BTN9990LV/BTN9970LV

Thermal performance and power dissipation

About this document

Scope and purpose

This application note provides information about power dissipation calculation and transient thermal resistance for the BTN99xx NovalithIC™ + device family. This document must be used in conjunction with the device datasheets.

Intended audience

Developers, working with the BTN99xx NovalithIC™ + devices.

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1 Introduction

The BTN99xx NovalithIC™ + devices are part of an integrated half-bridge family, suitable for driving DC motors and solenoids.

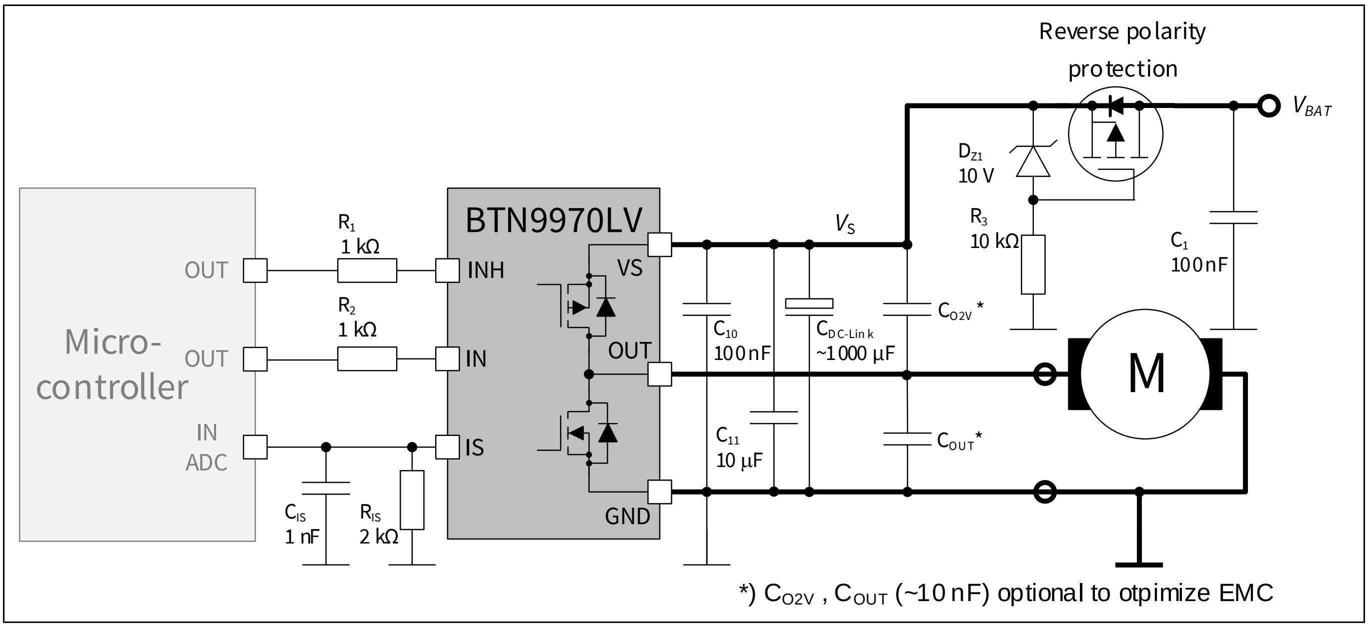


Figure 1 Typical application circuit example (motor to GND configuration)

2 Power dissipation

Power is dissipated in the control logic and in the two MOSFETs of the device. The load currents in the MOSFETs generate most of the power dissipation, therefore the power dissipation of the control logic is neglected. The following sections provide a basic method for calculating power dissipation in the MOSFET power stages to help the designers to estimate overall power dissipation of the device. The power dissipation in the MOSFETs consists mainly of conducted losses and switching losses. Losses in the body diode only occur during the cross current protection phase.

2.1 Conduction/R_{ON} power dissipation

In the ON-state, a MOSFET has a specific ON-state resistance, which is listed in the datasheet for each the high-side ($R_{ON(HS)}$) and the low-side ($R_{ON(LS)}$) MOSFET.
The output current I_{OUT} flowing through the active MOSFET generates the following conducted losses:

$$P_{RON} = I_{OUT}^2 \cdot R_{ON(LS/HS)}$$

Equation 1

When the BTN99xx is driven in a static condition, without PWM, **Equation *1*** can be used to estimate the static conduction losses for high-side or low-side MOSFETs.

For static reverse current operation of the MOSFETs, the corresponding ON-state resistance values are provided in the datasheet of the BTN99XX for both, high-side and low-side switches.

2.2 Switching losses in motor to GND configuration

With PWM control, switching losses need to be considered because they generate higher power dissipation with higher PWM frequencies.

