Information . . . . .	27
3.2. The Experiment . . . . .	28
3.3. Required Measurements and Assessments . . . . .	31

#### 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 5.4** 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 energising two phases simultaneously, while the other phase is kept afloat. The key to BLDC commutation is to sense the rotor position and then energise 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 which we can call sensorless control.

## 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. 3.1b** and **Fig. 3.1a**, 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. 3.1b** 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 BLDC Motor Control.cywrk` project into PSoC Creator IDE workspace.

Once the **Sensorless BLDC Motor Control** code example loaded into PSoC Creator IDE, you must first 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.

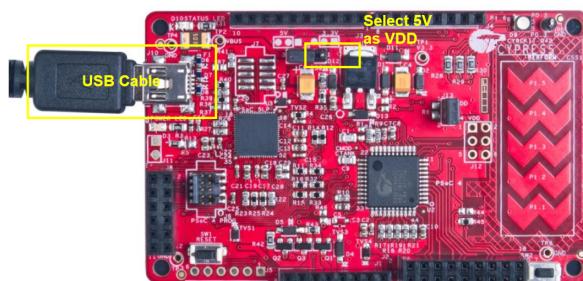
### 3.2.2. Simulation Framework

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

```
% 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.

```

6 % Duty cycle:
7 % set the PWM duty cycle to control the output voltage/current
8 duty_cycle = 0.6;
9
10 % Fundamental frequency:
11 % set the electrical frequency corresponding to measurements
12 f_fundamental = 265; % Electrical frequency (Hz)
13 f_pwm = 20000; % Sampling/Switching frequency (Hz)
14
15 % Solver step size
16 sover_max_step = 1e-6; % Solver step size
17
18 Vdc = 24; % DC-link voltage (V)
19
20 % MOSFET PARAMETERS -----
21
22 Ron = 5e-3; % MOSFET On-Resistance (Ohm)
23 Rd = 70e-3; % Reverse Diode Resistance (Ohm)
24 Vf = 0.87; % Reverse Diode forward Voltage (V)
25
26 % MOTOR PARAMETERS -----
27 %
28 % NOTE: Calculated for BLY172S-24V-4000, delta configuration.
29
30 p = 4; % Pole pairs (-)
31 Rs = 3/2 * 0.8; % Serial resistance (Delta) (Ohm)
32 Ls = 3/2 * 1.2e-3; % Serial inductance (Delta) (H)
33
34 % Back EMF Constant (rad.V/s)
35 Ke = sqrt(2) * 3.35e-3 * 60 / 2 / pi / p;
36
37 % Based on the Commutation method choose a load angle
38 if BLDC_120_180 == 1
39     load_angle=pi/3; % for 120
40 else
41     load_angle = pi/6; % for 180
42 end
43

```

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

**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 B.

**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 B.

**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 B.

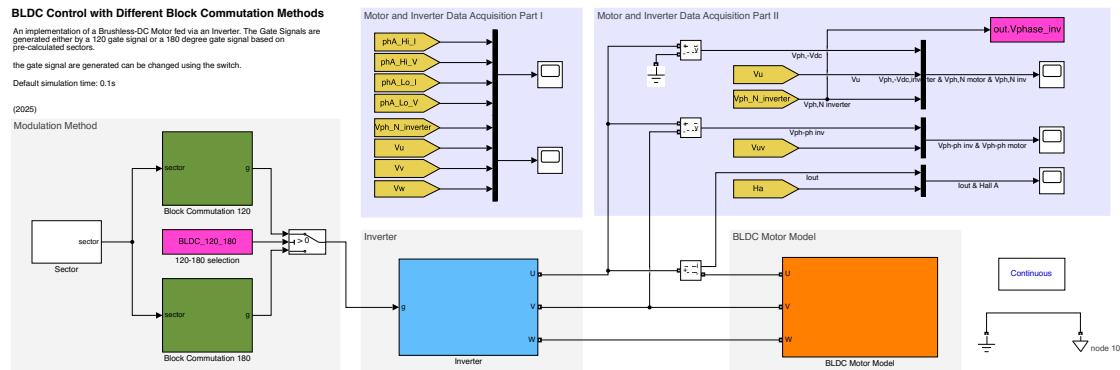


Figure 3.2.: The overview of the simulation of Commutation modulation of BLDC implemented in SIMULINK.

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  $-V_{dc}$ ,  $H_1$  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 sensor-less algorithm?
2. Generate time diagram explaining the commutation strategy and its implementation with particular regard to the BEMF measurement time intervals
3. Compare the achieved results with the implementation in the simulation.
4. Measure the phase A voltage with respect to  $-V_{dc}$ . In this case  $-V_{dc}$  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.

A Detailed instruction on what is required for the report along with how it should be formatted is given in Part 5.

# Chapter 4

## Sensorless FOC of PMSM

### Table of Contents

4.1. Preliminary Information . . . . .	33
4.2. The Experiment . . . . .	35
4.3. Required Measurements and Assessments . . . . .	39

#### 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 and not take the required position at all.

Low pole pair motors 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 **BEMF<sup>1</sup>**, which makes it possible to determine its position, therefore all methods for determining the initial position of the rotor is using:

- a. a special test signal fed to the stator of the motor, and
- b. a special algorithm for analysing the response to it.

<sup>1</sup>The electromotive force (EMF) manifesting as a voltage that opposes the change in current which induced 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 3<sup>rd</sup> 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<sup>2</sup>. 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.

<sup>2</sup>The signal is modulated

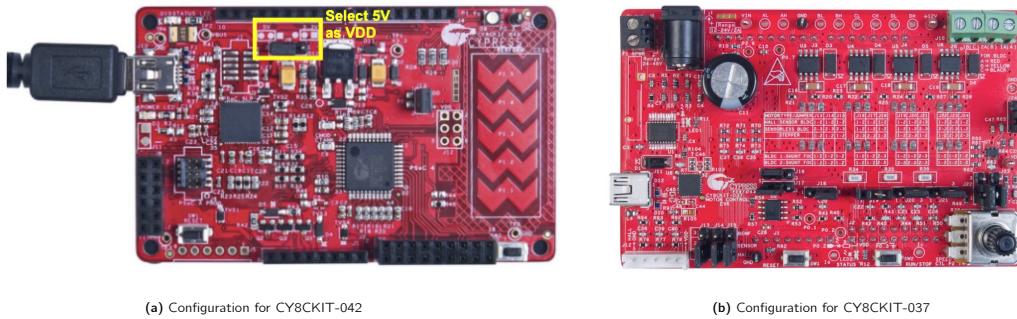


Figure 4.1.: The boards which will be used in this experiment. Make sure they are connected once the proper configuration has been done on them with CY8CKIT-042 being on the bottom and CY8CKIT-037 being on top.

## 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 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 first 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 likely be caused by the wrong jumper configuration of the CY8CKIT-037 which should be revisited.

### 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<sup>3</sup>. 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)

<sup>3</sup>As the name implies, it is an init file and SIMULINK cannot run anything without initialisation.

