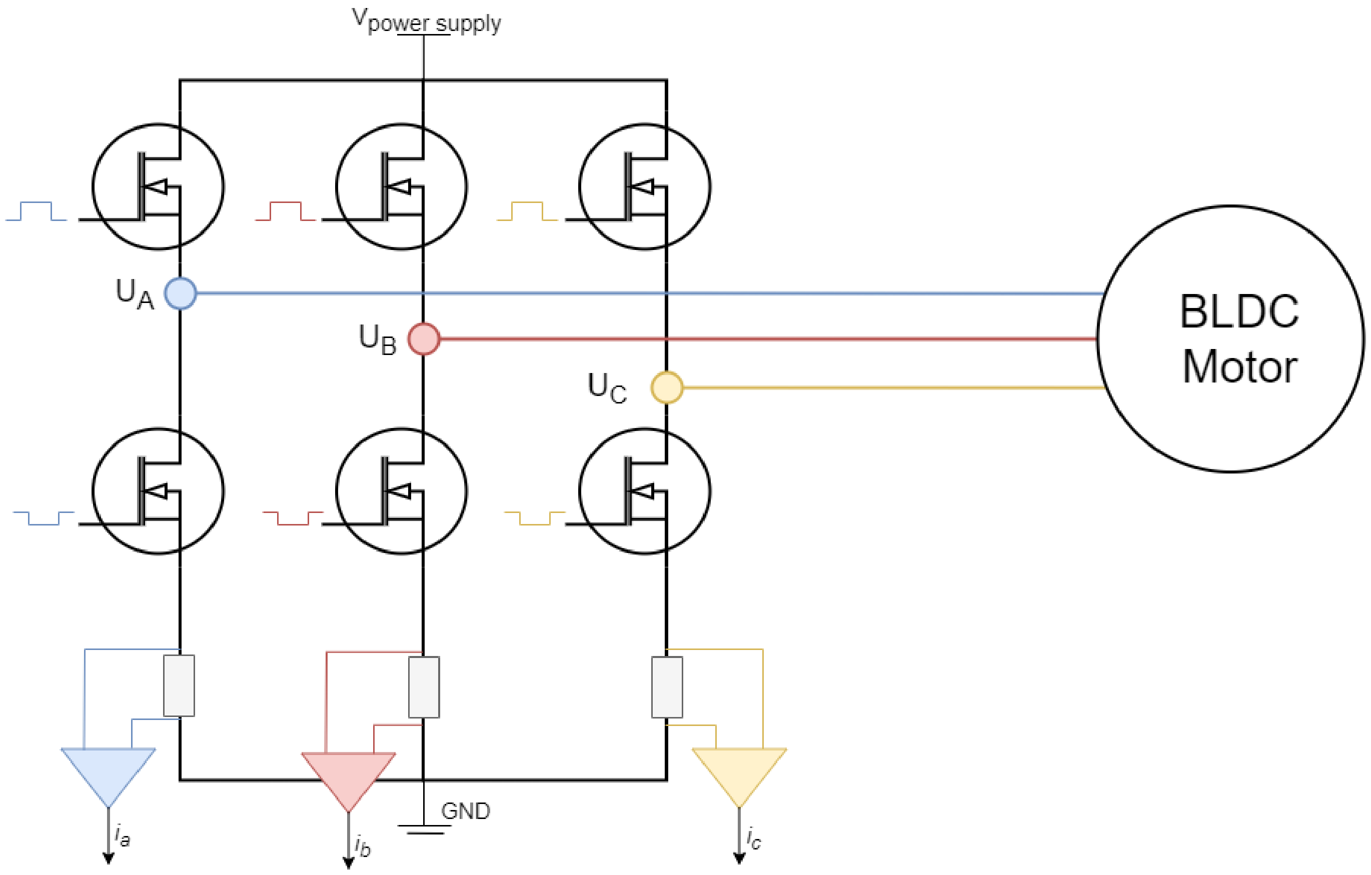