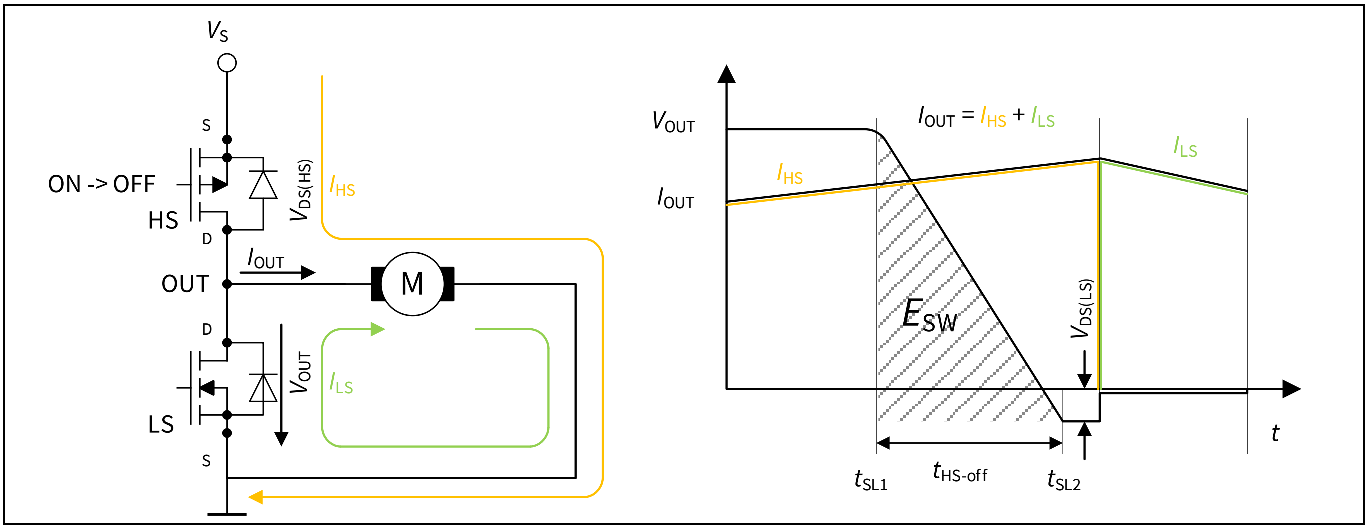


Figure 2 High-side switching (motor to GND configuration)

Figure 2 shows the half bridge configuration with motor connected to GND and the switching loss in the high-side MOSFET (HS) when turning off during a PWM cycle. The high-side switch is controlled by a PWM signal and is called the actuator MOSFET. With activated high-side MOSFET (HS) current flows from V_S through the output (OUT) of the half-bridge into the motor and further to GND. Energy is transferred to the motor to spin it.

Power dissipation

Once the high-side MOSFET (HS) is turning off, it operates during the time $t_{HS\text{-}off}$ in linear mode and dissipates power. Due to a motor has an inductance, the current (I_{HS}) keeps flowing through the high-side MOSFET (HS).

Once the high-side MOSFET (HS) is turned off completely, the body diode of the low-side MOSFET (LS) becomes conductive for a short time causing a negative voltage drop of $V_{DS(LS)}$. The power dissipation caused by the body diode is negligible and thus not considered in this estimation.

Once the low-side MOSFET (LS) is turned on, it provides a low resistive path for the freewheeling current.

The BTN99xx has a cross-current protection mechanism which ensures that an output MOSFET is turned on only when the other one is off.

The rise and fall time specified in the datasheet is the time period in which the output voltage decreases from 80% to 20%. To calculate the switching losses more accurately, the switching time $t_{HS\text{-}off}$ to decrease the output voltage from 100% to 0% is required. The time $t_{HS\text{-}off}$ can be estimated from the datasheet parameters rise time (t_r) and fall time (t_f) with the **Equation *2*** accordingly.

$$t_{\mathrm{HS-off}} = \frac{t_{\mathrm{f(HS)}}}{0.5}$$

Equation 2

Factor 0.5 is related to dV_{OUT} from 0% to 100%.

For the other switching times ($t_{HS\text{-}on}$, $t_{LS\text{-}off}$ and $t_{LS\text{-}on}$) **Equation *2*** can be used to perform the same calculation using the corresponding datasheet parameters ($t_{r(HS)}$, $t_{f(LS)}$ and $t_{r(LS)}$).