```

1 % VARIABLES ----- C.R. 1
2
3 % Setup for FOC
4 % Set 1 = FOC
5 % Set 0 = Free Angle
6 FOC = 1;
7
8 Isetpoint = 5; % used if FOC = 1
9 Vsetpoint = 5; % used if FOC = 0
10
11 % Fundamental frequency:
12 % set the electrical frequency corresponding to measurements
13 f_fundamental = 100; % Electrical frequency (Hz)
14 f_pwm = 20000; % Sampling/Switching frequency (Hz)
15
16 % Solver step size
17 sover_max_step = 1e-6; % Solver step size
18
19 Vdc = 24; % DC-link voltage (V)
20
21 % MOSFET PARAMETERS -----
22
23 Ron = 5e-3; % MOSFET On-Resistance (Ohm)
24 Rd = 70e-3; % Reverse Diode Resistance (Ohm)
25 Vf = 0.87; % Reverse Diode forward Voltage (V)
26
27 % MOTOR PARAMETERS -----
28 %
29 % NOTE: Calculated for BLY172S-24V-4000, delta configuration.
30
31 p = 4; % Pole pairs (-)
32 Rs = 3/2 * 0.8; % Serial resistance (Delta) (Ohm)
33 Ls = 3/2 * 1.2e-3; % Serial inductance (Delta) (H)
34
35 % Back EMF Constant (rad.V/s)
36 Ke = sqrt(2) * 3.35e-3 * 60 / 2 / pi / p;
37
38 load_angle_offset = 120/180*pi;
39
40 % Additional calculations for FOC
41 if FOC == 1
42     Iref = Isetpoint;
43     E = Ke * 2 * pi * f_fundamental / sqrt(3);
44     Vd = E + 1/3 * Rs * Iref;
45     Vq = 2 * pi * f_fundamental * Ls * 1/3 * Iref;
46     V_uvw = sqrt(Vd^2 + Vq^2);
47     voltage_angle = atan2(Vq,Vd);
48 else
49     V_uvw = Vsetpoint;
50 end
51
52 %voltage_angle = 0;

```

