

UNDERSTANDING THE EFFECT OF PWM WHEN CONTROLLING A BRUSHLESS DC MOTOR



Brushless motors offer a great combination of durability, efficiency, torque and speed in a compact package suitable for your application

Designers of motion systems often face challenges when selecting or developing electronics using PWM (Pulse Width Modulation) to drive brushless DC motors. It is useful to keep in mind some basic physical phenomena to avoid unexpected performance issues. This document provides general guidelines when using a PWM driver with a Portescap brushless DC motor.

COMMUTATION OF A BRUSHLESS DC MOTOR

Unlike brush DC motors (for which the commutation is made mechanically by brushes), brushless DC motors are electronically commutated. This means the phases of the motors are energized and unenergized in sequence according to the relative position of the rotor vs. the stator. For a 3-phase brushless DC motor, the driver is composed of 6 electronic switches (typically transistors), usually called a 3 phase H-bridge (see Figure 1). This configuration will allow 3 bidirectional outputs to energize the 3 phases of the motor.

Opening and closing the transistors in a specific sequence energizes the phases of the motor to maintain the optimal orientation of the magnetic field induced by the stator vs. rotor magnet (see Figure 2, Figure 3 & Figure 4).

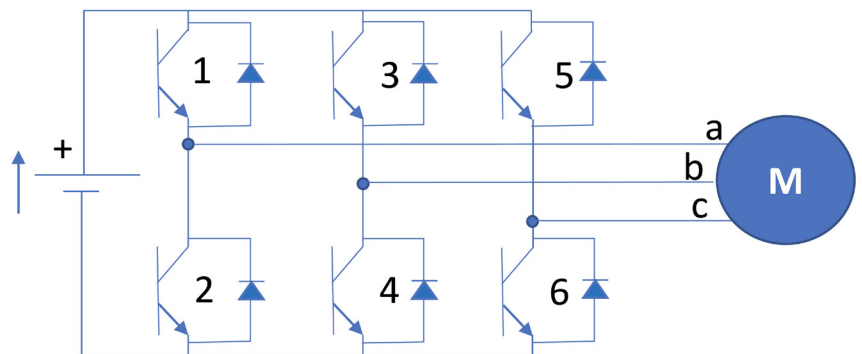


Figure 1 - Example of a 3-phase motor H-Bridge composed by 6 transistors with connections to the 3 motor phases

The motor can be driven in a 6-step trapezoidal commutation which is broadly used (see Figure 3), or it can be operated to achieve a more advanced vector control also called as Field Oriented Control (FOC), depending on the sophistication of the electronics (see Figure 4).

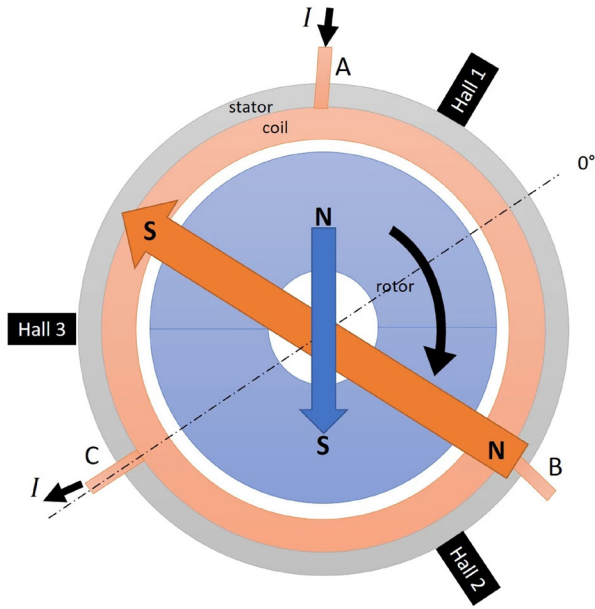


Figure 2 - Schematic cross-section of a slotless brushless DC motor starting step 3. The blue part is the rotor with a 2-pole permanent magnet. The magnetic field generated by the magnet is represented by the blue arrow. The orange part is the 3-phase winding. When the current is flowing from phase A to phase C, it induces a magnetic field which is represented by the orange arrow for simplification. The rotor will rotate as both arrows get aligned. The drive will commute the phases (rotating the stator magnetic field, orange arrow) to maintain an angle as close as possible to 90° between the stator and the rotor magnetic fields (maximum torque generated).

