Considerations on bootstrap circuitry for gate drivers

Introduction

Driving a half-bridge based on N-channel MOSFETs or IGBTs requires providing to the high-side switch a gate voltage greater than the main supply. Without this overdrive, the high-side switch is not properly biased, and the power stage performance is heavily impacted.

One of the most common methods to generate this extra voltage is a bootstrap circuitry composed by a capacitor and diode series connected to the switching node.

This document describes the basic principles of this circuitry and provide guidelines on the proper selection of the components.

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1 Basics

1.1 List of acronyms and abbreviations

The following is a list of the acronyms and abbreviations used in the document with their meanings.

Table 1. **List of acronyms and abbreviations**

|	Description
MOSFET	Metal-Oxide-Semiconductor Field-Effect Transistor
IGBT	Insulated Gate Bipolar Transistor
HS	High-side. It indicates, in general, a circuitry referred to the power stage output (i.e. switching node).
LS	Low-side. It indicates, in general, a circuitry referred to the power stage ground.
PWM	Pulse Width Modulation
UVLO	Undervoltage Lock Out. It is the protection forcing a circuit in a safe stage when its supply voltage is below a target threshold.
Six-step	Also known as trapezoidal control, it is a control algorithm for three-phase brushless motors.
FOC	Field Oriented Control. It is a closed-loop, the control algorithm driving for three-phase brushless motors.
SVM	Space Vector Modulation. It is a driving strategy for the power stage of a three-phase motor inverter.
Modulation index	In motor driving algorithms, it is the amplitude of the voltage vector applied to the motor expressed as percentage of the power stage's supply voltage.

1.2 Basic principle of operation

The typical schematic of the bootstrap circuit is presented in Figure 1.

Figure 1. **Bootstrap circuit**
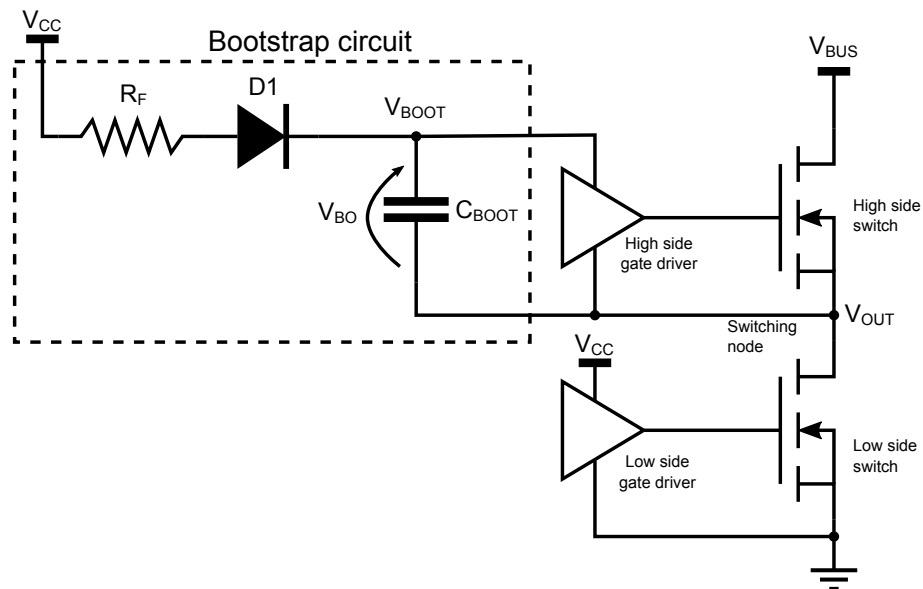
When the LS switch is on, the C_{BOOT} bootstrap capacitor is charged through the bootstrap diode (D1). Turning on the HS switch, the OUT node rises to V_{BUS} and diode is reverse biased. The voltage on C_{BOOT} (V_{BO}) is maintained, consequently V_{BOOT} rises above V_{BUS} providing the extra-voltage needed for keeping on the HS.
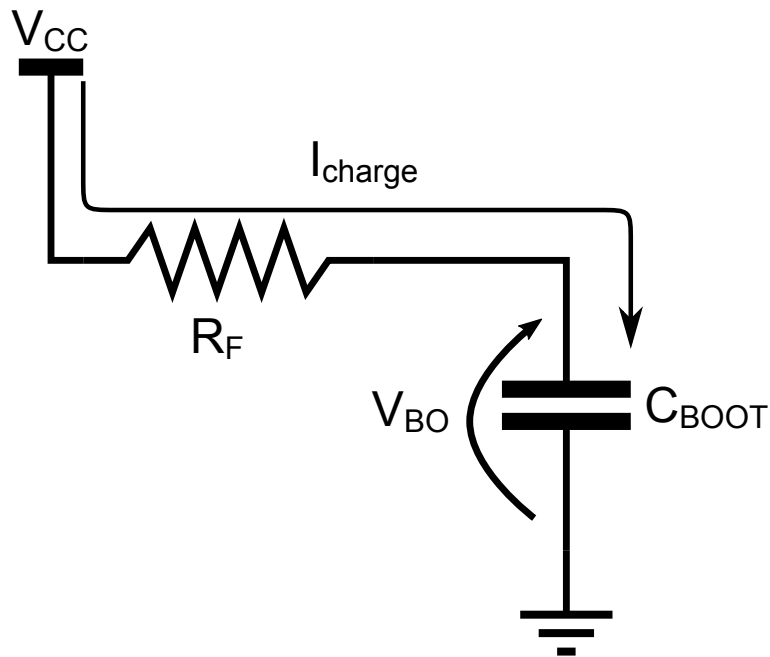
Figure 2. **Time diagram**
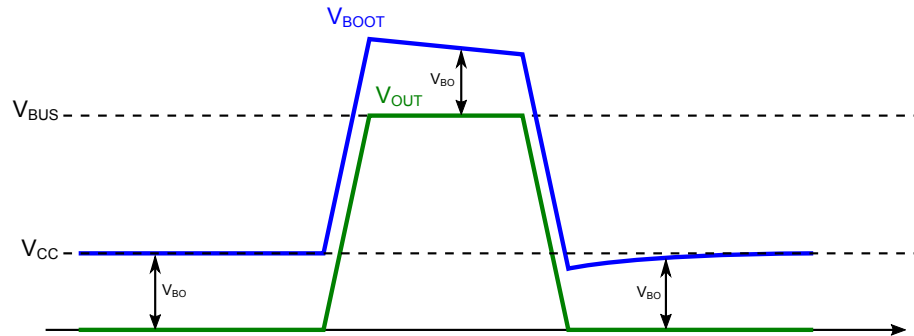
1.3 Charge and discharge phases