```

53
54 load_angle = load_angle_offset - voltage_angle;

```

C.R. 2  
matlab

`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).

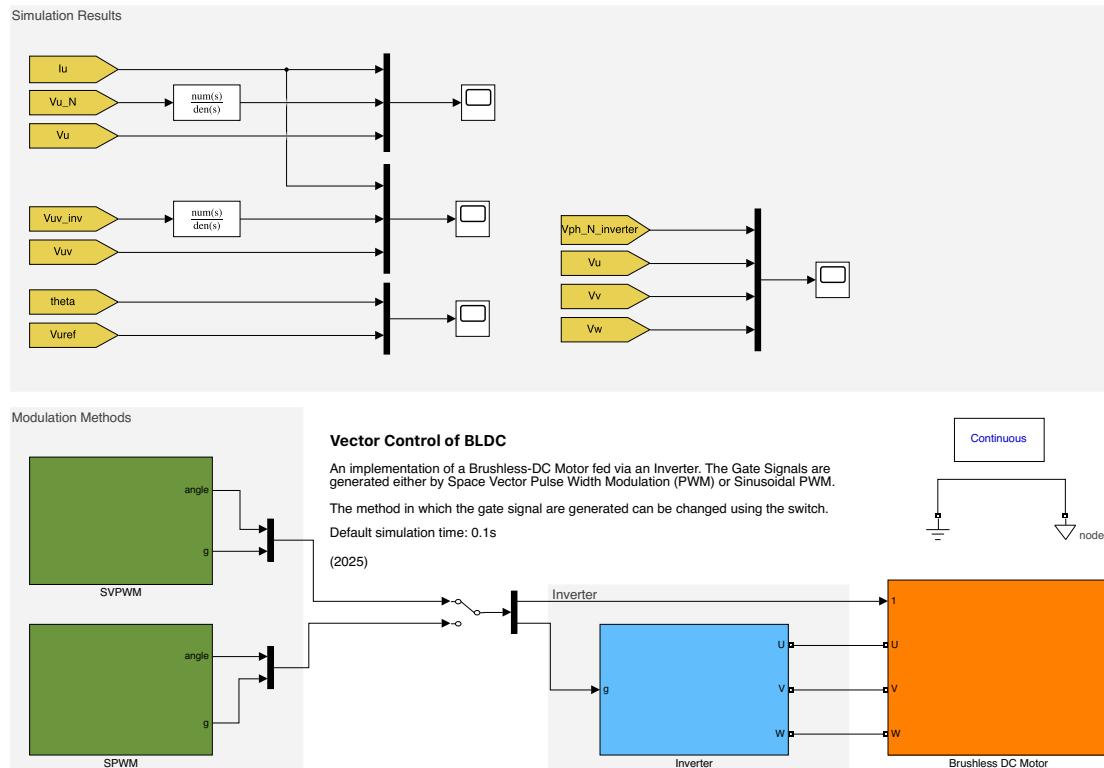


Figure 4.2.: The SIMULINK model you have been given for this experiment.

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

`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 B.

`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 B.

`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 B.

### 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  $-V_{dc}$ ,  $H_1$  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  $-V_{dc}$ . In this case  $+V_{dc}$  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.

A Detailed instruction on what is required for the report along with how it should be formatted is given in Part 5.

# Chapter 5

## Lab Report Requirements

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5.4. Requirements of the Report . . . . .	46

### 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<sup>1</sup>:

- |   |  |
|---|--|
| <ul style="list-style-type: none"> <li>1. Title Page,</li> <li>2. Abstract</li> <li>3. Introduction</li> <li>4. Methods and Materials</li> <li>5. Experimental Procedure</li> <li>6. Results</li> </ul> | <ul style="list-style-type: none"> <li>7. Discussion</li> <li>8. Conclusion</li> <li>9. References</li> <li>10. Appendices</li> <li>11. Further Reading (if applicable)</li> </ul> |
|---|--|

<sup>1</sup>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 thirty (30) 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-Scherrer Method").

The language will also play a role as the header and title format needs to be adjusted based on the language

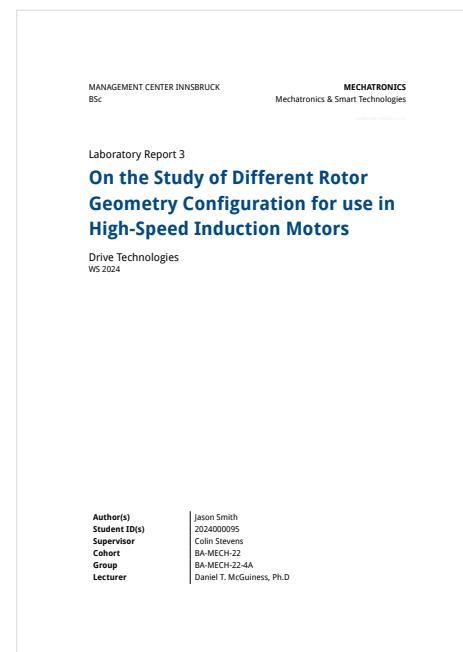


Figure 5.1.: An example of a good title page for a report or an assignment. This title page was created using the `mcidoc` document class which can be found [here](#).

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<sup>2</sup>
2. Describing the key findings of the experiment,
3. Their significance, and
4. Major conclusions.