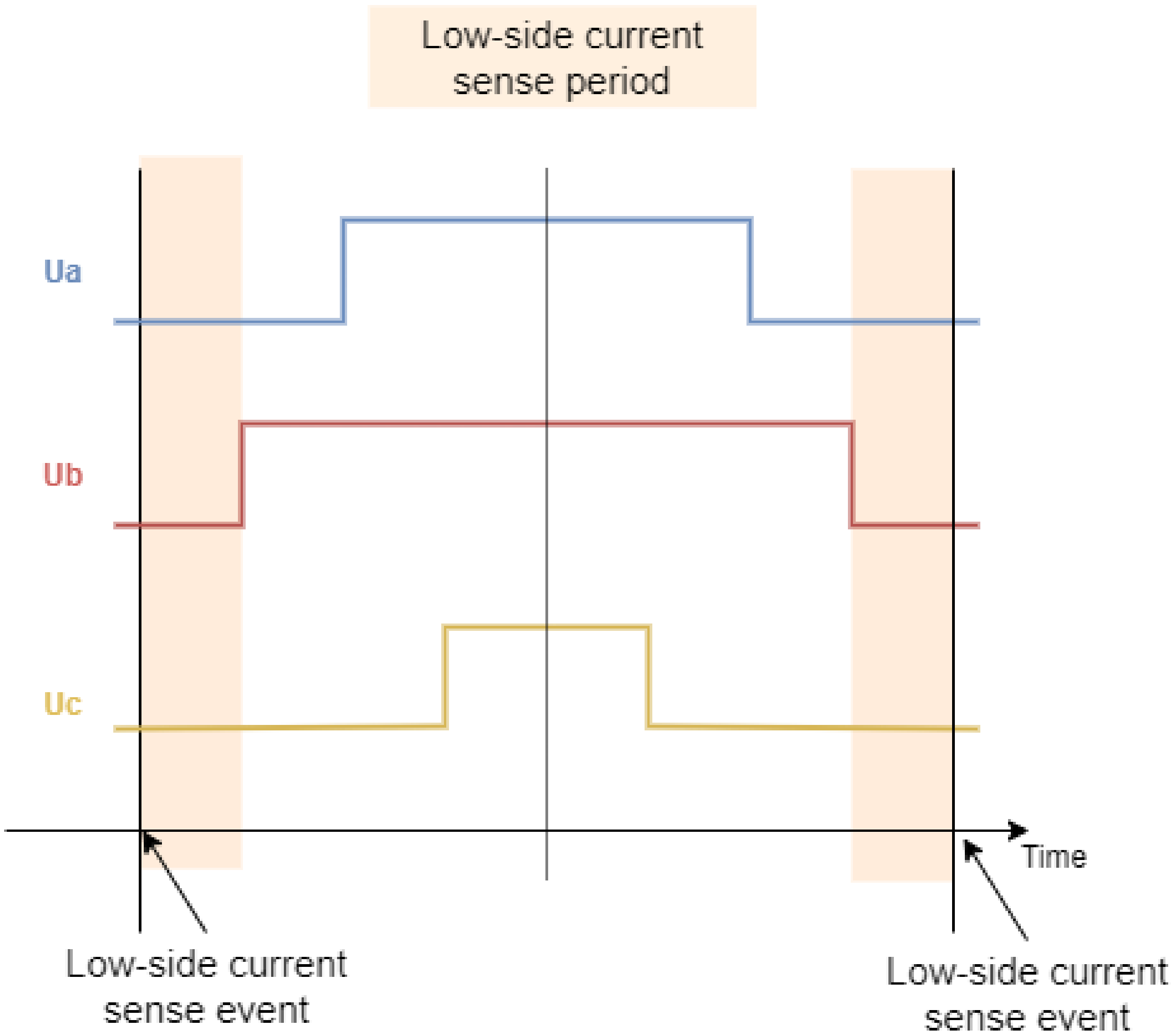
Low-side current sensing