PWM REGULATION

Whether for a brush (see Figure 5) or a brushless DC motor (see Figure 6), the working point (speed and torque) of an application can vary. The role of the amplifier is to vary the supply voltage or the current, or both, to achieve the desired motion output.

There are typically two different ways to vary the voltage or the current:

- Linear drivers (or linear amplifiers)
- Chopper drivers (or chopper amplifiers)

Linear amplifiers adapt the power delivered to the motor by linearly changing the voltage or current. It dissipates the power which is not delivered to the motor (lost power – see Figure 6). As a result, it requires a large heat sink to dissipate the power, increasing the amplifier size and making it more difficult to integrate in the application.

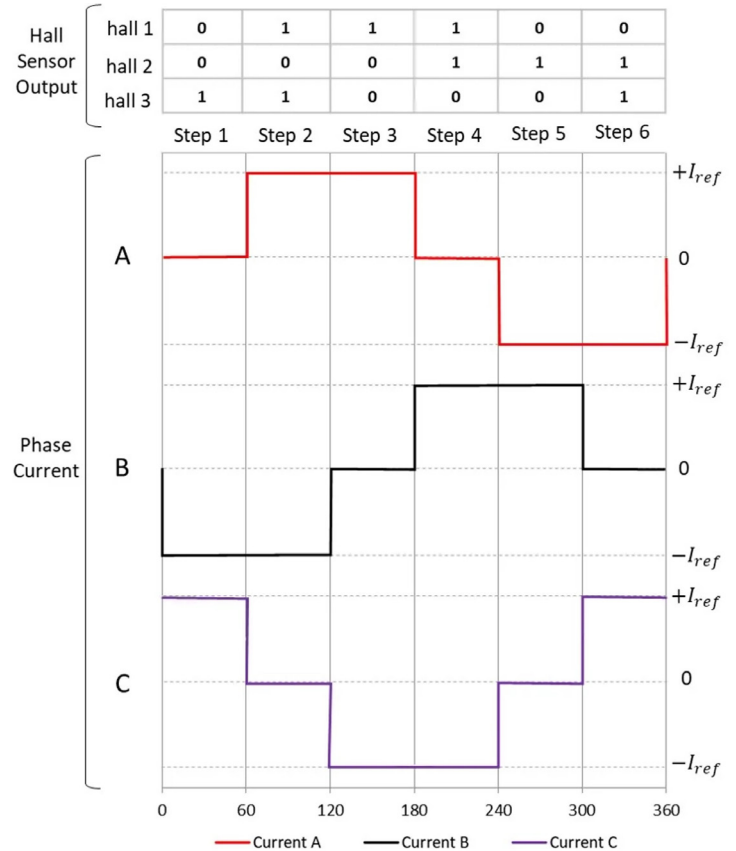


Figure 3 - Phase current and hall sensor state with a 6-step commutation

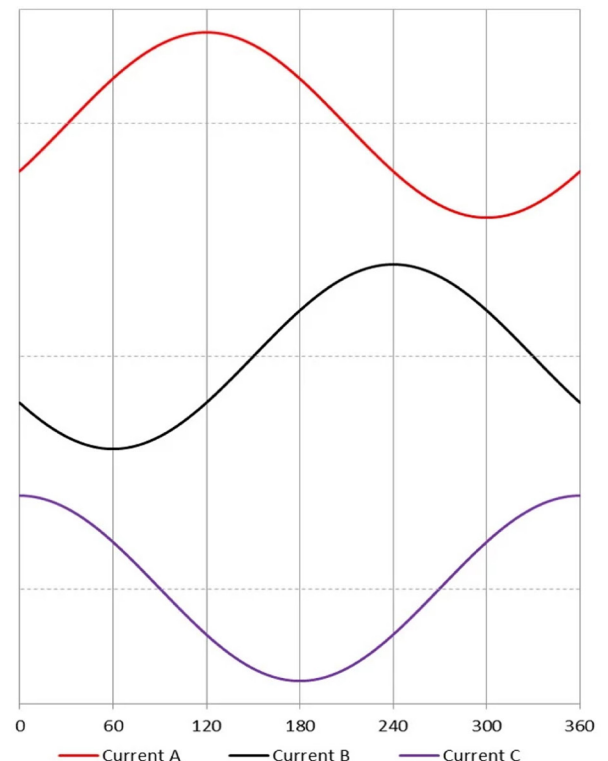


Figure 4 - Phase current using an FOC amplifier

A chopper amplifier modulates the voltage (and current) by switching on and off the power transistors. The primary advantage is that it saves power when the transistor is off. This helps save on the battery life of the application, causes less heating from the electronic and allows a smaller size of the electronics. Most of the time, chopper amplifiers are using a PWM method.