Other assumptions, with a minor effect on the results are:

- The load current during the switching process is constant
- The switching times are assumed as equal and in the following always referred to as $t_{HS\text{-}off}$

The switching energy E_{SW} shown in **Figure 2** can be estimated with **Equation *3***.

$$E_{\mathrm{SW}} = \int_{t_{\mathrm{SL1}}}^{t_{\mathrm{SL2}}} V_{\mathrm{S}} \cdot I_{\mathrm{OUT}} dt = \frac{1}{2} \cdot V_{\mathrm{S}} \cdot I_{\mathrm{OUT}} \cdot t_{\mathrm{HS-off}}$$

Equation 3

With the equation for the switching energy E_{SW} the average power loss P_{SW} can be calculated by multiplying E_{SW} with two times switching for every PWM period and the PWM frequency.

$$\overline{P_{\mathrm{SW}}} = \frac{1}{2} \cdot V_{\mathrm{S}} \cdot I_{\mathrm{OUT}} \cdot t_{\mathrm{HS-off}} \cdot 2 \cdot f_{\mathrm{PWM}} = V_{\mathrm{S}} \cdot I_{\mathrm{OUT}} \cdot t_{\mathrm{HS-off}} \cdot f_{\mathrm{PWM}}$$

Equation 4

2.3 Power dissipation of the MOSFETs in motor to GND configuration

The power dissipation in PWM mode consists of the switching losses and the conducted losses. The conducted losses occur in both the high-side (HS) and in the low-side (LS) MOSFET. In the configuration motor connected to GND, the switching losses occur in the high-side MOSFET (HS). The conducted losses occur in the high-side MOSFET during the ON-phase and in the low-side MOSFET in the freewheeling phase, as shown in **Figure 2** and **Figure 3**.

Power dissipation

In PWM mode, the PWM period time T_{PWM} is:

$$T_{PWM} = \frac{1}{f_{PWM}}$$

Equation 5

The duty cycle (*DC*) of the PWM mode is the relation between the ON-time and the PWM period time defined as:

$$DC = \frac{T_{ON}}{T_{PWM}}$$

Equation 6

The power dissipation contributors and its timings for a motor-to-GND scenario are illustrated in **Figure 3** below.

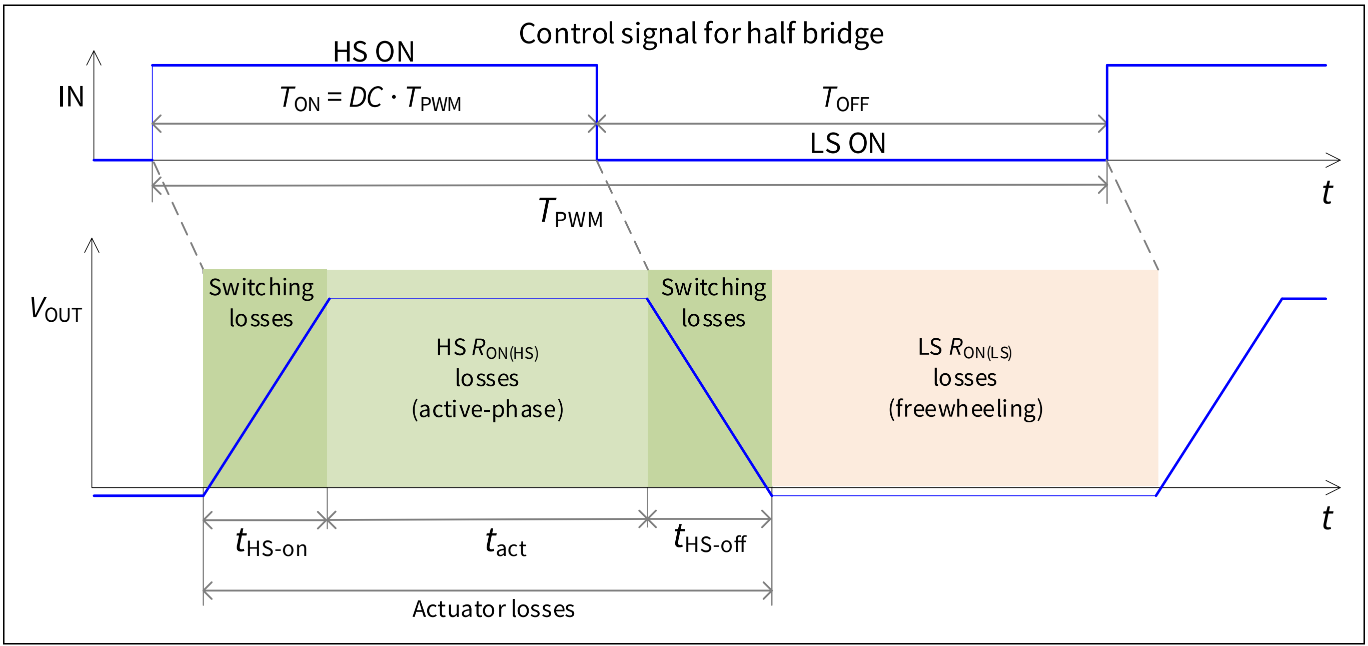


Figure 3 **Power dissipation of BTN99XX in the configuration motor connected to GND**