Low-side current sensing is probably the most common current sensing technique. The main reason why is because it does not require neither high-performance PWM rejection current sense amplifiers (as inline does) neither high-voltage supporting amplifiers (as high-side does). The shunt resistors are always placed in between low side mosfets and the ground making sure that the amplifiers always have very low voltages on their terminals. The main drawback of this approach is that, since the current passing through the shunt resistors is phase current only if the corresponding low side mosfet is ON, we can only measure it in those moments. The PWM frequency is usually 20 to 50 kHz, which means that the low-side mosfets turn on and off 20,000 to 50,000 times per second, therefore the synchronization in between PWM setting and ADC acquisition is very very important.

Low side current sensing for all the architectures is on our road-map and we are actively working on it. The main issue at the moment is very hardware specific synchronisation procedure of the PWM generation and ADC triggering. Therefore we are attacking one MCU architecture at the time. 😉



$V_{power\ supply}$
U_A
U_B
U_C
BLDC Motor
GND
i_a
i_b
i_c



Low-side current sense period
Ua
Ub
Uc
Time
Low-side current sense event
Low-side current sense event

Current sensing support per MCU architecture

Low side current sensing is currently supported for several MCU architectures supported by the *SimpleFOClibrary*. ESP32 architecture has the most generic support, supporting multiple motors per chip. Stm32 families f1, f4, l4, g4 and f7 are supported and support low-side sensing for only one motor. A special case of the STM32 board is the B-G431-ESC1 development kit which has very specific low-side implementation for its hardware configuration, and it is fully supported by the library. Samd21 architecture is under development, it has an initial support for only one motor, but for now as it has not been extensively tested, we suggest not to rely on our implementation. Teensy4 has an initial support for low-side sensing for one motor as well.

MCU	Low-side Current sensing
Arduino (8-bit)	✗
Arduino DUE	✗
STM32 (in general)	✗
STM32f1 family	✓ (one motor)
STM32f4 family	✓ (one motor)
STM32g4 family	✓ (one motor)
STM32l4 family	✓ (one motor)
STM32f7 family	✓ (one motor)
STM32 B_G431B_ESC1	✓
ESP32	✓
ESP8266	✗
SAMD21	✓/✗ (one motor, poorly tested)
SAMD51	✗
Teensy3	✗
Teensy4	✓ (inital)
Raspberry Pi Pico	✗
Portenta H7	✗
Renesas (UNO R4)	✗ (TBD)

Important hardware considerations

Low-side current sensing requires very high synchronisation of the PWM generated by the `driver` and the ADC triggering. There are two main considerations to have in mind when choosing your `driver` parameters:

1. PWM frequency considerations
2. Appropriate PWM and ADC pin considerations

See more info about driver paramers in the driver docs!

1. PWM FREQUENCY CONSIDERATIONS

As the ADC conversion takes some time to finish and as this conversion has to happen only during the specific time window (when all the phases are grounded - low-side mosfets are ON) it is important to use an appropriate PWM frequency. PWM frequency will determine how long each period of the PWM is and in term how much time the low-side switches are ON. Higher PWM frequency will leave less time for the ADC to read the current values.

On the other hand, having higher PWM frequency will produce smoother operation, so there is definitely a tradeoff here.

> **RULE OF THUMB: PWM frequency**
> The rule of thumb is to stay arround 20kHz. `driver.pwm_frequency = 20000;`

2. APPROPRIATE PWM AND ADC PIN CONSIDERATIONS

As ADC conversion has to be synchronised with the PWM generated on ALL the phases, it is important that all the PWM generated for all the phases have aligned PWM and that it supports triggering of the ADC conversion. Since the microcontrollers usually have more than one timer for PWM generation and more than one ADC for reading the analog values it is important to choose the right pins for the right phase.

> **RULE OF THUMB: PWM timer and ADC pins**
> In order to maximise your chances for the low-side current sensing to work well we suggest to make sure that the PWM pins chosen for your driver all belong to the same Timer, and the ADC pins chosen for your current sense all belong to the same ADC.
> 📢 Here is a quick guide to choosing appropriate PWM pins for different MCU architectures see in docs.
> 📢 Here is a quick guide to choosing appropriate ADC pins for different MCU architectures see in docs.

Hardware configuration

```
// LowsideCurrentSense constructor
//  - shunt_resistor  - shunt resistor value
//  - gain  - current-sense op-amp gain
//  - phA   - A phase adc pin
//  - phB   - B phase adc pin
//  - phC   - C phase adc pin (optional)
LowsideCurrentSense current_sense  = LowsideCurrentSense(0.01, 20, A0, A1, A2);
```

To instantiate the low-side current sensor using the *SimpleFOClibrary* just create an instance of the class `LowsideCurrentSense`. This class takes as a parameter shunt resistance value `shunt_resistor`, amplification gain `gain` and two or three ADC channel pins depending on the available measuring hardware that you might have. It is important to specify right adc channels for right driver/motor phase. So if your pin `A0` measures the phase current `A` and pin `A1` measures the phase current `B` make sure to put provide them to the constructor in that order.

Measuring 2 out of 3 currents

Field Oriented Control algorithm can run with both 2 or 3 phase current measurements. If measuring 2 out of 3 currents, when defining your `LowsideCurrentSense` class put the flag `_NC` (not connected) to the phase value you are not using.