As introduced in the previous section, the charge of the bootstrap capacitor is performed forcing to ground the OUT node through the LS switch.

Figure 3. **Equivalent circuit during CBOOT charging**

The voltage increase on the bootstrap capacitor during the charging phase is described by the following formula:

Equation 1

$$V_{BO}(t) = (V_{CC} - V_F) + (V_{BO}(t_0) - (V_{CC} - V_F)) \cdot e^{\frac{-t}{R_F \cdot C_{BOOT}}}$$ (1)

Where:

- V_{BO} is the voltage on the bootstrap capacitor C_{BOOT}
- $V_{BO}(t_0)$ is the starting voltage at beginning of charging phase
- V_{CC} is the gate driver supply voltage
- V_F is the forward voltage of the bootstrap diode (D1 in Figure 1)
- R_F is the equivalent series resistance of the bootstrap circuit including the on-resistance of the bootstrap diode (D1 in Figure 1).

When the HS is on, the bootstrap capacitor is discharged.

Figure 4. . Equivalent circuit during CBOOT discharging
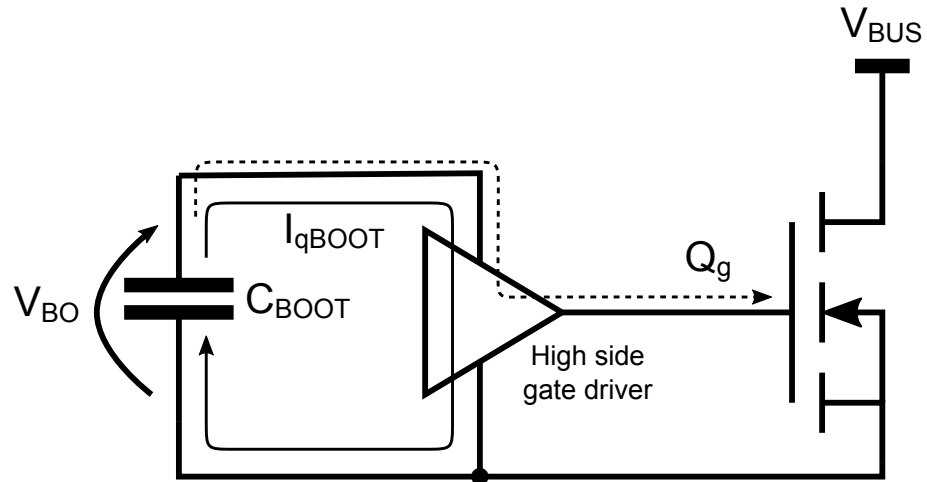
In this case it is more convenient to calculate the V_{BO} variation using the charge provided to the driving circuitry. Composed by two parts: the one provided by the HS gate driving circuitry to turn on the switch (i.e. the Total Gate Charge) and the one needed to keep the circuitry biased.

The resulting formula is:

Equation 2

$$\Delta V_{BO}(t) = \frac{Q_g + I_{BOOTq} \times t}{C_{BOOT}}$$

(2)

Where:

- ΔV_{BO} is the voltage reduction during the discharge phase
- Q_g is the Total Gate Charge of the HS
- I_{BOOTq} is the quiescent current of the circuitry connected to C_{BOOT}.

Using Equation 2 to calculate $V_{BO}(t_0)$ for Equation 1, it is possible to estimate the resulting VBO voltage at the end of each charge and discharge cycle.

2 Use cases

In the following sections some common use cases are described.

2.1 Constant duty-cycle

In case of operation with constant switching frequency and duty-cycle, the on-time of HS and LS switches are also constant.

After a settling time of about 5 times the $R_F \cdot C_{BOOT}$, the bootstrap overdrive voltage stabilizes with a charge voltage variation equal to the discharge one.

Starting from Equation 1 and Equation 2, the minimum voltage (i.e. at the end of discharge phase) can be calculated with the following formula:

Equation 3

$$\Delta V_{BO}(t_{onLS}) = \Delta V_{BO}(t_{onHS}) \tag{3}$$

$$V_{BO,min} = (V_{CC} - V_F) - \frac{Q_g + I_{BOOTq} \times t_{onHS}}{C_{BOOT}} / \left(1 - e^{-\frac{t_{onLS}}{R_F \cdot C_{BOOT}}}\right)$$

Where:

- t_{onLS} is the LS switch-on time,
- t_{onHS} is the HS switch-on time.

2.2 Maximum on-time

The maximum HS on-time can be calculated starting from Equation 2:

Equation 4

$$\Delta V_{BO}\left(t_{onHS,\max}\right) = V_{BO}(t_0) - V_{UV} \tag{4}$$

$$t_{onHS,\max} = \frac{\left(V_{OB}\left(t_0\right) - V_{UV}\right) \times C_{BOOT} - Q_g}{I_{BOOTq}}$$

Where:

- $V_{BO}(t_0)$ is the starting voltage. Best case is when the bootstrap capacitor is fully charged and it is equal to $V_{CC} - V_F$.
- V_{UV} is the undervoltage threshold below which it is not possible to guarantee the proper operation of the HS switch. In most cases this is equal to the UVLO level of the gate driver IC.

2.3 Motor driving

If the half-bridge is a part of a three-phase motor driver, its duty-cycle varies in order to generate a rotating current on the motor.

The rotating current generation can be based on a trapezoidal (six-step) or a sinusoidal (e.g. FOC) commutation.

Trapezoidal commutation divides the electrical rotation of the motor in six segments of 60°: based on which quadrant the vector is, a different driving to the three phases is applied.

Only one direction for each quadrant is used, six in total, which gives the name six-step to the commutation method.

In sinusoidal commutation, the most common driving strategy is the Space Vector Modulation (SVM). The duty-cycle of each half-bridge is adjusted according to the target vector direction obtaining a continuous rotation and, consequently, a sinusoidal current.

