SPIDER+

Control of stepper motors

About this document

Scope and purpose

This application note shows a practical example of how the products of the SPIDER+ family can be used for driving a stepper motor. This document provides a step-by-step implementation guide, starting from simulation to the real world application.

Intended audience

This document is addressed to anyone who is interested in using the products of the SPIDER+ family.

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1 Introduction SPIDER+

Infineon Technologies SPIDER+ family of products (SPI Drivers for enhanced relay control) has been successful driving off-board relays in automotive applications for several years, particularly in the body electronics area, enabling integration, scalability, flexibility and robustness for the application.

The automotive industry is highly demanding in time-to-market requirements, reliability and cost. To satisfy these requirements, vehicle manufacturers standardize architectures and consolidate requirements across different vehicle platforms. Additionally, the electronic content in vehicles is rapidly increasing and the number of features and options is very widespread, therefore flexibility and scalability is also required. The electronic module design is a key factor in supporting the demands of the industry.

This application note describes the serial peripheral interface in general and its commands used for the practical application of controlling a stepper motor in different drive modes.

2 Serial peripheral interface (SPI)

In this chapter a SPIDER+ TLE75008-ESD is taken as an example.

The serial peripheral interface (SPI) is a full duplex synchronous serial slave interface, which uses four lines: serial output (SO), serial input (SI), serial clock (SCLK) and chip select (CSN). Data is transferred by the lines SI and SO at the rate given by SCLK. The falling edge of CSN indicates the beginning of an access. Data is sampled in on line SI at the falling edge of SCLK and shifted out on line SO at the rising edge of SCLK. Each access must be terminated by a rising edge of CSN. A modulo 8/16 counter ensures that data is taken only when a multiple of 8 bits has been transferred after the first 16 bits. Otherwise a TER bit is asserted. In this way the interface provides daisy chain capability with 16-bit as well as with 8-bit SPI devices.

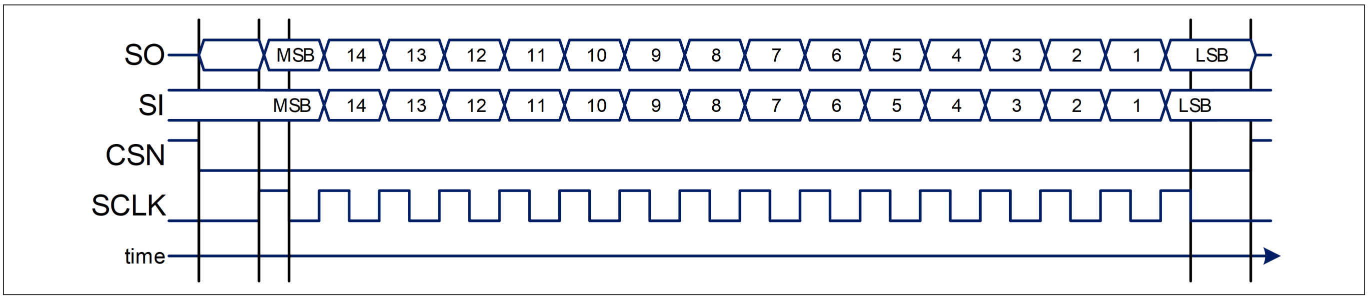


Figure 1 **Serial peripheral interface**

2.1 SPI signal description

The system microcontroller selects the SPIDER+ device by means of the CSN pin. Whenever the pin is in “low” state, data transfer can take place. When CSN is in "high" state, any signals at the SCLK and SI pins are ignored and SO is forced into a high impedance state.

2.2 CSN high-to-low transition

- The requested information is transferred into the shift register.
- SO changes from high impedance state to "high" or “low” state depending on the logic OR combination between the transmission error flag (TER) and the signal level at pin SI. This allows to detect a faulty transmission even in daisy chain configuration.
- If the device is in Sleep mode, SO pin remains in high impedance state and no SPI transmission occurs.