For example if measuring the current on phases A (analog pin A0) and C (analog pin A1) and not measuring the current on the phase B, then you'll define your current sense class as:

```
// LowsideCurrentSense constructor
LowsideCurrentSense current_sense  = LowsideCurrentSense(shunt_resistor, gain, A0, _NC, A1);
```

Some more examples:

```
// LowsideCurrentSense constructor
LowsideCurrentSense current_sense  = LowsideCurrentSense(shunt_resistor, gain, _NC, A0, A1); // when r

// LowsideCurrentSense constructor
LowsideCurrentSense current_sense  = LowsideCurrentSense(shunt_resistor, gain, A0, A1, _NC); // when r
// or
LowsideCurrentSense current_sense  = LowsideCurrentSense(shunt_resistor, gain, A0, A1); // when measur
```

Custom gains

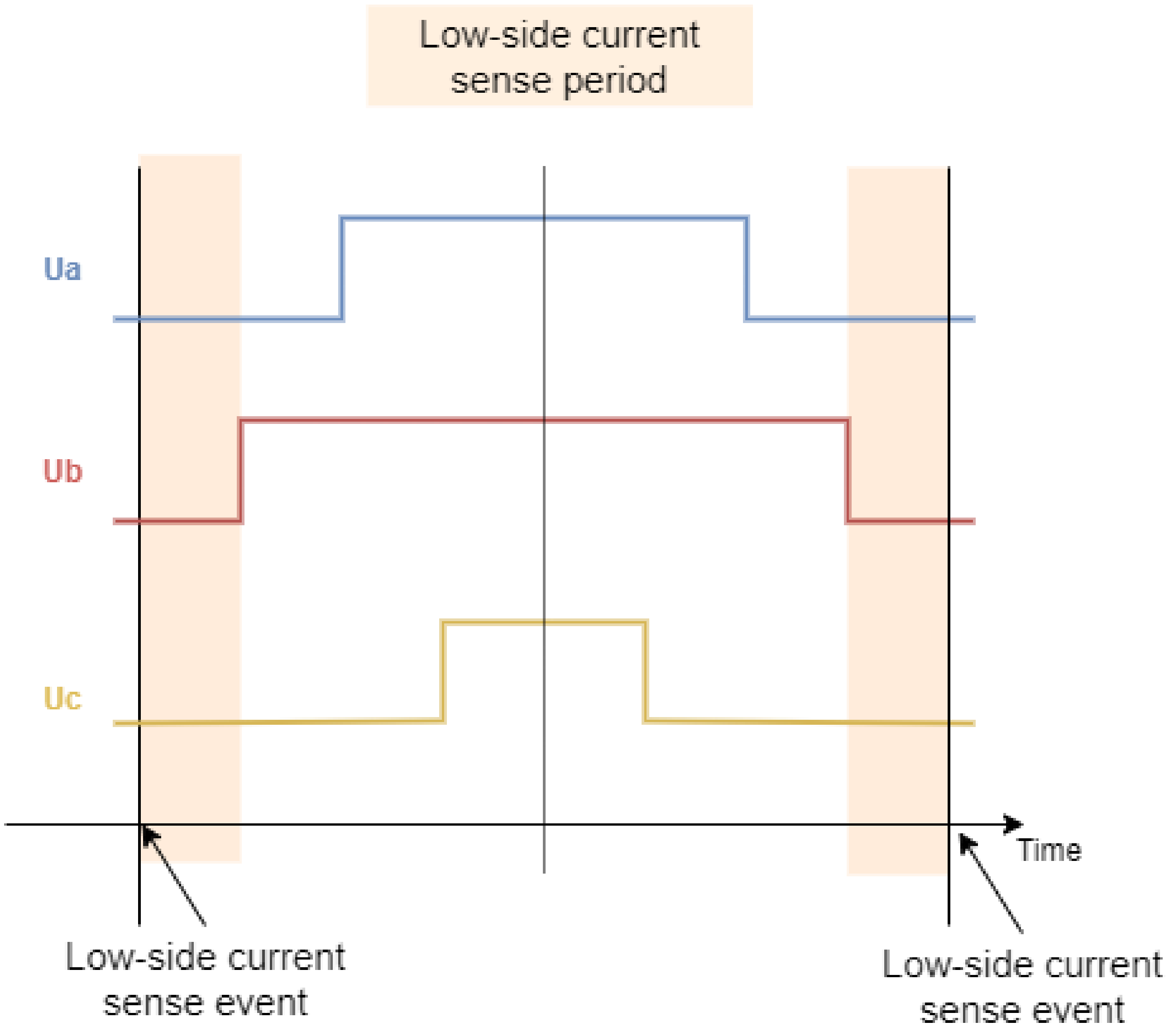
The constructor of the `LowsideCurrentSense` class only allows you to specify one shunt resistor value and one amplification gain. If your hardware configuration has different shunt/amp values for different phases you can specify them by changing the `gain_x` attribute:

```
// default values of per phase gains
current_sense.gain_a = 1.0 / shunt_resistor / gain;
current_sense.gain_b = 1.0 / shunt_resistor / gain;
current_sense.gain_c = 1.0 / shunt_resistor / gain;
```