2.3.1 Trapezoidal commutation (six-step)

The duty-cycle applied in each state can be considered constant, for this reason the behavior of bootstrap circuitry is equivalent to the case described in Section 2.1

**Figure 5.** Trapezoidal driving example (modulation index 80%)

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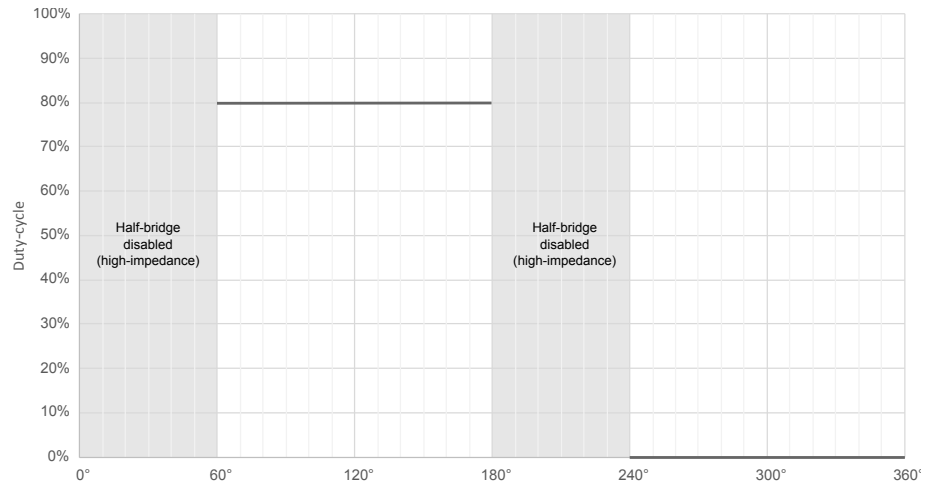
2.3.2 Space Vector Modulation with discontinuous PWM

This implementation of the SVM uses, for each segment, two of the half-bridges to control the vector direction keeping the third one fixed at duty-cycle 0% (i.e. constantly connected to ground).

Figure 6. SVM with discontinuous PWM example (modulation index 80%)
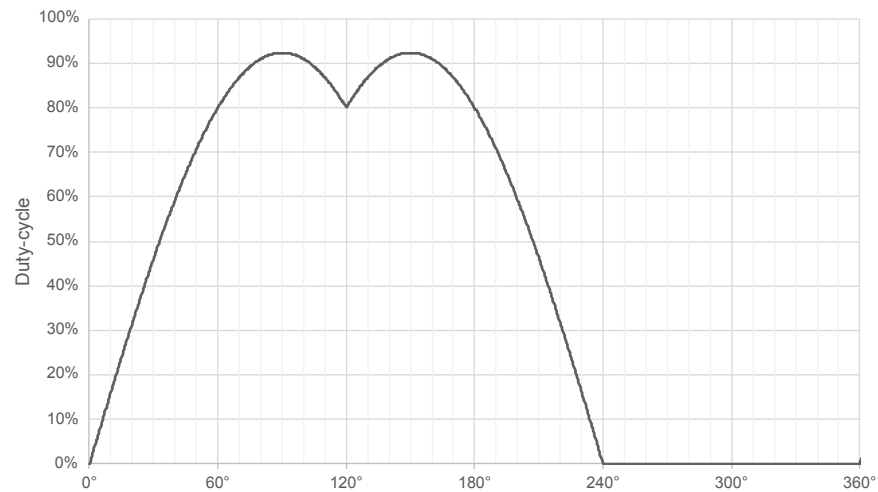
This sequence allows a full recharge of the bootstrap capacitor during the 0% duty-cycle phase making the dimensioning of the circuitry easier.

Due to the continuous variation of the duty-cycle, it is difficult to define a formula for the calculation of the minimum V_{BO} and usually a simulation is required.