The dissipated energy in the high-side MOSFET consists of two times the switching losses plus the conducted losses in the active-phase, as shown in **Figure 3**. For the motor-to-GND scenario the switching times for turning on and off can be considered as equal. The active-phase time in PWM mode for the high-side MOSFET can be calculated according to **Equation 7**.

$$t_{act} = T_{ON} - t_{HS-off}$$

Equation 7

The dissipated energy per PWM cycle for the actuator MOSFET (HS) is:

$$E_{act} = E_{SW} + E_{RON(HS)} = V_S \cdot I_{OUT} \cdot t_{HS-off} + I_{OUT}^2 \cdot R_{ON(HS)} \cdot t_{act}$$

Equation 8

Power dissipation

The average power dissipation in the actuator MOSFET (HS) results in:

$$\overline{P_{\mathrm{act}}} = E_{\mathrm{act}} \cdot f_{\mathrm{PWM}} = \left(V_{\mathrm{S}} \cdot I_{\mathrm{OUT}} \cdot t_{\mathrm{HS-off}} + I_{\mathrm{OUT}}^2 \cdot R_{\mathrm{ON(HS)}} \cdot t_{\mathrm{act}}\right) \cdot f_{\mathrm{PWM}}$$

Equation 9

In the motor-to-GND scenario, the freewheeling MOSFET is the low-side MOSFET (LS), as shown in **Figure 2**. The power dissipation consists of the conduction losses in the freewheeling phase, shown in **Figure 3**.

The duration of the active freewheeling phase in PWM mode is:

$$t_{\mathrm{FW}} = T_{\mathrm{PWM}} - T_{\mathrm{ON}} - t_{\mathrm{HS-off}}$$

Equation 10

The dissipated energy during the active freewheeling phase in the low-side MOSFET (LS) can be calculated to:

$$E_{\mathrm{FW}} = I_{\mathrm{OUT}}^2 \cdot R_{\mathrm{ON(LS)}} \cdot t_{\mathrm{FW}} = I_{\mathrm{OUT}}^2 \cdot R_{\mathrm{ON(LS)}} \cdot (T_{\mathrm{PWM}} - T_{\mathrm{ON}} - t_{\mathrm{HS-off}})$$

Equation 11

Out of the energy equation above, the average power dissipation in the freewheeling MOSFET (LS) can be determined by multiplying it by f_{PWM}:

$$\overline{P_{\mathrm{FW}}} = E_{\mathrm{FW}} \cdot f_{\mathrm{PWM}} = I_{\mathrm{OUT}}^2 \cdot R_{\mathrm{ON(LS)}} \cdot (T_{\mathrm{PWM}} - T_{\mathrm{ON}} - t_{\mathrm{HS-off}}) \cdot f_{\mathrm{PWM}}$$