For example AliExpress DRV8302 board has all the current sensing phases inverted inverted. So in its case you can specify:

```
// inverse current sensing gain
current_sense.gain_a *= -1;
current_sense.gain_b *= -1;
current_sense.gain_c *= -1;
```

Synchronising the current sense with the driver PWM


Low-side current sense period
Ua
Ub
Uc
Time
Low-side current sense event
Low-side current sense event

Since the low-side current sensing technique requires triggering of the ADC acquisition exactly when all the low-side mosfets are ON (when all the phases are grounded), to use the `LowsideCurrentSense` with the FOC algorithm, first thing you'll need to do is to associate (link) your current sense with the `BLDCDriver`:

```
// link current sense and driver
current_sense.linkDriver(&driver);
```

Current sense will be using driver parameters for different synchronisation and calibration procedures.

> **API change - *SimpleFOClibrary* v2.2.2**
> Driver linking to the current sense is introduced from the library version v2.2.2 in order to propagate different hardware specific parameters in between ADC and PWM timers needed for advanced synchronisation for current sensing.

Initialising the current sense

Once the current sense has been created and linked with the driver it can be initialised. This `init()` function configures the ADC hardware for reading and finds the zero offsets of the ADC for each channel.

```
// init current sense
current_sense.init();
```

Init function is responsible for

- configuring ADC for current sensing
- calibration - offset removal

If for some reason the ADC configuration fails this function will return `0` if everything went well the function will return `1`. So we suggest you to check if the init function was executed successfully before continuing:

```
// init current sense
if (current_sense.init())  Serial.println("Current sense init success!");
else{
  Serial.println("Current sense init failed!");
  return;
}
```

When your current sense has been intialised and calibrated you can start measuring the currents!

Using the current sense with FOC algorithm

To use the `LowsideCurrentSense` with the FOC algorithm all you need to do is link it with the `BLDCMotor` you wish to use it with:

```
// link motor and current sense
motor.linkCurrentSense(&current_sense);
```

Where to place the `current_sense` configuration in your FOC code?

It is very important that the the current sensing `init` function is called after the `BLDCDriver` init function is called. This will make sure that the driver is enabled when current sense calibration is taking place. Also, it is important that the current sense `init` function is called before initializing the motor and starting the foc algorithm with the `initFOC` function.

So the suggested code structure would be:

```
void setup(){
  ....
  // driver init
  driver.init();
  // link the driver to the current sense
  current_sense.linkDriver(&driver);
  ....
  // motor init
  motor.init();
  ....
  // init current sense
  current_sense.init();
  // link the current sense to the motor
  motor.linkCurrentSense(&current_sense);
  ...
  // start the FOC
  motor.initFOC();
}
```

Function `initFOC()` will make sure that the `BLDCDriver` and `LowsideCurrentSense` classes are both well aligned, it is very important that the phase `A` of the current sense is exactly the phase `A` of the driver, phase `B` of the current sense exactly pahse `B` of the driver and the same for the phase `C`. To verify this, the `initFOC` will be calling the current sense's function `current_sense.driverAlign(...)`.