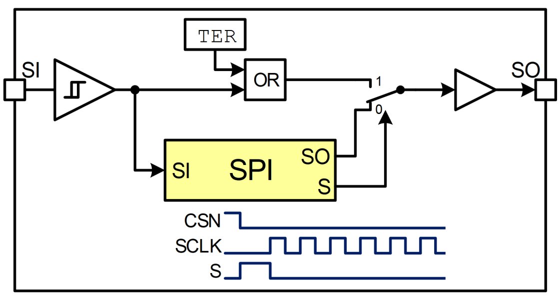


Figure 2 **Combinatorial logic for TER bit**

2.3 CSN low-to-high transition

- Command decoding is only done, when after the falling edge of CSN exactly a multiple (1, 2, 3, …) of eight SCLK pulses have been detected after the first 16 SCLK pulses. In case of faulty transmission, the transmission error bit (TER) is set and the command is ignored.
- Data from shift register is transferred into the addressed register.

2.4 SCLK - serial clock

This input pin clocks the internal shift register. The serial input (SI) transfers data into the shift register on the falling edge of SCLK while the serial output (SO) shifts diagnostic information out on the rising edge of the serial clock. It is essential that the SCLK pin is in "low" state whenever chip select CSN makes any transition, otherwise the command may be not accepted.

2.5 SI - serial input

Serial input data bits are shift-in at this pin, the most significant bit first. SI information is read on the falling edge of SCLK. The input data consists of two parts, control bits followed by data bits.

2.6 SO - serial output

Data is shifted out serially at this pin, the most significant bit first. SO is in high impedance state until the CSN pin goes to "low" state. New data appears at the SO pin following the rising edge of SCLK.

2.7 Daisy chain capability

The SPI of SPIDER+ devices provides daisy chain capability. In this configuration several devices are activated by the same CSN signal MCSN. The SI line of one device is connected with the SO line of another device, in order to build a chain (see ***Figure 3***). The end of the chain is connected to the output and input of the master device, MO and MI respectively. The master device provides the master clock (MCLK) which is connected to the SCLK line of each device in the chain.

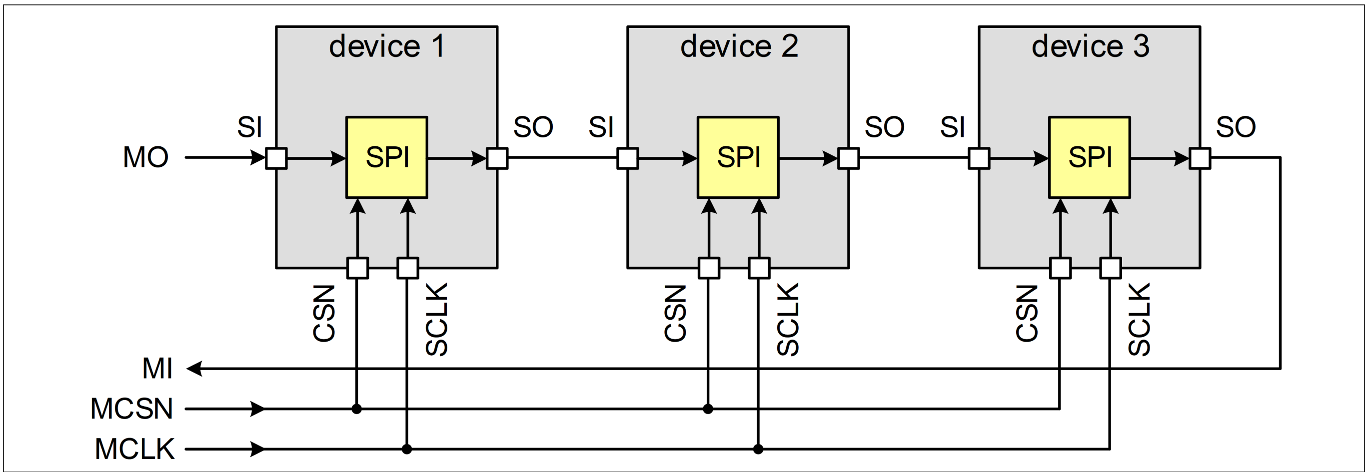


Figure 3 **Daisy chain configuration**

In the SPI block of each device, there is one shift register where each bit from SI line is shifted in each SCLK cycle. The bit shifted out occurs at the SO pin. After sixteen SCLK cycles, the data transfer for one device is complete.