The PWM method consists of varying the duty cycle at a fixed frequency (see Figure 7) to adjust the voltage or current within the desired target value.

Note that one advantage of the PWM technique to chop the current vs. others is that the switching frequency is a fixed parameter. It will make it easy for electronic designers to filter acoustic and electromagnetic noise generated.

When the transistor of the PWM is open 100% of the time, the voltage applied to the motor is the full bus voltage. When the transistor is open 50% of the time, the average voltage applied to the motor is half the bus voltage. When the transistor is closed 100% of the time, no voltage is applied to the motor.

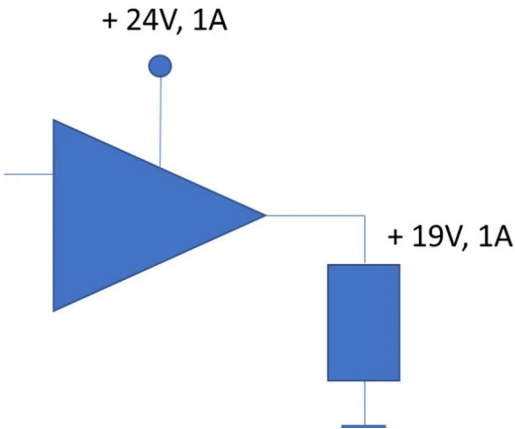


Figure 6 - Example of a linear amplifier energizing the motor. The power dissipated continuously by the driver for this motor coil is: $P_{\text{dissipated (amplifier)}} = (24 - 19) \cdot 1 = 5W$

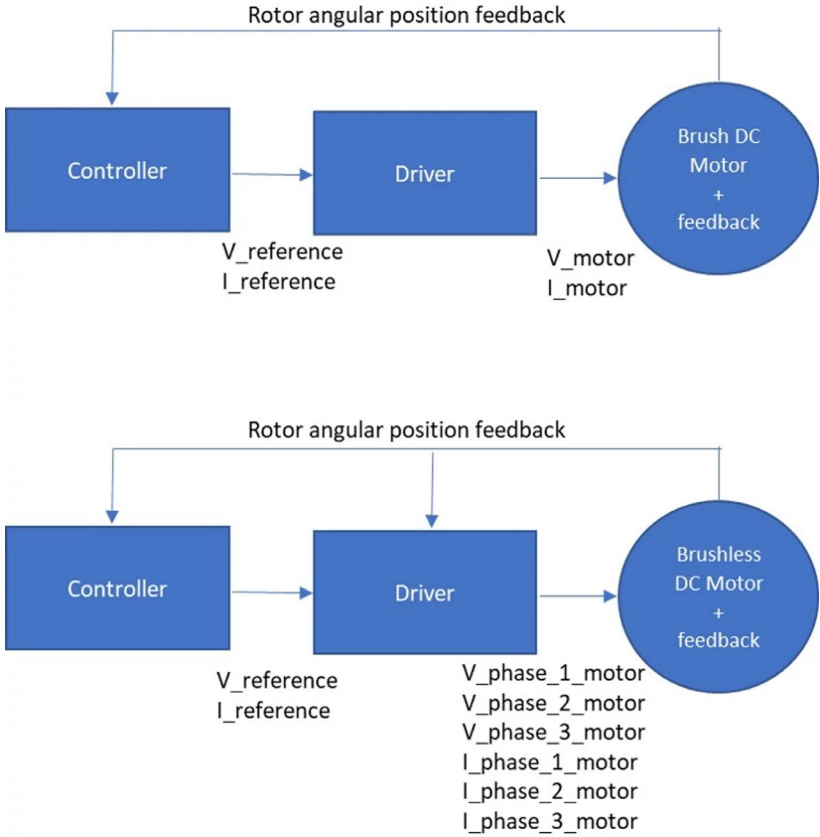


Figure 5 - Motion control architecture comparison between a brush DC and a brushless DC motor