<sup>2</sup>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 subject's 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<sup>3</sup>. State the topic of your report clearly and concisely, in one or two sentences. As an example please look below [10]:

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 provide 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 Bragg's 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 statements to be written in **present tense**:

*"The purpose of this report is . . ."*

*"Bragg's Law for diffraction is . . ."*

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

<sup>3</sup>This is generally known as the *literature review* within the academic circle.

## 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.**

Manufacturer	Model	Description
Anaheim 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 GSa s-

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

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

*"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,  $R = 0.1244 \text{ nm}$  ..."*

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

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

<sup>4</sup>e.g., **Figure 1.1:**  
Input Frequency  
and Capacitor  
Value

choice<sup>5</sup> 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.

<sup>5</sup> MATLAB, gnuplot, pstricks, pgfplots, ...

An important strategy for making your results effective is to draw the reader's 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  $\text{\LaTeX}$ . 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  $\text{\LaTeX}$  such as Overleaf or the TeX stack-exchange and of course the following books would give you more information than you could possibly need<sup>6</sup>:

- The  $\text{\LaTeX}$  Companion (3<sup>rd</sup> Edition)
- The  $\text{\LaTeX}$  Graphics Companion (2<sup>nd</sup> Edition)

The author of this section has also authored a  $\text{\LaTeX}$  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 `mci.doc`.

## 5.4. Requirements of the Report

- The report must conform to the MCI writing guidelines.
- Each laboratory session must have its own literature review, methods, equipment, etc. the structure which has been discussed in this part. Therefore please read this Part prior to writing your report.