In single chip configuration, the CSN line must turn "high" to make the device acknowledge the transferred data. In daisy chain configuration, the data shifted out at device 1 has been shifted in to device 2. When using three devices in daisy chain, several multiples of 8 bits have to be shifted through the devices (depending on how many devices with 8 bit SPI and how many with 16 bit SPI). After that, the MCSN line must turn "high" (see ***Figure 4***).

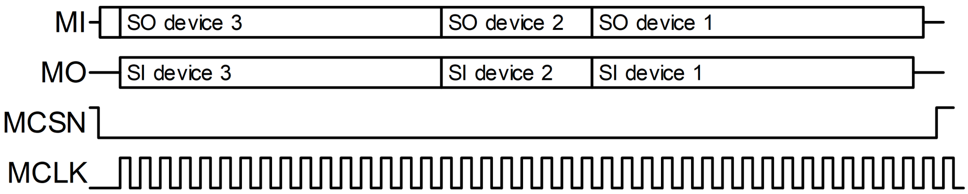


Figure 4 **Data transfer in daisy chain configuration**

2.8 SPI protocol

The relationship between SI and SO content during SPI communication is shown in ***Figure 5***. SI line represents the frame sent from the µC and SO line is the response provided by the SPIDER+ device.

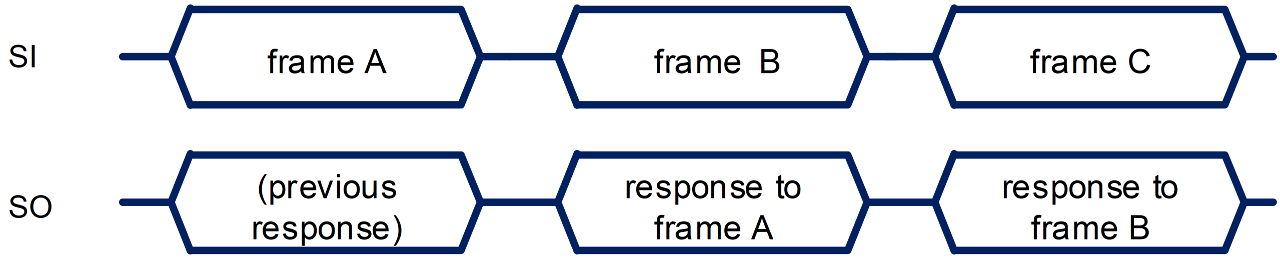


Figure 5 **Relationship between SI and SO during SPI communication**

The SPI protocol provides the response to a command frame only with the next transmission triggered by the µC. Although the majority of commands and frames implemented in TLE75008-ESD can be decoded without the knowledge of previous occurrences, it is advisable to consider what the µC sent in the previous transmission to decode TLE75008-ESD response frame completely. A detailed sequence of commands to "read" and "write" the content of a register is depicted in ***Figure 6***.