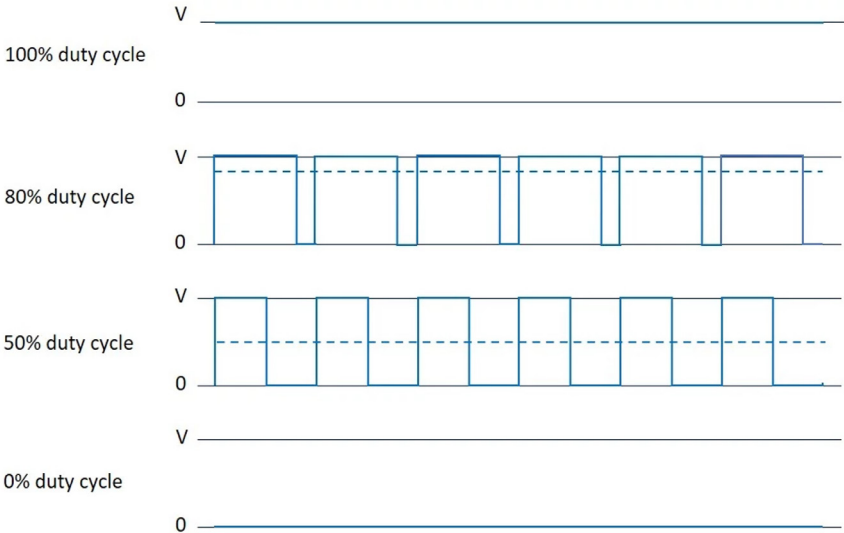


Figure 7 - Different PWM duty cycles. Notice that frequency is the same for all cases, whereas the average voltage (dotted line) is proportional to the duty cycle.

INDUCTANCE EFFECT

A DC motor is characterized by an inductance L , a resistance R and a back electromotive force (back-EMF) E in series. The back-EMF is a voltage caused by the magnetic induction (Faraday-Lenz law of induction) that opposes the applied voltage and is proportional to the motor speed. See Figure 8 showing the motor when the PWM is ON, and when the PWM is OFF.

For now, to keep things simple, let's not consider the back EMF.

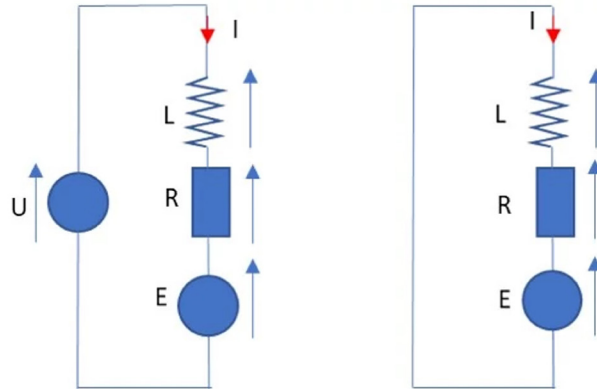


Figure 8 - Simplified equivalent circuit diagrams representing a DC motor when the PWM is ON (left) and OFF (right). For simplicity, the right circuit corresponds to a slow decay mode (current recirculating in the motor).

When applying voltage or switching off voltage to a RL circuit, the inductor will oppose to the change of the current. Applying a voltage U to the RL circuit, the current will follow a first-order exponential rise, whose dynamic depends on the electric time constant τ equal to the ratio L / R (see Figure 9). It will asymptotically reach the steady state value, i.e. 99.3% of U / R , after 5 times the time constant.

The same exponential behavior will be observed when the RL circuit will discharge. See Figure 10.