Figure 7. SVM with discontinuous PWM: V$_{CC}$ - V$_{BO,min}$ variation with PWM frequency and Q$_g$
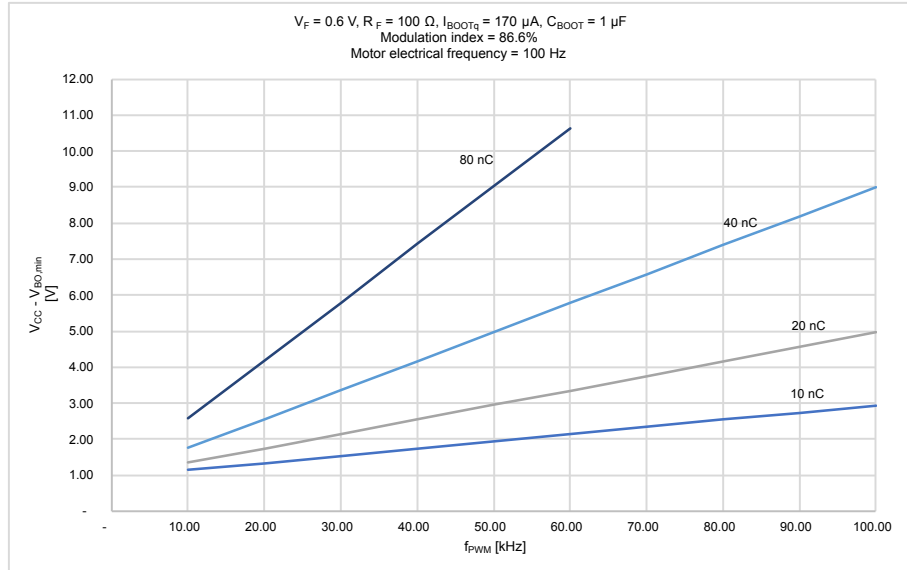
Figure 8. SVM with discontinuous PWM example: V$_{CC}$ - V$_{BO,min}$ variation with modulation index and Q$_g$
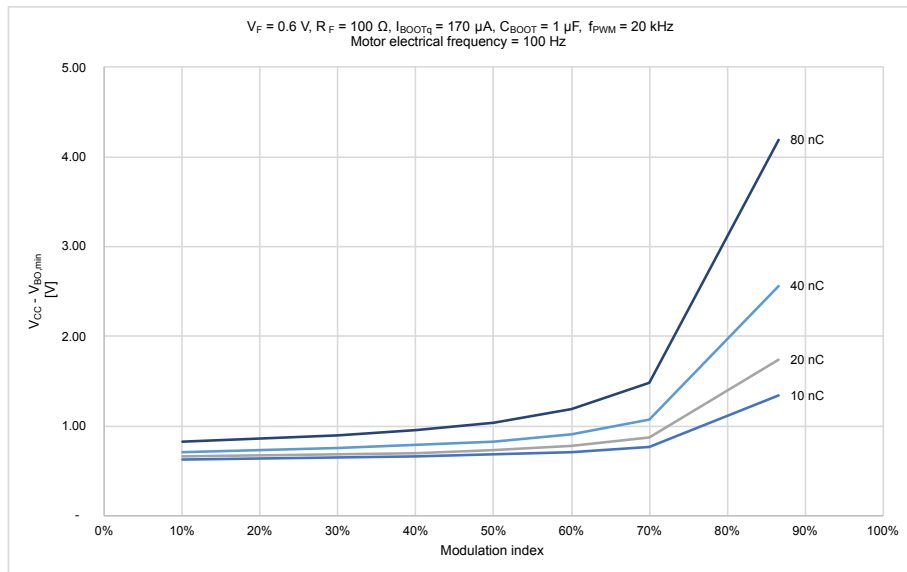
2.3.3 Space Vector Modulation with continuous PWM

This implementation of the SVM applies a variable duty-cycle to all the half-bridges, so the bootstrap capacitor is always subject to charge and discharge phases.

Figure 9. SVM with continuous PWM example (modulation index 80%)
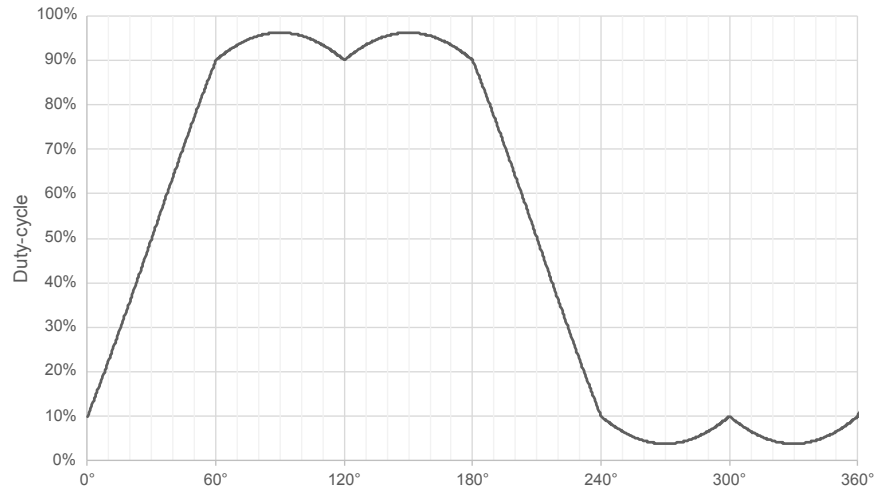
Also in this case, it is difficult to define a formula for the calculation of the minimum V_{BO} and the system behavior can be estimated only through simulation.