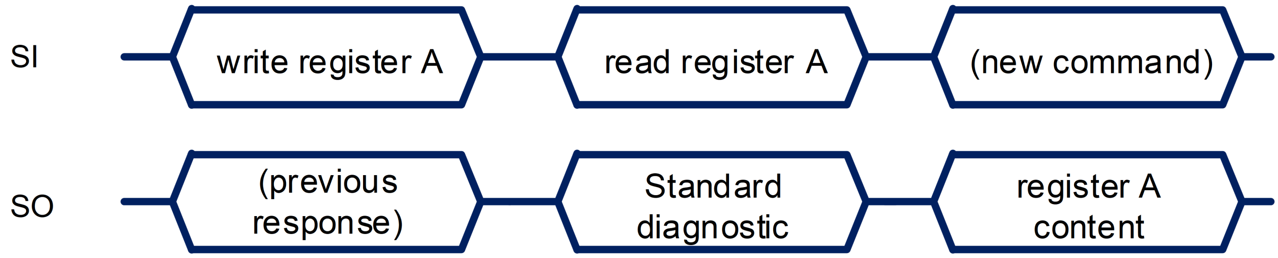


Figure 6 **Register content sent back to µC**

Three special circumstances where the frame sent back to the µC is not related directly to the previously received frame:

- In case an error in transmission occurred during the previous frame (for instance, the clock pulses were not a multiple of 8 with a minimum of 16 bits), shown in ***Figure 7***
- When the SPIDER+ device logic supply comes out of power-on reset condition or after a software reset, as shown in ***Figure 8***
- In case of command syntax errors, shown in ***Figure 9***
  - "write" command starting with "11" instead of "10"
  - "read" command starting with "00" instead of "01"
  - "read" or "write" commands on registers which are "reserved" or "not used"