Equation 12

2.4 Switching losses in motor to VS configuration

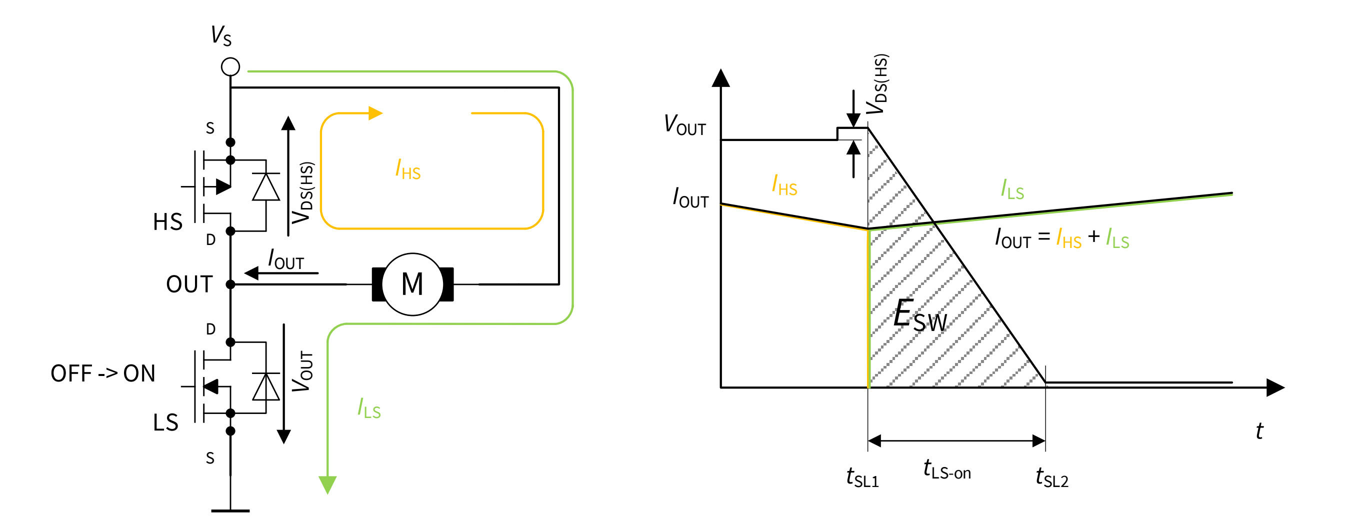


Figure 4 **Low-side switching of BTN99xx (motor to V_S configuration)**

Figure 4 shows the half bridge configuration with motor connected to VS and the switching loss in the low-side MOSFET (LS) when turning on during a PWM cycle. The low-side switch is controlled by a PWM signal and is the actuator MOSFET. With activated low-side MOSFET (LS) current flows from V_S through the motor into the output (OUT) of the half-bridge and through the low-side MOSFET (LS) further to GND. Energy is transferred to the motor to spin it.

Power dissipation

Once the low-side MOSFET (LS) is turning on, it operates during the time $t_{HS\text{-}on}$ in linear mode and dissipates power. Due to a motor has an inductance, the current (I_{HS}) keeps flowing through the low-side MOSFET (LS). In this configuration, the high-side MOSFET (HS) is providing the freewheeling path, once the low-side MOSFET (LS) is turned off. Before the high-side MOSFET is turned, its body diode becomes conductive for short period of time causing a positive voltage increase of $V_{DS(HS)}$.

The same assumptions and considerations like in the motor to GND configuration apply here.

$$t_{\mathrm{LS-on}} = \frac{t_{\mathrm{f(LS)}}}{0.5}$$

Equation 13

The switching energy E_{SW} shown in **Figure 4** can be estimated with **Equation *14*** and the resulting switching power loss with **Equation *15***.

$$E_{\mathrm{SW}} = \int_{t_{\mathrm{SL1}}}^{t_{\mathrm{SL2}}} V_{\mathrm{S}} \cdot I_{\mathrm{OUT}} dt = \frac{1}{2} \cdot V_{\mathrm{S}} \cdot I_{\mathrm{OUT}} \cdot t_{\mathrm{LS-on}}$$

Equation 14

$$\overline{P_{\mathrm{SW}}} = \frac{1}{2} \cdot V_{\mathrm{S}} \cdot I_{\mathrm{OUT}} \cdot t_{\mathrm{LS-on}} \cdot 2 \cdot f_{\mathrm{PWM}} = V_{\mathrm{S}} \cdot I_{\mathrm{OUT}} \cdot t_{\mathrm{LS-on}} \cdot f_{\mathrm{PWM}}$$

Equation 15

2.5 Power dissipation of the MOSFETs in motor to VS configuration

The power dissipation in PWM mode consists of the switching losses and the conducted losses. Opposite to the motor to GND configuration, the switching losses now occur in the low-side MOSFET (LS). The conducted losses occur in the low-side MOSFET during the active-phase and in the high-side MOSFET in the freewheeling phase, as shown in **Figure 8**.
The equations to calculate the power losses are equivalent to the equations shown in the motor to GND configuration.

The dissipated energy in the low-side MOSFET (LS) consists of two times the switching losses plus the conducted losses in the active-phase, as shown in **Figure 8**.

The switching times for the low-side MOSFET and the high-side MOSFET can be considered as similar with $t_{LS\text{-}on} = t_{LS\text{-}off} = t_{HS\text{-}on} = t_{HS\text{-}off}$.

The ON-state resistance values $R_{ON(LS)}$ and $R_{ON(HS)}$ of the low-side (LS) and high-side (HS) MOSFETs differ and need to be chosen from the datasheet.