In practice, brushless DC amplifiers have a rather high PWM frequency and do not allow the current to reach steady state. This frequency is generally above 50 kHz so that the current can be modulated properly with enough cycles occurring during each commutation step. For a PWM frequency of 50kHz, the cycle time to close and open a transistor is equal to 20 μ s. Considering a 6-step commutation, the time for one commutation, 1-pole pair motor running at 40'000 rpm (667Hz), would take 250 μ s. This would allow at least $250/20 = 12.5$ cycles of the PWM during one step of the commutation.

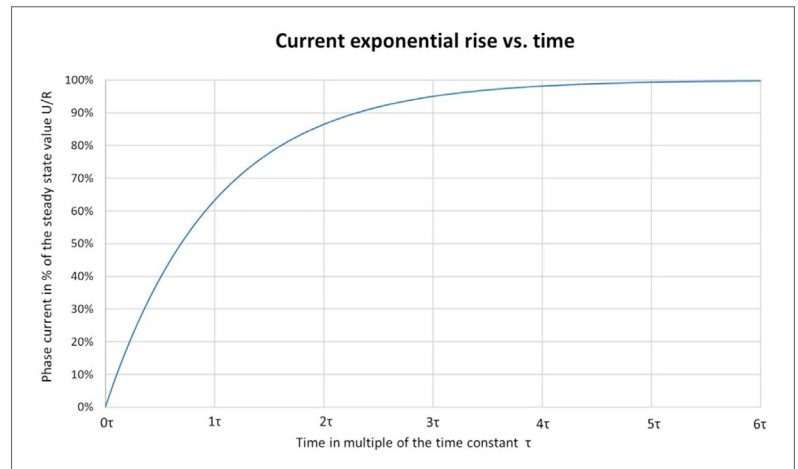


Figure 9 - Exponential current rise in an RL circuit

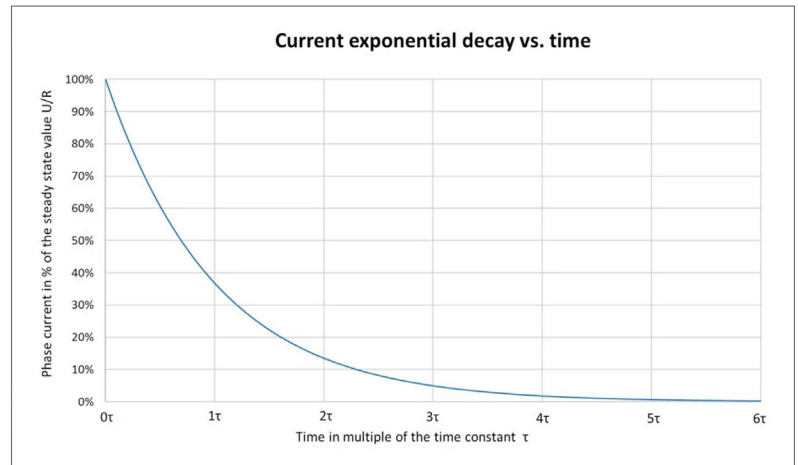


Figure 10 - Exponential current fall in an RL circuit

Portescap brushless DC motors have an electrical time constant τ of a few hundred microseconds, therefore the current will have the time to react during each PWM cycle (see Figure 11 below).

However, the mechanical time constant is in the range of a few milliseconds, so there is roughly a factor of 10 between the mechanical and the electrical time constant. Therefore, the rotor of the motor itself will not have enough time to react when the voltage is switched at typical PWM frequencies. Low PWM frequencies of a few thousand Hertz may generate rotor vibrations and audible noise. It is advisable to go above the audible spectrum, meaning at least above 20 kHz.

LIMITATIONS OF PWM

PWM will lead to current rise and fall at each cycle, the variation between the minimum and the maximum value of the current is called the current ripple ΔI (see Figure 11). High current ripple can be problematic, and it is advisable to keep it as low as possible.