Alignment with the motor phases `driverAlign(...)`

The current sense and the driver alignment inside `initFOC` is done by calling the function:

```
current_sense.driverAlign(voltage_sensor_align);
```

This function will be using the `driver` instance (linked to the current sense with `current_sense.linkDriver(&driver)`) to apply the voltage (voltage can be set using the parameter `motor.voltage_sensor_align`) to each of the phases and checks if the measured currents correspond to the directions of the applied voltages. This alignment procedure is able to correct for:

- Incorrect order of adc pins
- Incorrect gain sign

If monitoring is enabled for the motor during the `initFOC` the monitor will display the alignment status:

- `0` - fail
- `1` - success and nothing changed
- `2` - success but pins reconfigured
- `3` - success but gains inverted
- `4` - success but pins reconfigured and gains inverted

If you are sure in your configuration and if you wish to skip the alignment procedure you can specify set the `skip_align` flag before calling `motor.initFOC()`:

```
// skip alignment procedure
current_sense.skip_align = true;
```

For example for the AliExpress DRV8302 board, you would have code similar to this:

```
// one possible combination of current sensing pins for SimpleFOCShield v2
// shunt - 5milliOhm
// gain  -  12.22 V/V
LowsideCurrentSense current_sense = LowsideCurrentSense(0.005f, 12.22f, IOUTA, IOUTB, IOUTC);

voi loop(){
  ....
  // driver init
  driver.init();
  // link the driver to the current sense
  current_sense.linkDriver(&driver);
  ....
  // motor init
  motor.init();
  ....
  // init current sense
  current_sense.init();
  // link the current sense to the motor
  motor.linkCurrentSense(&current_sense);
  ...
  // invert phase b gain
  current_sense.gain_a *=-1;
  current_sense.gain_b *=-1;
  current_sense.gain_c *=-1;
  // skip alignment
  current_sense.skip_align = true;
  ...
  // start the FOC
  motor.initFOC();
}
```

See the full example for the Aliexpress DRB8302 based board in the library examples `/examples/hardware_specific_examples/DRV8302_driver/esp32_current_control_low_side`.

Standalone current sense

Since the low-side current sense has to be synchornised with PWM of a driver of interest it does not make sense to use it as a stand-alone sensor. But once you have linked the current sense with the `BLDCMotor` you can use it to read your phase currents, overall current magnitude and DQ currents.

Reading the phase currents can be done by calling:

```
PhaseCurrent_s  current = current_sense.getPhaseCurrents();
```

This function returns the `PhaseCurrent_s` structure that which has three variables `a`, `b` and `c`. So you can print them out for example;

```
Serial.println(current.a);
Serial.println(current.b);
Serial.println(current.c); // 0 if only two currents mode
```

If you are using only two phase current measurements in your `LowsideCurrentSense`, it will return the third current `current.c` equal to 0.

Sometimes the phase currents are hard to interpret, therefore this current sense class enables you to read the transformed current vector magnitude. The absolute DC current the motor is drawing.

```
float current_mag = current_sense.getDCCurrent();
```

Futhermore if you have an access to the position sensor of the motor connected to the driver you can get signed value of the DC current the motor is drawing by providing it to the `getDCCurrent` method.

```
float current = current_sense.getDCCurrent(motor_electrical_angle);
```

Finally if you have the access to the motor position sensor you current sense class will be able to tell you the FOC currents D and Q that your motor is drawing.

```
DQCurrent_s current = current_sense.getFOCCurrents(motor_electrical_angle);
```

This function returns the `DQCurrent_s` structure which has two variables, `d` and `q`. You can print them out for example:

```
Serial.println(current.d);
Serial.println(current.q);
```

Example code

Here is a simple example of a low-side current sense using the *SimpleFOClibrary* and to read the motor currents directly.

```
#include <SimpleFOC.h>


// define the motor and the driver
motor = ...
driver = ...

// current sensor
// shunt resistor value
// gain value
// pins phase A,B
LowsideCurrentSense current_sense = LowsideCurrentSense(0.01, 50.0, A0, A2);

void setup() {

  // init driver
  driver.init();
  current_sense.linkDriver(&driver);
  ...

  // init motor
  motor.init();
  ...

  // initialise the current sensing
  current_sense.init();
  motor.linkCurrentSense(&current_sense);

  ...
  motor.initFOC();
  ...

  Serial.begin(115200);
  Serial.println("Setup ready.");
}

void loop() {
    // foc and motion controls
    motor.loopFOC();
    motor.move();

    PhaseCurrent_s currents = current_sense.getPhaseCurrents();
    float current_magnitude = current_sense.getDCCurrent();

    Serial.print(currents.a*1000); // milli Amps
    Serial.print("\t");
    Serial.print(currents.b*1000); // milli Amps
    Serial.print("\t");
    Serial.print(currents.c*1000); // milli Amps
    Serial.print("\t");
    Serial.println(current_magnitude*1000); // milli Amps
}
```