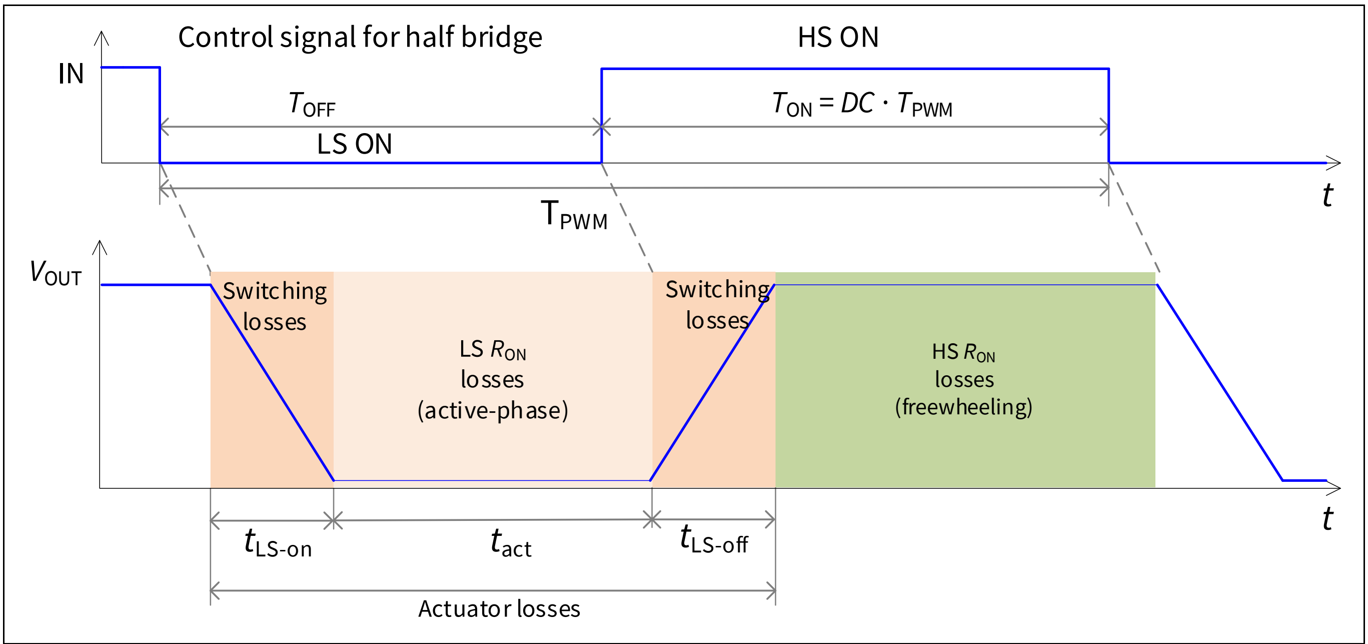


Figure 5 **Power dissipation of BTN99XX in the configuration motor connected to VS**

However, the active time t_{act} of the actuator MOSFET (LS) is now:

$$t_{act} = T_{OFF} - t_{LS-on}$$

Equation 16

With T_{OFF}:

$$T_{OFF} = T_{PWM} - T_{ON}$$

Equation 17

The dissipated energy per PWM cycle for the actuator MOSFET (LS) is:

$$E_{act} = E_{SW} + E_{RON(LS)} = V_S \cdot I_{OUT} \cdot t_{LS-on} + I_{OUT}^2 \cdot R_{ON(LS)} \cdot t_{act}$$

Equation 18

The average power dissipation in the actuator MOSFET (LS) results in:

$$\overline{P_{act}} = E_{act} \cdot f_{PWM} = \left(V_S \cdot I_{OUT} \cdot t_{LS-on} + I_{OUT}^2 \cdot R_{ON(LS)} \cdot t_{act}\right) \cdot f_{PWM}$$

Equation 19

In the motor-to VS scenario, the freewheeling MOSFET is the high-side MOSFET. The power dissipation consists of the conduction losses in the freewheeling phase, shown in **Figure 5**.

The duration of the active freewheeling phase in PWM mode is:

$$t_{FW} = T_{ON} - t_{LS-on}$$

Equation 20

The dissipated energy during the active freewheeling phase in the low-side MOSFET can be calculated to:

Power dissipation

$$E_{\mathrm{FW}} = I_{\mathrm{OUT}}^2 \cdot R_{\mathrm{ON(HS)}} \cdot t_{\mathrm{FW}} = I_{\mathrm{OUT}}^2 \cdot R_{\mathrm{ON(HS)}} \cdot (T_{\mathrm{ON}} - t_{\mathrm{LS-on}})$$

Equation 21

Out of the energy equation above, the average power dissipation in the freewheeling MOSFET (LS) can be determined by multiplying it by the PWM frequency f_{PWM}:

$$\overline{P_{\mathrm{FW}}} = E_{\mathrm{FW}} \cdot f_{\mathrm{PWM}} = I_{\mathrm{OUT}}^2 \cdot R_{\mathrm{ON(HS)}} \cdot (T_{\mathrm{ON}} - t_{\mathrm{LS-on}}) \cdot f_{\mathrm{PWM}}$$

Equation 22

3 Transient thermal resistance Z_{thJA}

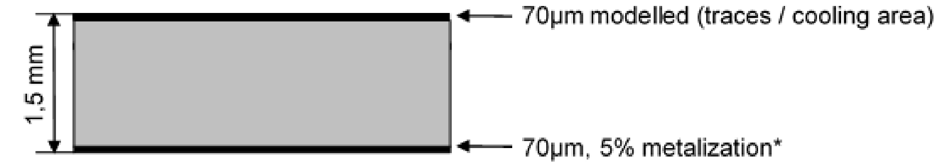
The steady state thermal resistance parameters like R_{thJA} (thermal resistance junction to ambient) and R_{thJC} (thermal resistance junction to case) are specified in the datasheet.

However, for motor control applications an important parameter is the transient thermal resistance (thermal impedance) Z_{thJA}.