### Bibliography

- [1] J.-F. Geras and J. Saari, "Performance calculation for a high-speed solid-rotor induction motor," *IEEE transactions on industrial electronics*, vol. 59, no. 6, pp. 2689–2700, 2011.
- [2] J. Pyhälä, "The high-speed induction motor: Calculating the effects of solid-rotor material on machine characteristics," *Acta Polytechnica Scandinavica, Electrical Engineering Series*(Finland), vol. 68, 1991.
- [3] J. Lähteenmäki et al., *Design and voltage supply of high-speed induction machines*. Helsinki University of Technology, 2002.
- [4] J. Saari et al., *Thermal analysis of high-speed induction machines*. Helsinki University of Technology, 1998.

<sup>6</sup>Of course these are recommendations for people who want to understand  $\text{\LaTeX}$  as a programming language rather than just a template.

**Figure 5.2.:** An example of a bibliography using Bib-Tex and IEEE citation standard. This bibliography entry was created using the `mci.doc` document class which can be found [here](#).

- The literature review should cover information about the lab topic and include proper citations to journals/publications.
- The report must be submitted within two (2) weeks after the last appointment which will be done via SAKAI.
- Make sure the report is written in a scientific manner and written in a form to make sure it is reproducible.
- The report should also contain a summary of the FOC approach with particular focus on the sensorless angle and speed estimation shall be part of the final report, which could be integrated to the literature review for Part 5.
- Try to keep the report under thirty (30) pages.
- Make sure all your photos are taken of highest quality and photos of oscilloscope will **NOT** be accepted. Data acquisition from the oscilloscope needs to be done via USB.
- During submission you must also submit all your data along with your PDF.
- If  $\text{\LaTeX}$  is chosen as the primary method, all of its source code must be sent to SAKAI.

**Part II.**

**Appendix**

# A

## Appendix

## Simulink Schematics

### Table of Contents

A.1. Introduction . . . . .	i