Figure 10. SVM with continuous PWM – VBO,min variation with PWM frequency Q_g
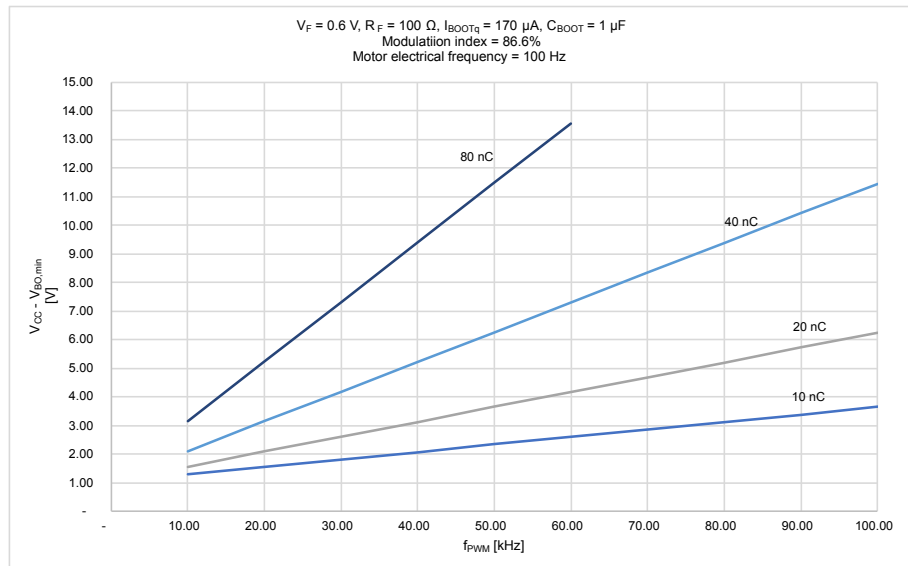
Figure 11. SVM with continuous PWM example – VBO,min variation with modulation index and Q$_g$
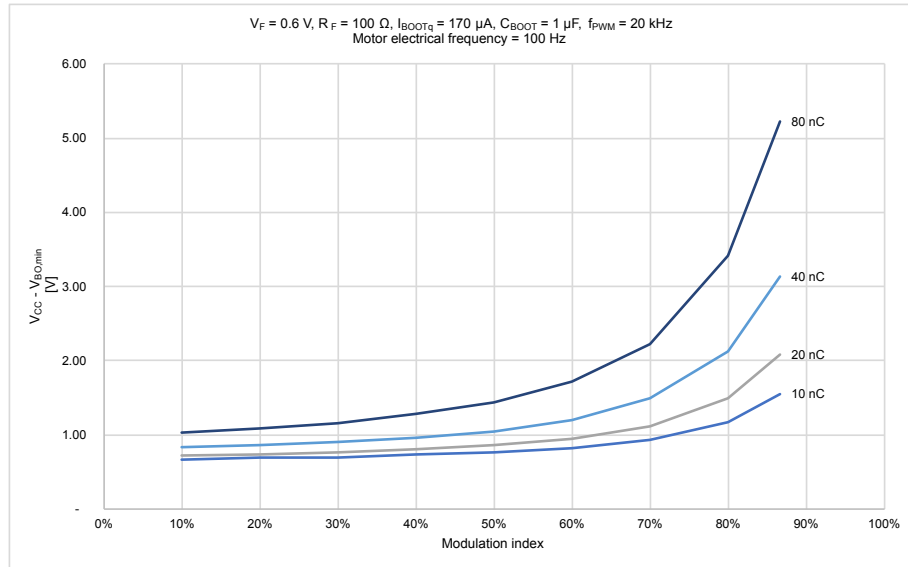
Revision history

Table 2. Document revision history

Date	Version	Changes
23-Mar-2022	1	Initial release.

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