The transient thermal resistance Z_{thJA} has been simulated for different JEDEC 1s0p (footprint / 300 mm^2 / 600 mm^2) and 2s2p board configurations with a power dissipation of 1 W at an ambient temperature T_A of 85°C.

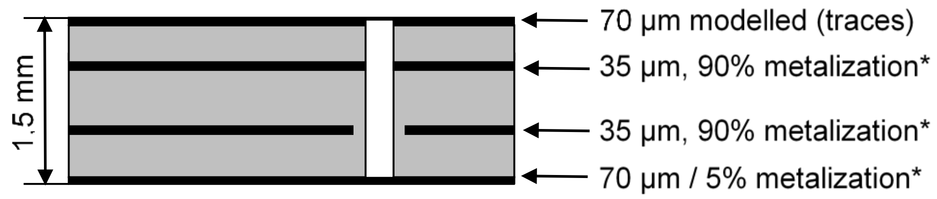
Table 1 PCB

Dimension [mm^3]	76.2 × 114.3 × 1.6	λ_{therm} [W/m·K]	ρ[kg/m^3]	c[J/kg/K]
Material	FR4	0.30-0.43	1800	1100
Metalization (Cu)	JEDEC 2s2p (JESD 51-7, JESD 51-5) JEDEC 1s0p (JESD 51-3)	388	8930	396
Thermal via (25 pcs)	∅ = 0.3 mm; plating 50 µm	388	8930	396
Package attach [50 µm]	Solder	55	10350	124



*: means percentual Cu metalization on each layer

Figure 6 Cross section (JEDEC 1s0p Board)



*: means percentual Cu metalization on each layer

Figure 7 Cross section (JEDEC 2s2p)