A.2. Modelling the Block Commutation . . . . .	ii
A.3. Modelling the Field Oriented Control . . . . .	viii

### A.1. Introduction

This appendix 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  $120^\circ$   $180^\circ$ .

*The following pages contains the models.*

## A.2. Modelling the Block Commutation

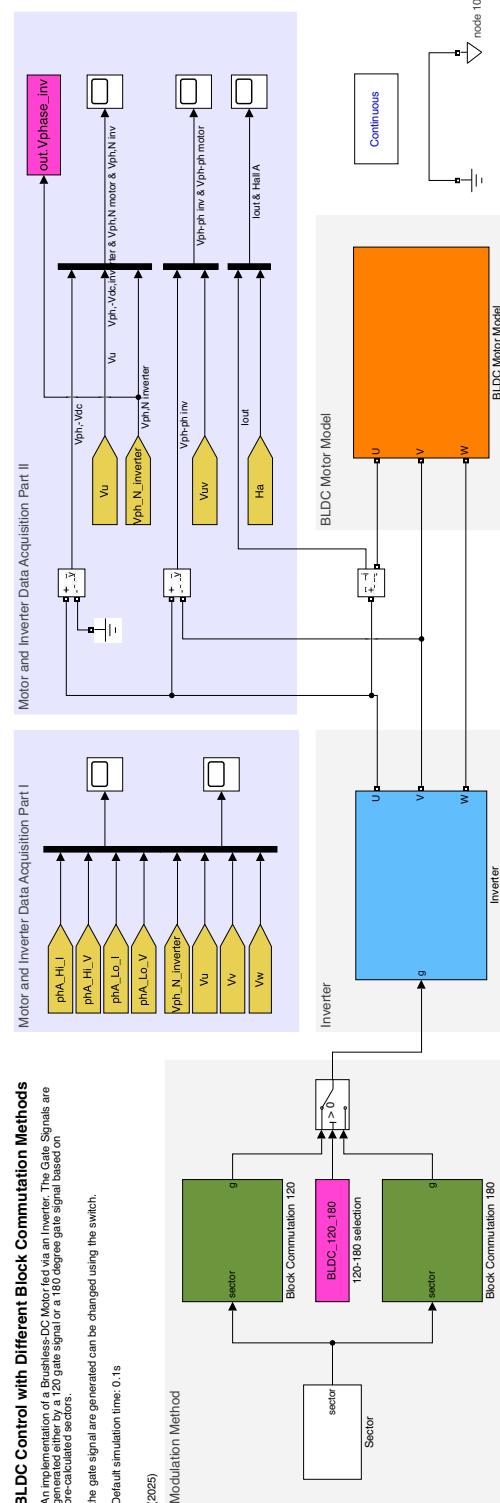


Figure A.1.: All the SIMULINK schematics for Sensor and sensor-less BLDC Control (Page 1).

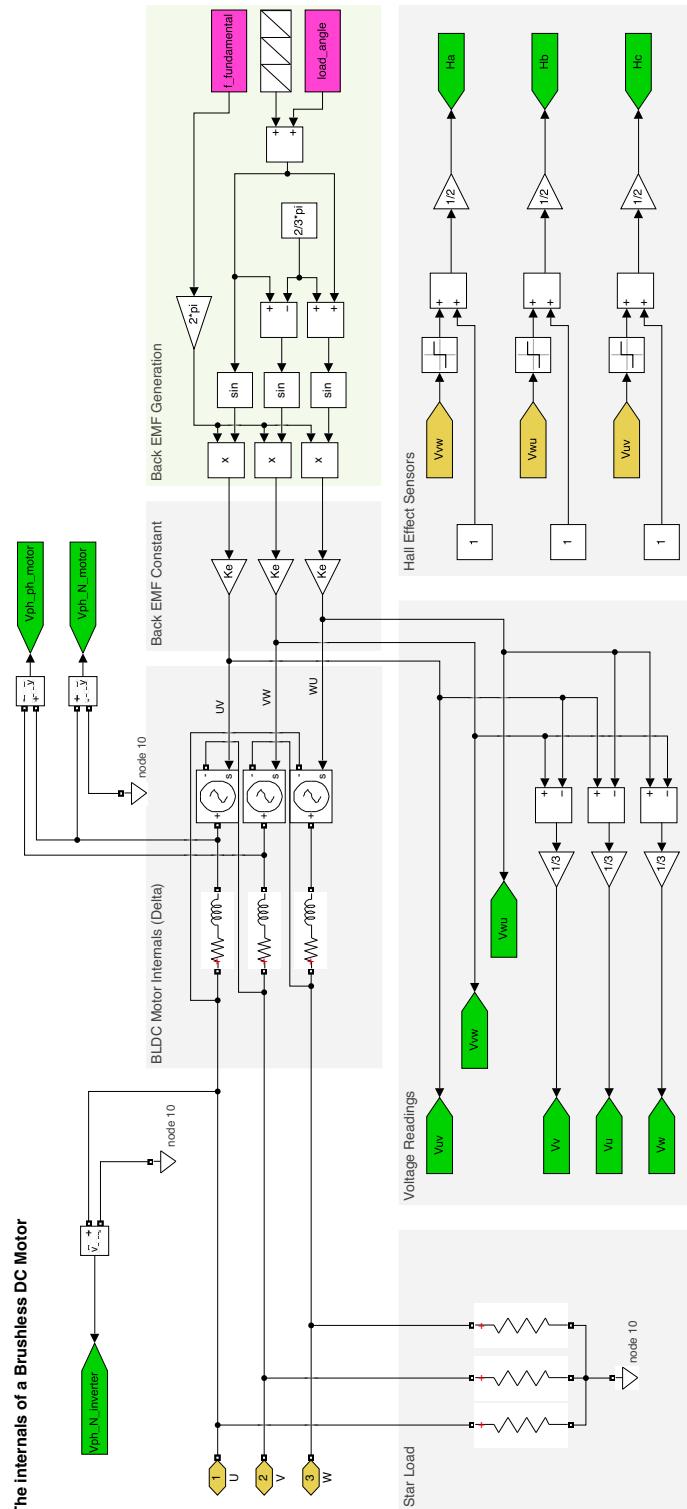


Figure A.2.: All the SIMULINK schematics for Sensor and sensor-less BLDC Control (Page 2).

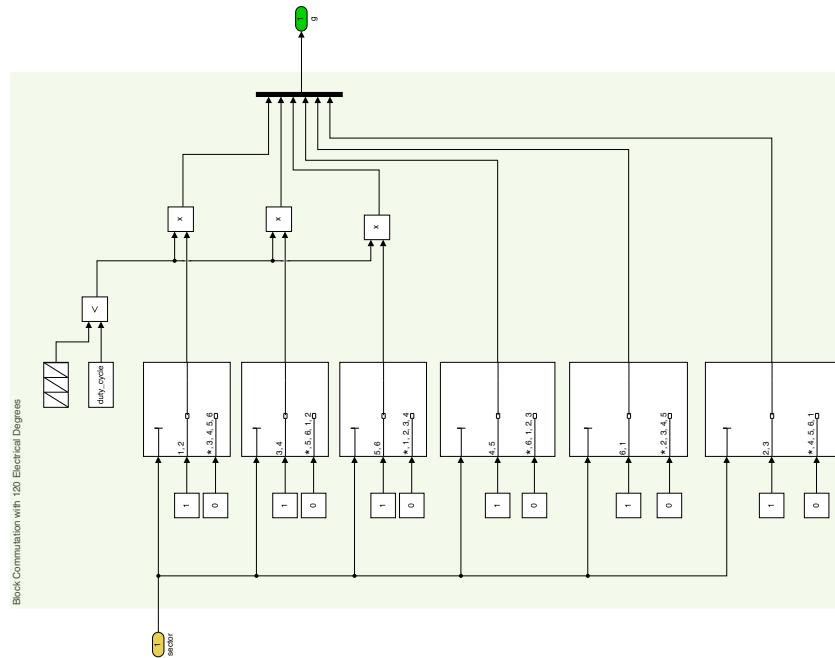


Figure A.3.: All the SIMULINK schematics for Sensor and sensor-less BLDC Control (Page 3).

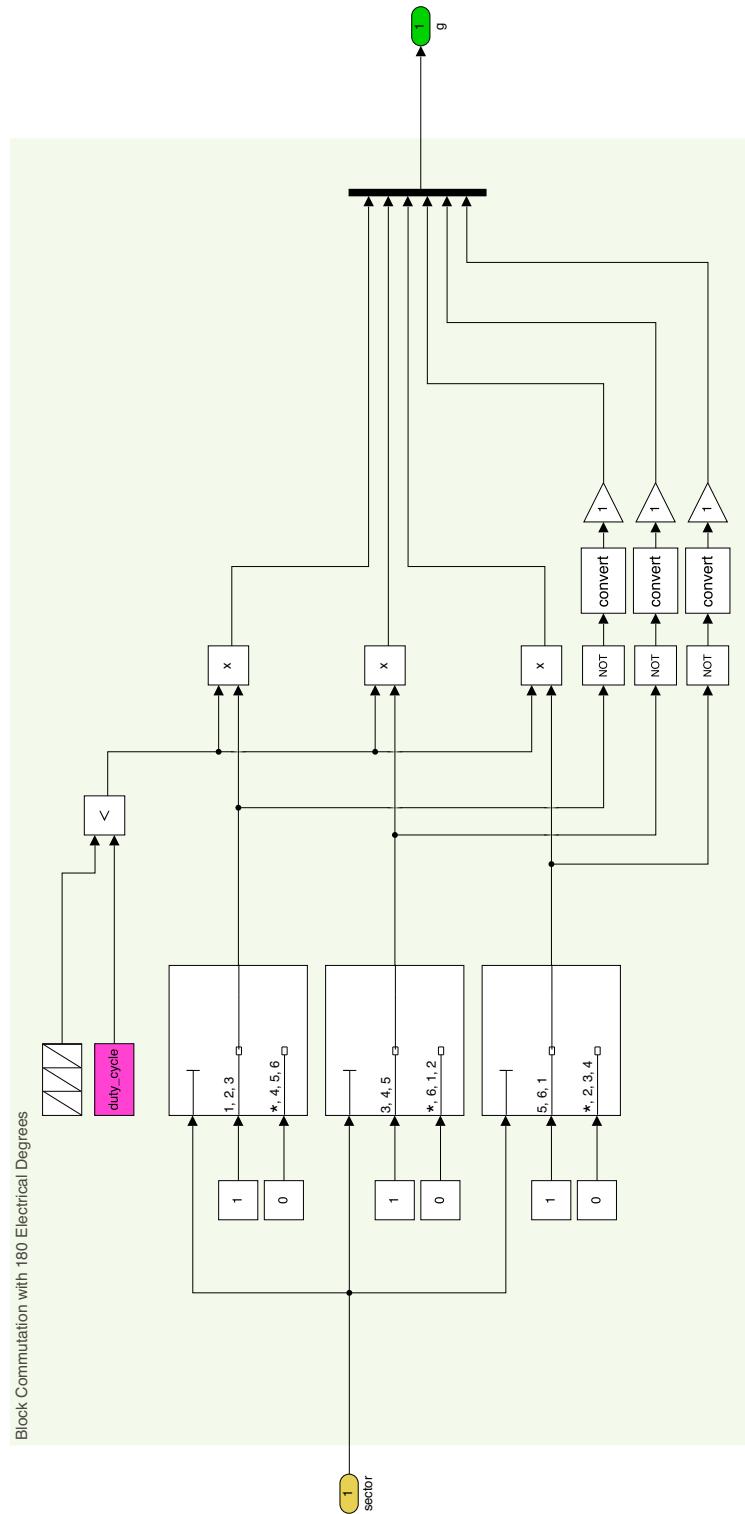


Figure A.4.: All the SIMULINK schematics for Sensor and sensor-less BLDC Control (Page 4).

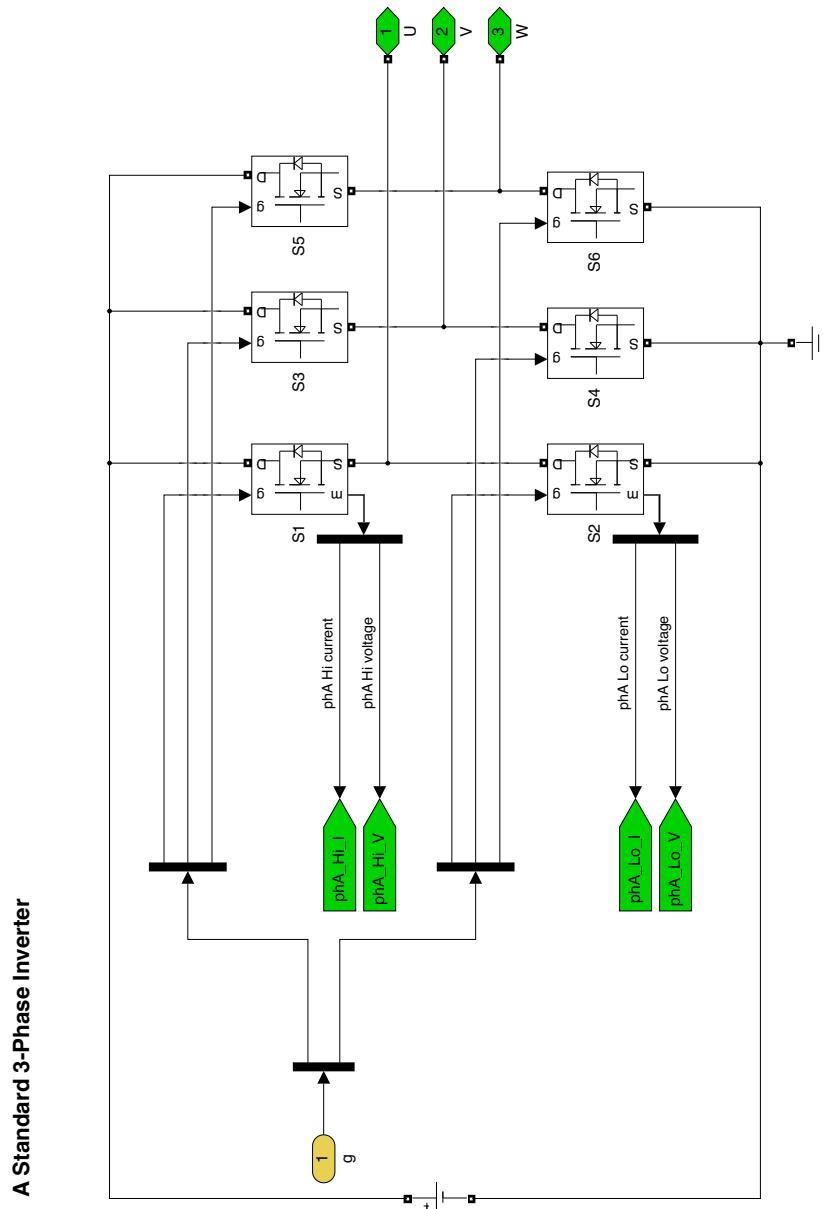


Figure A.5.: All the SIMULINK schematics for Sensor and sensor-less BLDC Control (Page 5).

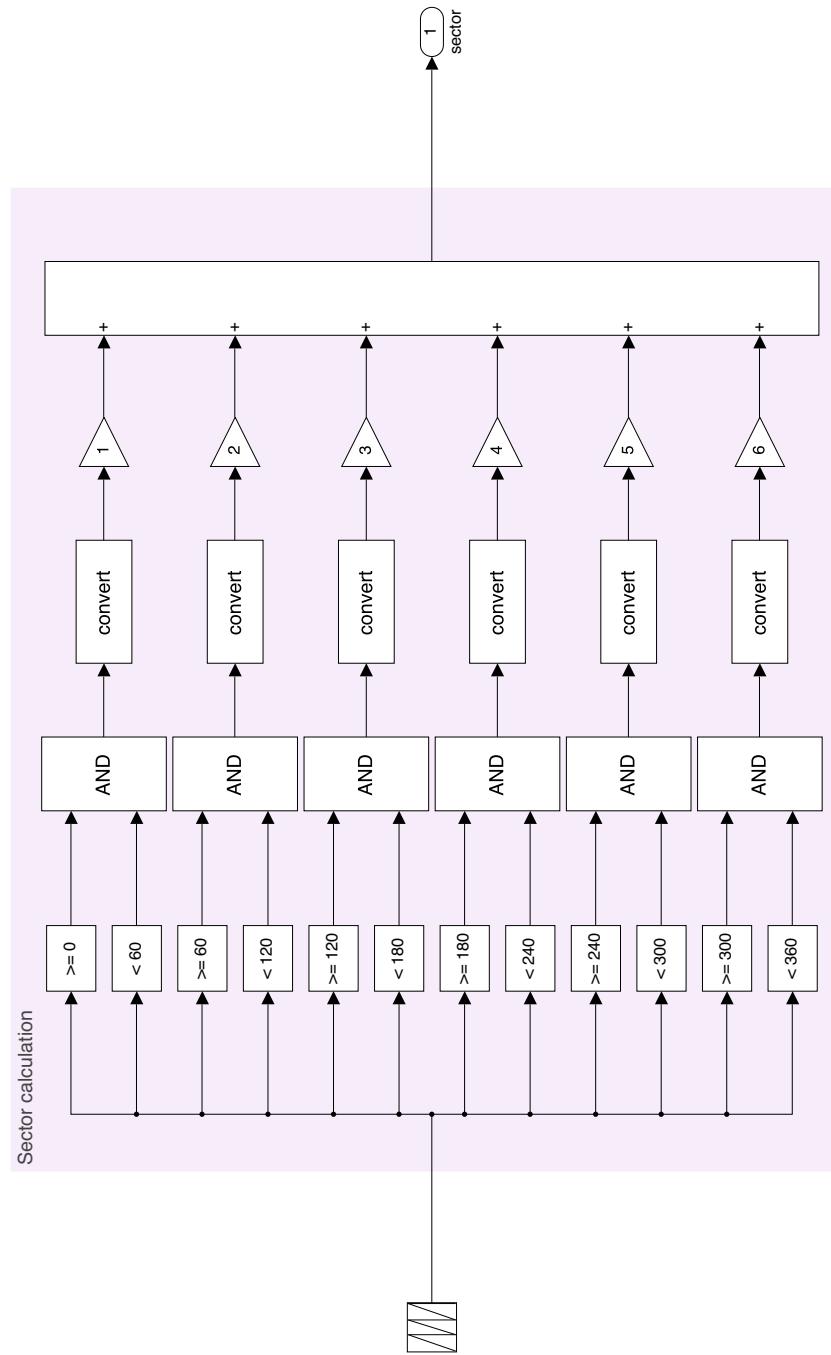


Figure A.6.: All the SIMULINK schematics for Sensor and sensor-less BLDC Control (Page 6).

### A.3. Modelling the Field Oriented Control

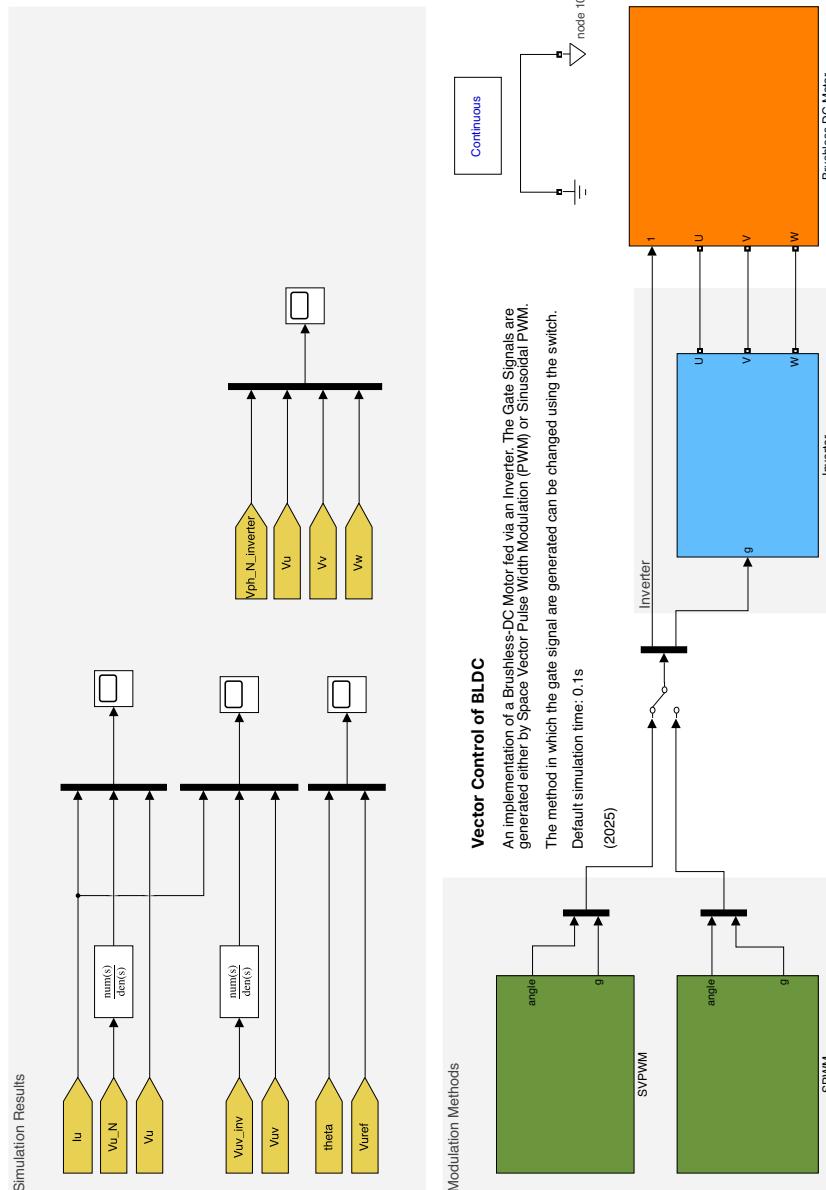


Figure A.7.: Schematic of a BLDC control with FOC (Page 1).

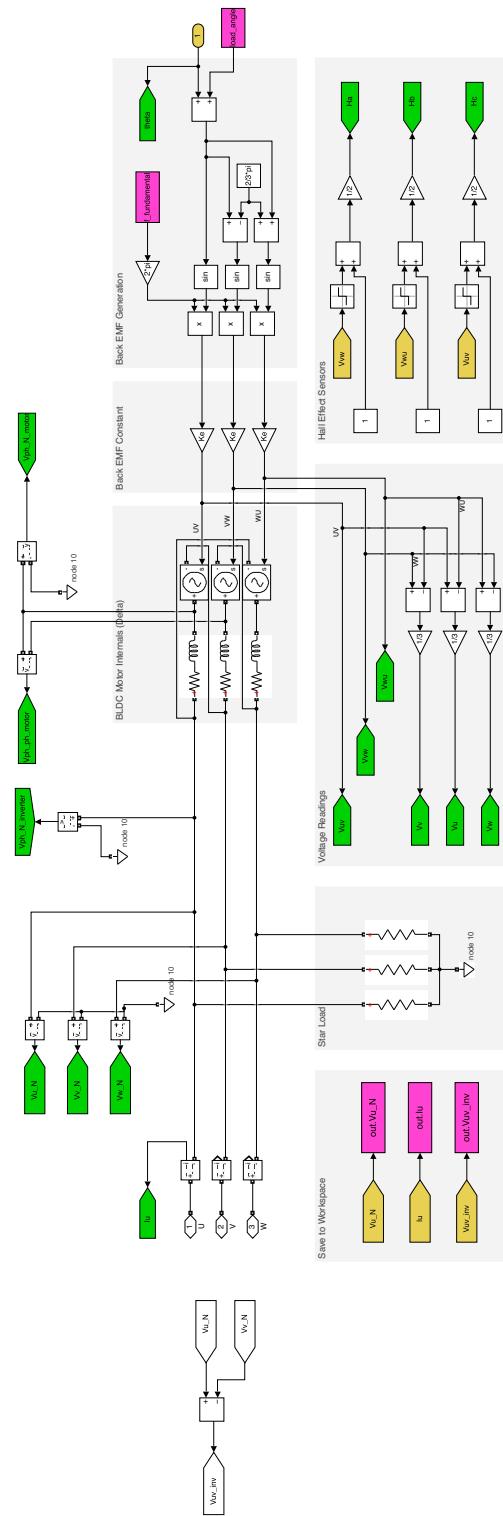


Figure A.8.: Schematic of a BLDC control with FOC (Page 2).

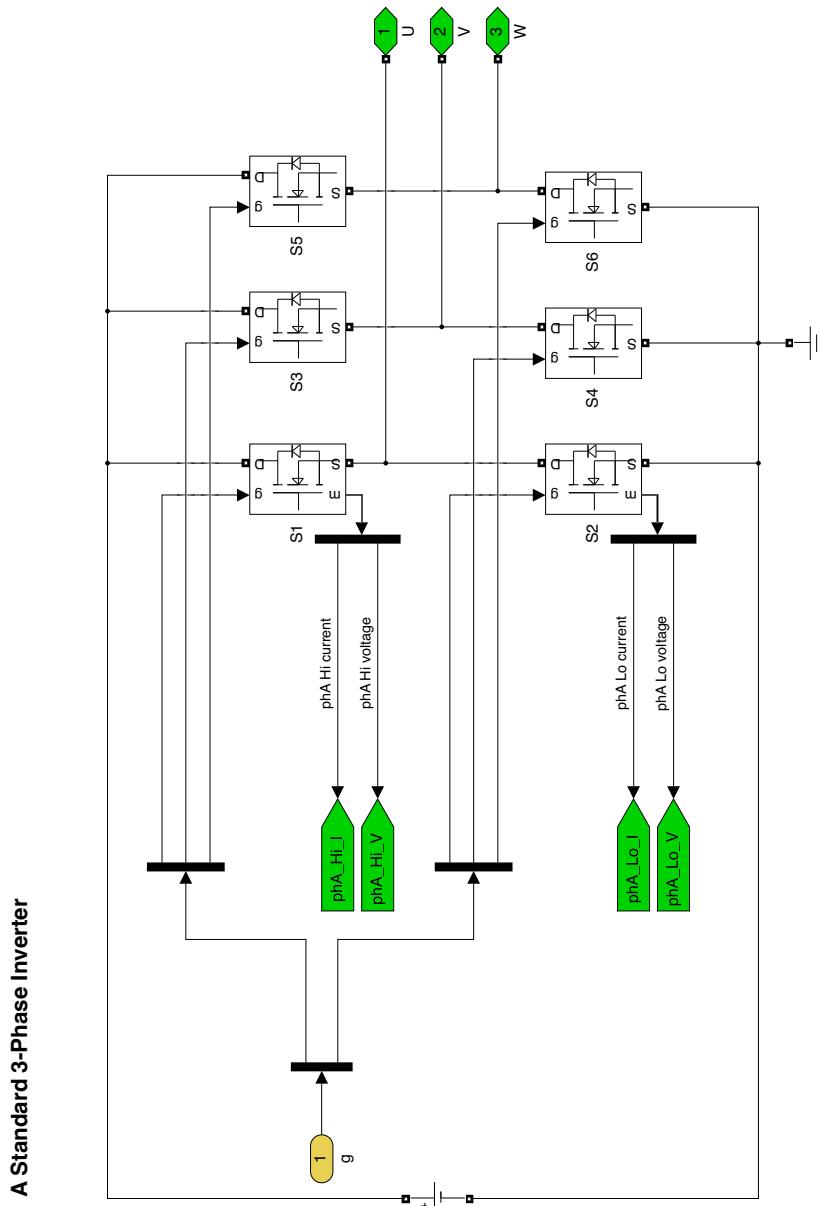


Figure A.9.: Schematic of a BLDC control with FOC (Page 3).

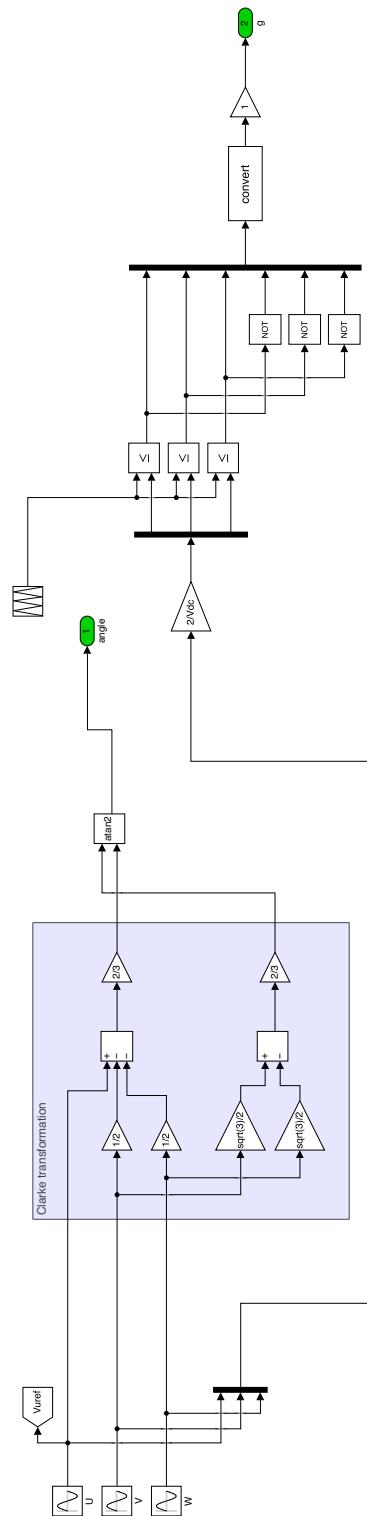


Figure A.10.: Schematic of a BLDC control with FOC (Page 4).

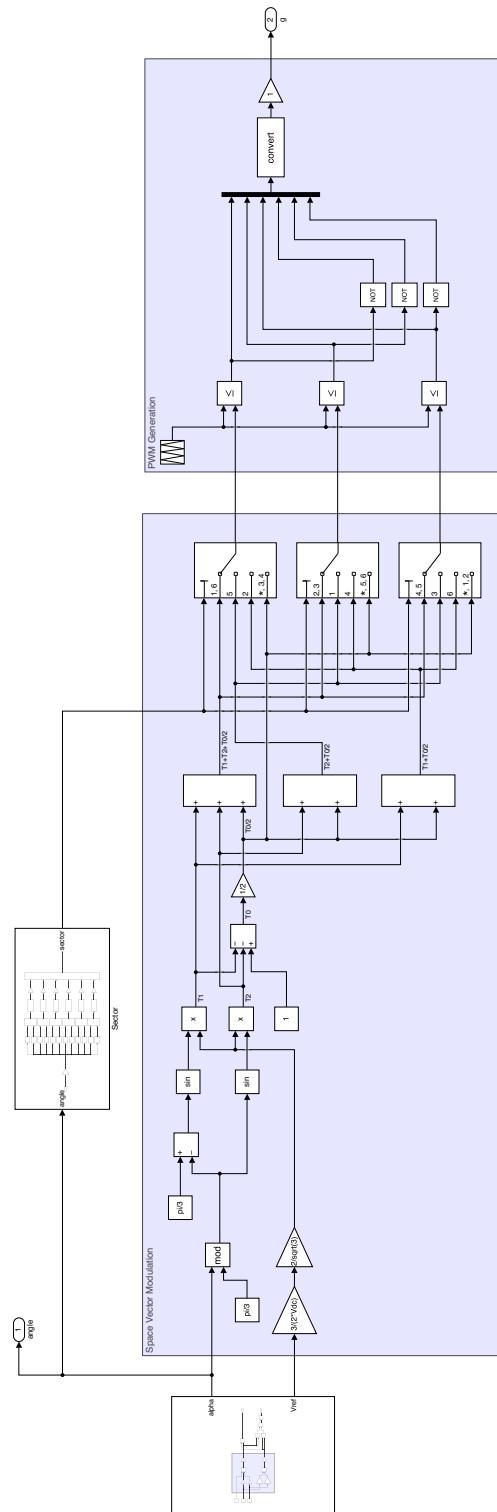


Figure A.11.: Schematic of a BLDC control with FOC (Page 5).

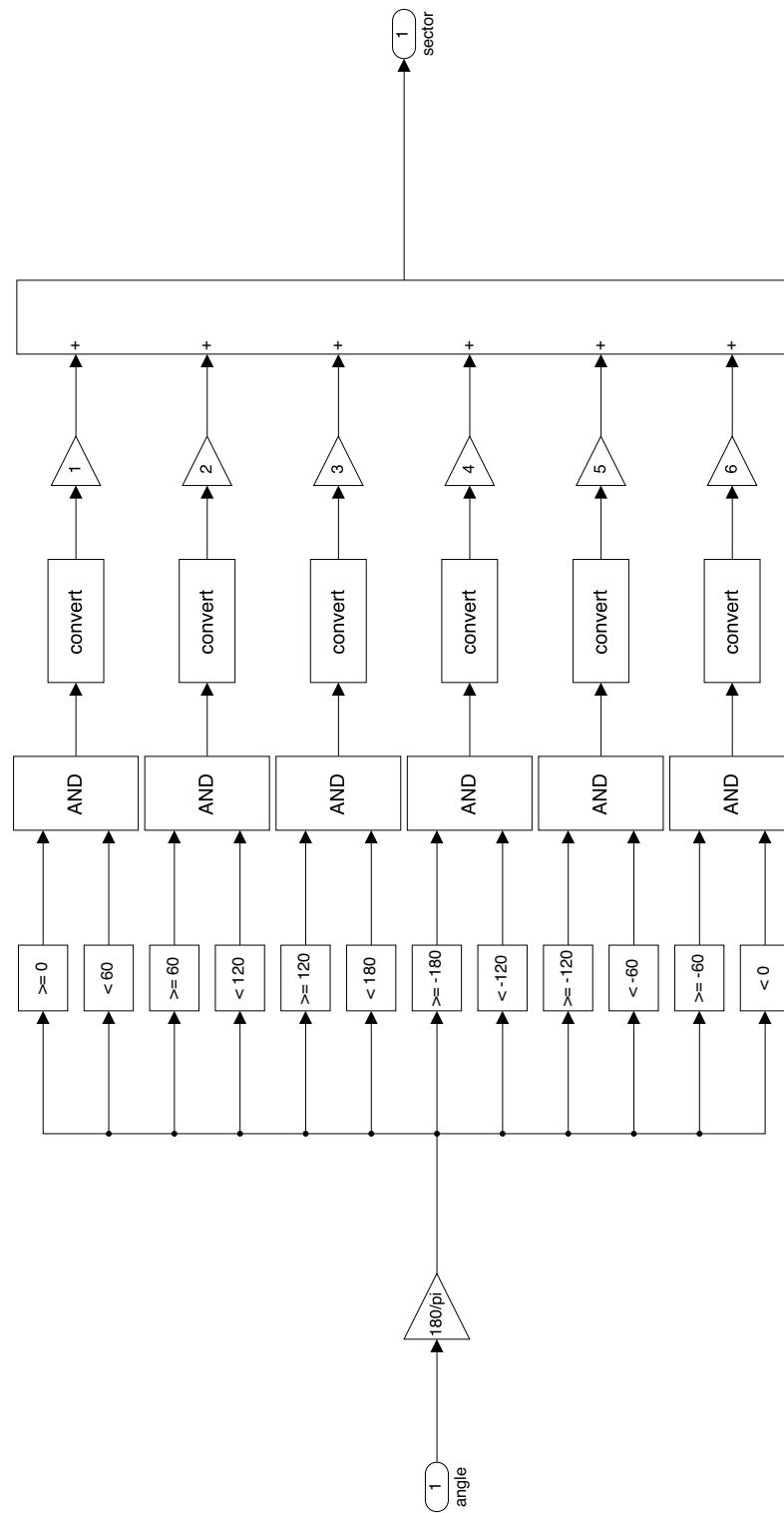


Figure A.12.: Schematic of a BLDC control with FOC (Page 6).

# Appendix **B**

## MATLAB Codes

### Table of Contents

B.1. Introduction . . . . .	xiv
B.2. MATLAB Codes . . . . .	xv

### B.1. Introduction

This appendix gives a detailed printing of all the codes used in the laboratory manual. All these MATLAB models have been provided to you via GitHub.

*The following pages contains the MATLAB scripts.*

## B.2. MATLAB Codes

### B.2.1. initBCPWM