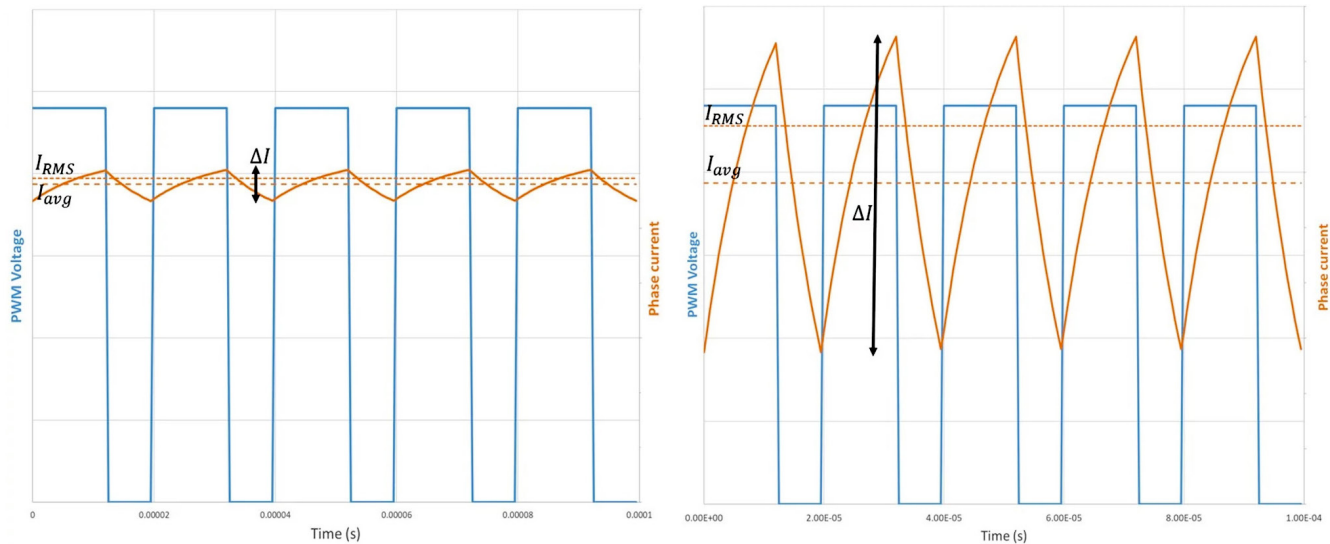


Figure 11 - Typical current ripple generated by a 50 kHz PWM at steady state (duty cycle of 80%) The duty cycle is the same in both cases, therefore the average current is the same. Left graph shows a low current ripple, the RMS current value is close to the average current value. Right graph shows a high current ripple, the RMS current value is significantly higher than the average current value.

The torque of a DC motor is proportional to the average current, as illustrated by the formula:

$$T_{motor} = k_t I_{avg} \quad \text{EQ. 1}$$

Note that the average current I_{avg} needs to be considered for the motor torque. The average current only depends on the duty cycle and is independent of the current ripple. As it can be observed on Figure 11, the average current is the same in both cases (same duty cycle), whereas the ripple is much different (different electrical time constant).

Unlike brush DC motors, brushless DC motors do not have brushes, therefore high current ripple is not problematic for the lifetime itself. The current ripple will have a great impact on the motor losses, causing unnecessary heat. The current ripple will generate two types of losses:

- Joules losses: The current ripple will increase the RMS (Root Mean Square) current value, which is the value considered for joules losses calculation. The ripple will simply generate additional heating, without increasing the average current, hence without increasing the torque. Notice that it is a square variation in function to the RMS current.

$$P_{Joules} = R I_{RMS}^2 \quad \text{EQ. 2}$$

With T being the time-period of the PWM ($T = \frac{1}{f_{PWM}}$), the RMS current can be calculated with the formula:

$$I_{RMS} = \sqrt{\frac{1}{T} \int_t^{t+T} i^2(t) dt} \quad \text{EQ. 3}$$

- Iron losses: According to Faraday's law of electromagnetic induction (Eq. 4), the variation of the magnetic field in a conducting material will induce a voltage, which will then generate circulating currents called eddy currents.

$$u_{ind} = -\frac{\partial \Phi}{\partial t} \quad \text{EQ. 4}$$

Eddy current losses are proportional to the square of the motor speed and to the square of the motor current. Based on practical measurements, when the current ripple is high, the additional iron losses generated can become significant. Therefore, it is important to keep the current ripple as low as possible.