Transient thermal resistance ZthJA

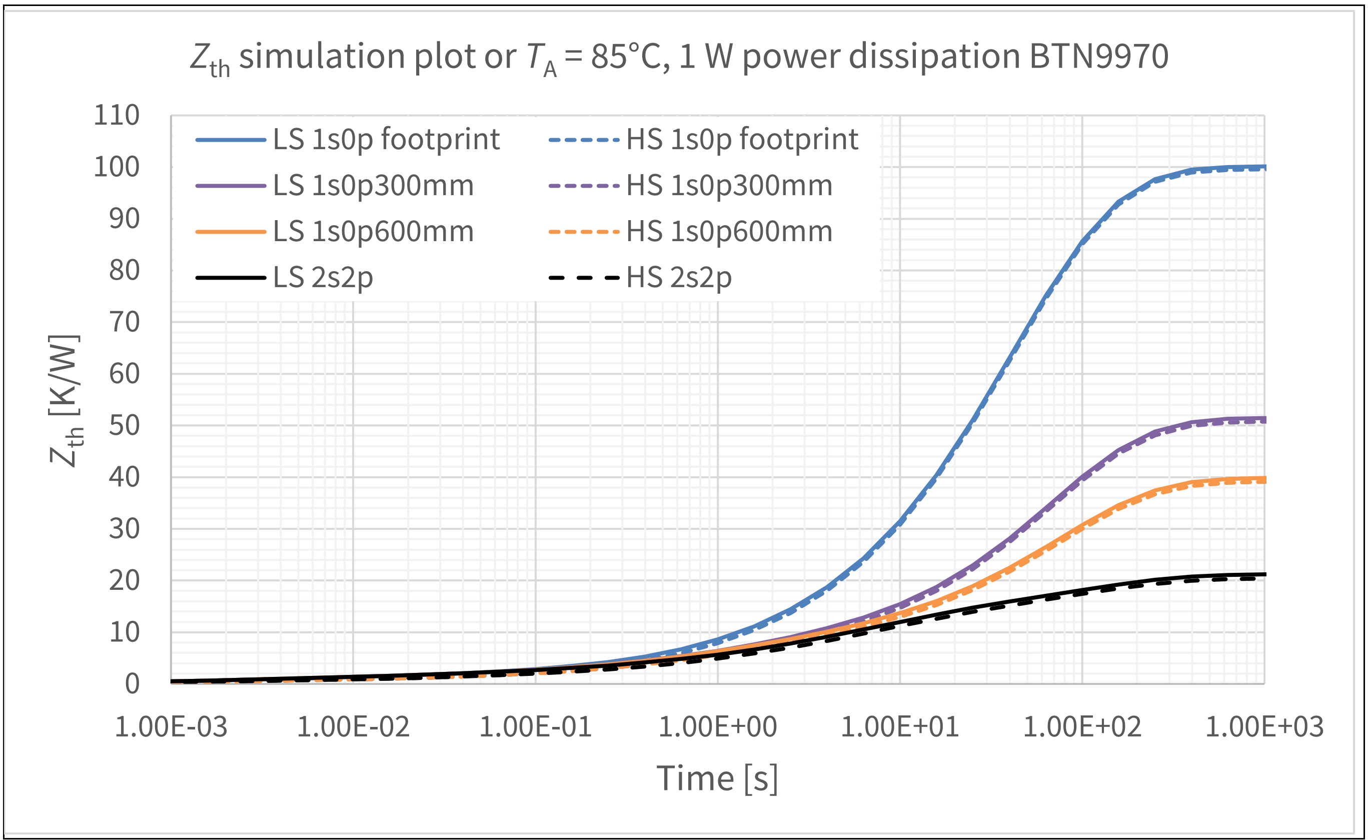


Figure 8 **BTN9970 typical transient thermal resistance Z_{thJA} (junction-to-ambient) simulation**

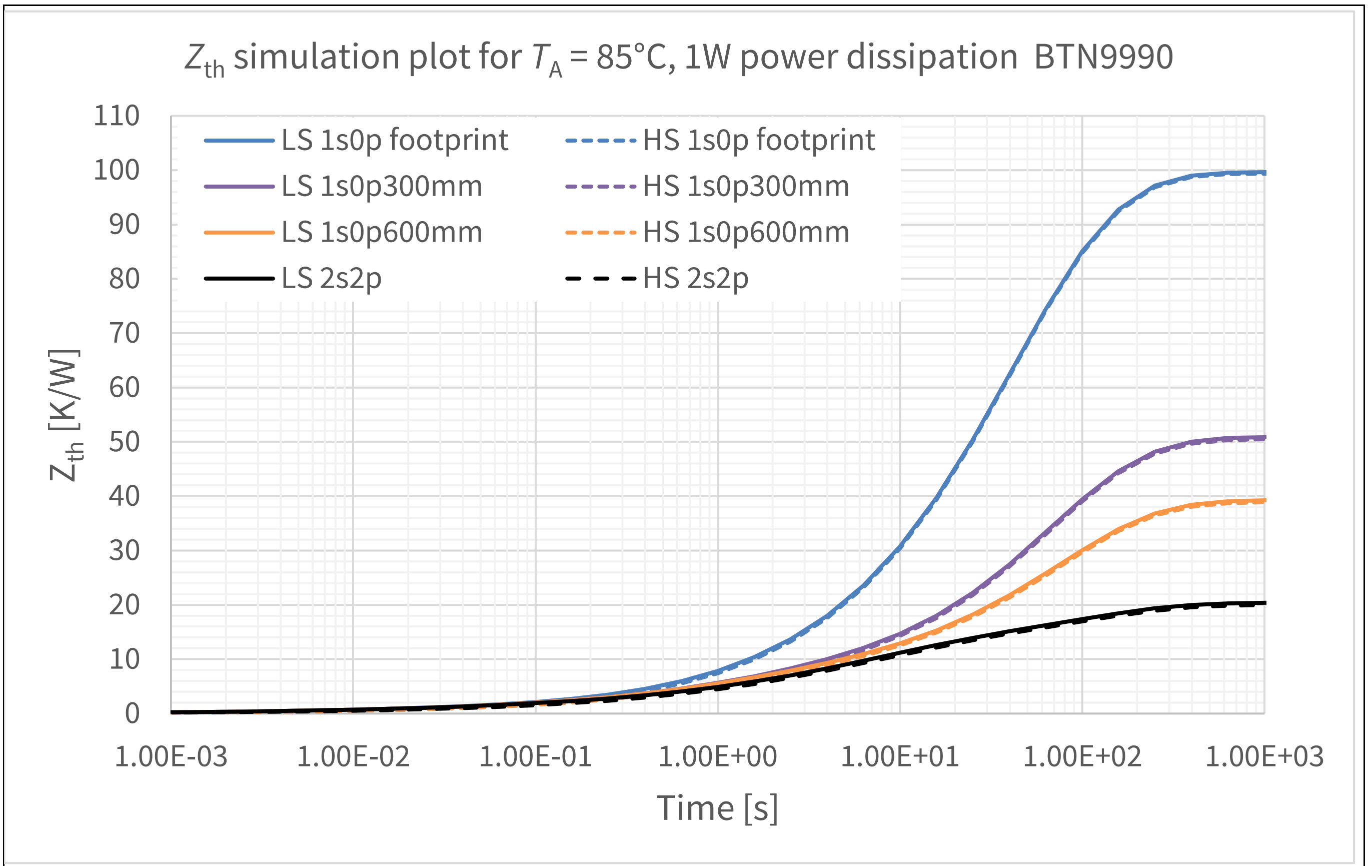


Figure 9 **BTN9990 typical transient thermal resistance Z_{thJA} (junction-to-ambient) simulation**

Revision history

Document version	Date of release	Description of changes
01.00	2021-10-01	Initial document release

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