```

1 %{
2 ****
3 *      Initialisation script for use in Block Commutation Simulation of a *
4 *      Brushless DC Motor using SIMULINK. Please run this script PRIOR to   *
5 *      running the SIMULINK model.                                         *
6 *                                                               *
7 *      (2025)                                                 *
8 ****
9 %}
10
11 % CLEANING OUT THE HOUSE -----
12 % Clear the workspace from all previous statements/values
13 clc;
14 clear;
15 close all;
16
17 % VARIABLES -----
18 % Selection of switching commutation strategy 120/180
19 % Set 1 = 120 degree commutation
20 % Set 0 = 180 degree commutation
21 BLDC_120_180    = 1;
22
23 % Duty cycle:
24 % set the PWM duty cycle to control the output voltage/current
25 duty_cycle      = 0.6;
26
27 % Fundamental frequency:
28 % set the electrical frequency corresponding to measurements
29 f_fundamental   = 265;           % Electrical frequency          (Hz)
30 f_pwm            = 20000;         % Sampling/Switching frequency (Hz)
31
32 % Solver step size
33 sover_max_step  = 1e-6;          % Solver step size
34
35 Vdc              = 24;           % DC-link voltage             (V)
36
37 % MOSFET PARAMETERS -----
38
39 Ron              = 5e-3;          % MOSFET On-Resistance        (Ohm)
40 Rd               = 70e-3;          % Reverse Diode Resistance    (Ohm)
41 Vf               = 0.87;          % Reverse Diode forward Voltage (V)
42
43 % MOTOR PARAMETERS -----
44 %
45 % NOTE: Calculated for BLY172S-24V-4000, delta configuration.
46

```