Let's determine the formula for the current ripple, so we can define guidelines to minimize it. From the schematic of the motor (see Figure 8), we can derive the motor equation:

$$v(t) = U_R(t) + E(t) + L \frac{di(t)}{dt} \quad \text{EQ. 5}$$

$$\frac{di(t)}{dt} = \frac{v(t) - U_R(t) - E(t)}{L} \quad \text{EQ. 6}$$

Let's assume that the variation of the current is linear over the short periods of time T_{ON} and T_{OFF} , therefore, we can rewrite the differential equation as follows:

$$\text{during } dt = T_{ON}, \quad di = \Delta I_{ON}, \quad v = V_{ON}, \quad \frac{\Delta I_{ON}}{T_{ON}} = \frac{V_{ON} - (U_R + E)}{L} \quad \text{EQ. 7}$$

$$\text{during } dt = T_{OFF}, \quad di = \Delta I_{OFF}, \quad v = V_{OFF}, \quad \frac{\Delta I_{OFF}}{T_{OFF}} = \frac{V_{OFF} - (U_R + E)}{L} \quad \text{EQ. 8}$$

Assuming steady state, the current ripple is constant:

$$\Delta I_{ON} = -\Delta I_{OFF} = \Delta I \quad \text{EQ. 9}$$

Therefore, the two equations can be combined into one:

$$U_R + E = V_{ON} - \frac{L \Delta I}{T_{ON}} = V_{OFF} + \frac{L \Delta I}{T_{OFF}} \quad \text{EQ. 10}$$

$$V_{ON} - V_{OFF} = L \Delta I \left(\frac{1}{T_{ON}} + \frac{1}{T_{OFF}} \right) = L \Delta I \left(\frac{T_{OFF} + T_{ON}}{T_{ON} T_{OFF}} \right) \quad \text{EQ. 11}$$

We can simplify the equation by introducing the duty cycle D and the PWM frequency f_{PWM} :

$$T_{ON} = D (T_{ON} + T_{OFF}) = \frac{D}{f_{PWM}} \quad \text{EQ. 12}$$

$$T_{OFF} = (1 - D) (T_{ON} + T_{OFF}) = \frac{1 - D}{f_{PWM}} \quad \text{EQ. 13}$$

$$\text{THEN: } V_{ON} - V_{OFF} = L \Delta I \left(\frac{\frac{1}{f_{PWM}}}{\frac{D(1-D)}{f_{PWM}^2}} \right) \quad \text{EQ. 14}$$

From which we can derive the formula of the current ripple ΔI :

$$\Delta I = \frac{D(1-D)(V_{ON} - V_{OFF})}{L f_{PWM}} = \frac{U_{PWM} D(1-D)}{L f_{PWM}} \quad \text{EQ. 15}$$

The variation of the current ripple in function of PWM duty cycle is a parabola, as shown in Figure 12.

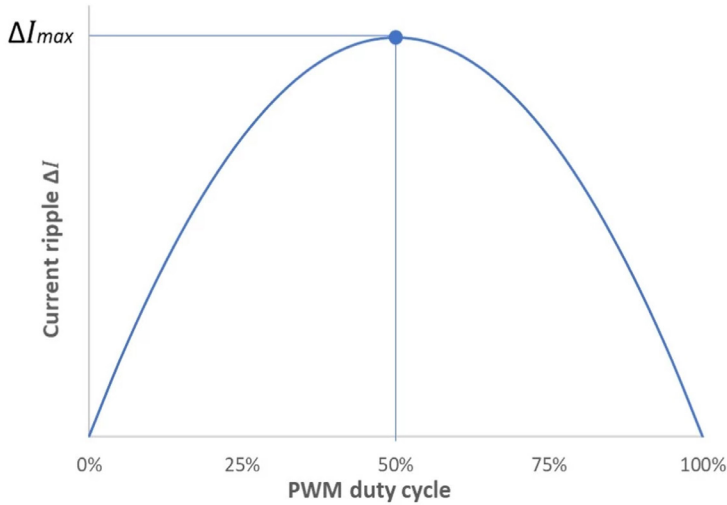


Figure 12 - Current ripple vs. PWM duty cycle

The maximum value of the ripple is obtained when the duty cycle is 50%, meaning $D=0.5$:

$$\Delta I_{max} = \frac{U_{PWM}}{4 L f_{PWM}} \quad \text{EQ. 16}$$

From equation Eq. 15, there are several parameters influencing:

- The power supply U_{PWM}
- The duty cycle D
- The PWM frequency f_{PWM}
- The inductance L

RECOMMENDATIONS TO MINIMIZE THE CURRENT RIPPLE

Reduce or adapt the power supply voltage

The current ripple is directly proportional to the power supply voltage. Having a high supply voltage can be useful to reach extreme working points, requiring high speed or higher power. However, if the application does not require high speed or power, a lower supply voltage will be beneficial to reduce the current ripple. Operating under the same load point with a lower power supply voltage will also increase the duty cycle, which will reduce the current ripple even more. Generally, it is important to keep the duty cycle of the PWM as far as possible from 50%, which is the worst case (Figure 12).

Increase the PWM frequency

A higher frequency will cause a shorter cycle time of the PWM; hence the current will have less time to rise. Portescap recommends using PWM frequencies not less than 50 kHz for brushless DC motors. PWM frequencies of 80 kHz or more would be even more appropriate for motors having very small electrical time constant.

Increase the inductance

Portescap brushless DC motors have a very small inductance value. Therefore, it is a good idea to add external inductances as it will slow down the rise and fall of the current, hence reducing the current ripple. Also, the inductance value specified in Portescap catalogue is given for a PWM frequency of 1 kHz. Since the motor inductance varies depending on the PWM frequency, at typical PWM frequency of 50 kHz, the inductance may decrease to as low as 70% of the catalog value. Typically, additional inductances of several tens of μH are added. The optimal value of the inductance is usually confirmed experimentally. The additional inductances need to be added as shown below on Figure 13.

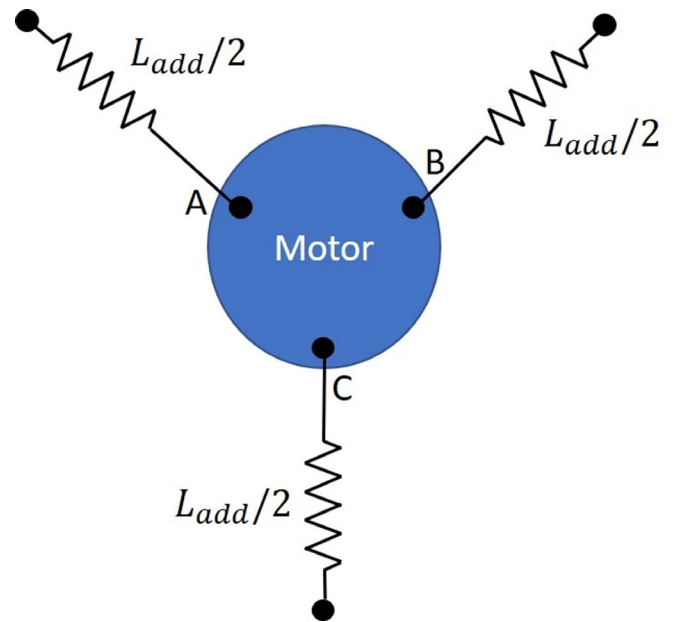


Figure 13 - Brushless motor with additional line inductance

Though this solution would solve the current ripple concern, it might not be easy to integrate additional inductances, especially when space is limited. Therefore, it is usually wiser to explore the two other options first.

CONCLUSION

PWM has many advantages and is the most widely used solution for brushless DC drivers. Setting an adequate PWM voltage and using a high PWM frequency will help to reduce the ripple and can avoid the use of additional inductances. Today's cost of electronic components makes it a simple solution to go with high PWM frequency. Electronic designers should consider carefully these parameters when developing a motion system, especially when size and weight of the electronic is a concern (i.e. portable devices with embedded electronics) or when battery life is a key criteria (additional energy dissipated by Joules losses for the internal resistance of extra inductances). Portescap engineers can help you define suitable electronic with our brushless DC motors, contact us in case you need any support. **P**

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