```

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

50
51 % Back EMF Constant (rad.V/s)
52 Ke = sqrt(2) * 3.35e-3 * 60 / 2 / pi / p;

53
54 % Based on the Commutation method choose a load angle
55 if BLDC_120_180 == 1
56     load_angle=pi/3; % for 120
57 else
58     load_angle = pi/6; % for 180
59 end
60
61 % END OF CODE -----

```

C.R. 2

matlab

## B.2.2. initSVPWM

```

1 %
2 ****
3 *      Initialisation script for use in Space Vector modulation of a *
4 *      Brushless DC Motor using SIMULINK. Please run this script PRIOR to *
5 *      running the SIMULINK model. *
6 * *
7 *      (2025) *
8 ****
9 %

10
11 % CLEANING OUT THE HOUSE -----
12 % Clear the workspace from all previous statements/values
13 clc;
14 clear;
15 close all;

16
17 % VARIABLES -----
18
19 % Setup for FOC
20 % Set 1 = FOC
21 % Set 0 = Free Angle
22 FOC = 1;

23
24 Isetpoint = 5; % used if FOC = 1
25 Vsetpoint = 5; % used if FOC = 0

26
27 % Fundamental frequency:
28 % set the electrical frequency corresponding to measurements
29 f_fundamental = 100; % Electrical frequency (Hz)
30 f_pwm = 20000; % Sampling/Switching frequency (Hz)
31

```

C.R. 3

matlab

```

32 % Solver step size
33 sover_max_step = 1e-6; % Solver step size
34
35 Vdc = 24; % DC-link voltage (V)
36
37 % MOSFET PARAMETERS -----
38
39 Ron = 5e-3; % MOSFET On-Resistance (Ohm)
40 Rd = 70e-3; % Reverse Diode Resistance (Ohm)
41 Vf = 0.87; % Reverse Diode forward Voltage (V)
42
43 % MOTOR PARAMETERS -----
44 %
45 % NOTE: Calculated for BLY172S-24V-4000, delta configuration.
46
47 p = 4; % Pole pairs (-)
48 Rs = 3/2 * 0.8; % Serial resistance (Delta) (Ohm)
49 Ls = 3/2 * 1.2e-3; % Serial inductance (Delta) (H)
50
51 % Back EMF Constant (rad.V/s)
52 Ke = sqrt(2) * 3.35e-3 * 60 / 2 / pi / p;
53
54 load_angle_offset = 120/180*pi;
55
56 % Additional calculations for FOC
57 if FOC == 1
58     Iref = Isetpoint;
59     E = Ke * 2 * pi * f_fundamental / sqrt(3);
60     Vd = E + 1/3 * Rs * Iref;
61     Vq = 2 * pi * f_fundamental * Ls * 1/3 * Iref;
62     V_uvw = sqrt(Vd^2 + Vq^2);
63     voltage_angle = atan2(Vq,Vd);
64 else
65     V_uvw = Vsetpoint;
66 end
67
68 %voltage_angle = 0;
69
70 load_angle = load_angle_offset - voltage_angle;
71
72 % END OF CODE -----

```

### B.2.3. doFilter

```

1 function y = doFilter(x,yFs)
2 %DOFILTER Filters input x and returns output y.
3
4 % MATLAB Code
5 % Generated by MATLAB(R) 9.8 and DSP System Toolbox 9.10.

```

```

6 % Generated on: 30-Mar-2022 16:01:35
7
8 persistent Hd;
9
10 if isempty(Hd)
11
12     Fpass = 1000;      % Passband Frequency
13     Fstop = 5000;      % Stopband Frequency
14     Apass = 1;         % Passband Ripple (dB)
15     Astop = 40;        % Stopband Attenuation (dB)
16     Fs    = yFs;       % Sampling Frequency
17
18     h = fdesign.lowpass('fp,fst,ap,ast', Fpass, Fstop, Apass, Astop, Fs);
19
20     Hd = design(h, 'equiripple', ...
21                 'MinOrder', 'any', ...
22                 'StopbandShape', 'flat');
23
24
25     set(Hd, 'PersistentMemory', true);
26
27 end
28
29 y = filter(Hd,x);
30
31

```

#### B.2.4. doSigAnalysis

```

1 function [f,P1,timeVector,voltageVector_LP]=do_sig_analysis(timeVector,voltageVector)
2
3 Fs=1/mean(diff(timeVector));
4 T = 1/Fs;           % Sampling period
5 L = length(voltageVector);          % Length of signal
6 t = (0:L-1)*T;        % Time vector
7
8 voltageVector_LP = doFilter(voltageVector,Fs);
9 %plot(timeVector,voltageVector,timeVector,voltageVector_LP);
10
11 X=voltageVector;
12 Y = fft(X);
13 P2 = abs(Y/L);
14 P1 = P2(1:L/2+1);
15 P1(2:end-1) = 2*P1(2:end-1);
16 f = Fs*(0:(L/2))/L;
17 %figure
18 %plot(f,P1)
19 end

```

# Glossary

**BEMF** Back Electro-motive Force. 5, 19, 20, 27, 28, 31, 34, 35

**BLDC** Brushless DC. viii–xiii, 5, 6, 10–13, 15, 18–22, 25, 27, 28

**DC** Direct Current. 11, 13, 19

**DIN** Deutschen Instituts für Normung. 16

**FOC** Field Oriented Control. viii–xiii, 6, 33, 35, 36

**PM** Permanent Magnet. 5, 19

**PMSM** Permanent Magnet Synchronous Motor. 10, 11, 13, 19, 33

# Bibliography

- [1] *Rotating electrical machines - Part 8: Terminal markings and direction of rotation*. Standard. Geneva, CH: International Electrotechnical Commision, 2007.
- [2] Deepak Mohanraj et al. "A review of BLDC motor: state of art, advanced control techniques, and applications". In: *ieee Access* 10 (2022), pp. 54833–54869.
- [3] CR Edwin Selva Rex et al. "Speed Control of BLDC Motor Using Trapezoidal Commutation & PWM Technique". In: *2023 4th IEEE Global Conference for Advancement in Technology (GCAT)*. IEEE. 2023, pp. 1–5.
- [4] Greensky Power. *What are the disadvantages of brushless DC motor?* 2023. URL: <https://greensky-power.com/disadvantages-of-brushless-dc-motor/>.
- [5] Melexis. *Hall-effect sensor latch - Medium sensitivity*. 2025. URL: <https://www.melexis.com/en/product/us1883/hall-effect-sensor-latch-medium-sensitivity>.
- [6] Natalia García Doménech et al. "How to write a scientific lab report: a short-term intervention for improving chemistry writing skills". In: *Journal of Chemical Education* 101.3 (2024), pp. 903–909.
- [7] F Elizabeth Gray, Lisa Emerson, and Bruce MacKay. "Meeting the demands of the workplace: Science students and written skills". In: *Journal of science education and technology* 14 (2005), pp. 425–435.
- [8] John Olmsted. "Teaching varied technical writing styles in the upper division laboratory". In: *Journal of Chemical Education* 61.9 (1984), p. 798.
- [9] Anne Waddingham. *New Hart's Rules: The Oxford Style Guide*. Oxford University Press, 2014.
- [10] TorontoUniWriting. *The Lab Report*. 2025. URL: <https://advice.writing.utoronto.ca/types-of-writing/lab-report/>.
- [11] John Maxwell Cowley. *Diffraction physics*. Elsevier, 1995.
- [12] William Henry Bragg and William Lawrence Bragg. "The reflection of X-rays by crystals". In: *Proceedings of the Royal Society of London. Series A, Containing Papers of a Mathematical and Physical Character* 88.605 (1913), pp. 428–438.
- [13] Donald Ervin Knuth and Duane Bibby. *The texbook*. Vol. 15. Addison-Wesley Reading, 1984.