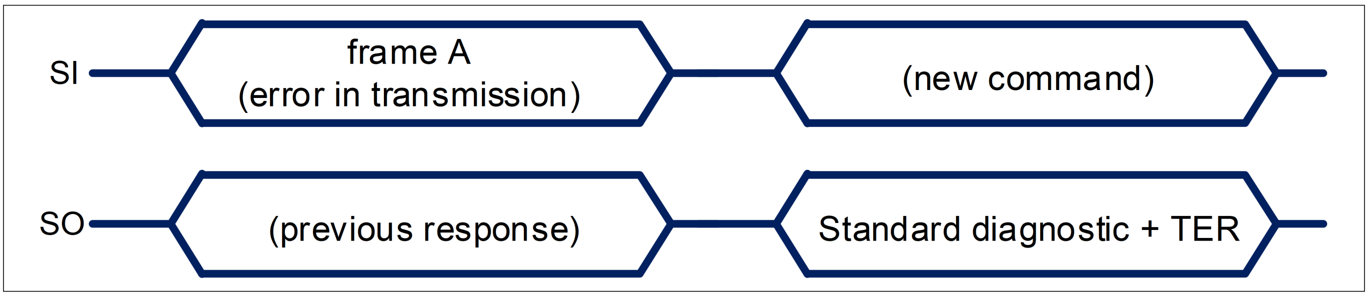


Figure 7 TLE75008-ESD response after an error in transmission

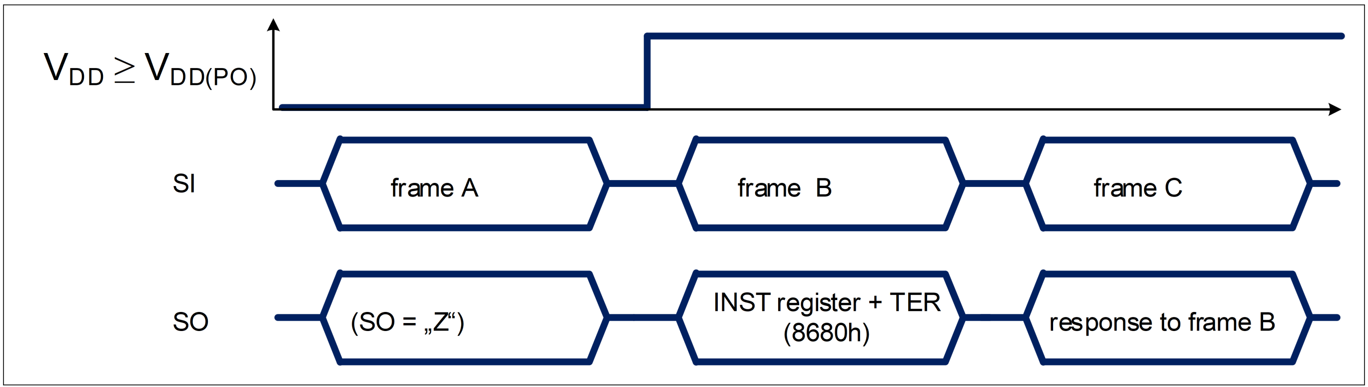


Figure 8 TLE75008-ESD response after coming out of Power-On reset at V_{DD}

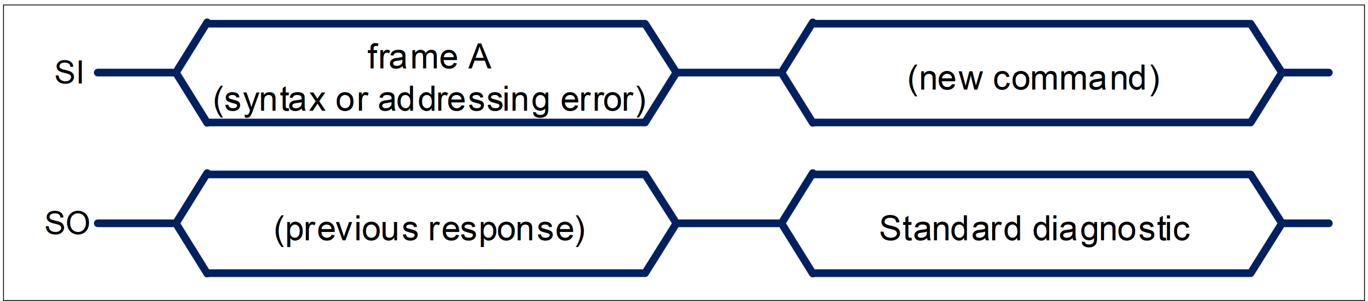


Figure 9 TLE75008-ESD response after a command

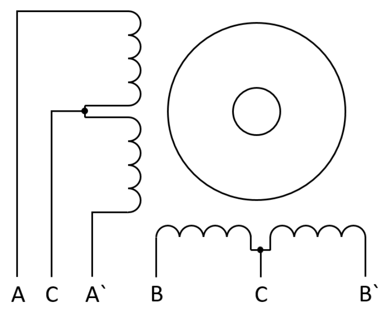
3 Application example: stepper motor control with SPIDER+

There are many applications where the SPIDER+ can be used. The example provided describes the control of a stepper motor in full step mode using one phase at the time. It is divided into several parts, beginning with the simulation in the Infineon Designer *[1]*. In addition, the stepper motor is described briefly and all tools and equipment required, are outlined.

3.1 Stepper motor

The motor can be driven in different drive modes, namely full step one phase on, full step two phase on, half-step or micro-stepping. The stepper motor is a unipolar two-phase 6-wire stepper motor with the specifications, depicted in ***Table 1***.

Table 1 Unipolar two-phase stepper motor specification

Specification	Value	Unit	Unipolar 6-wire stepper motor schematic
Rated voltage (V)	12	[V]	
Rated current (I)	0.4	[A]	
Inductance (L)	14	[mH]	
Resistance (R)	30	[Ω]	
Step angle	1.8	[°]	
Step angle accuracy	5	[%]	

3.1.1 Drive modes

Stepper motors can be driven in different modes, depending on the application. Three drive modes are commonly used:

- Full step mode (one phase or two phase on)
  - In full step mode, the step angle is 1.8 degrees, where either one or two phases are energized at the same time, see ***Table 2*** and ***Table 3***. The full step mode with two phases on provides the highest torque.
- Half step mode (one phase and two phase on)
  - In half step mode, the step angle is decreased to 0.9 degrees, resulting in a better resolution. One drawback is that this mode cannot provide the same torque as the full step mode, since in every second step only one coil is energized, see ***Table 4***.
- Micro stepping
  - For micro stepping, the coils are energized by shifted sinusoidal signals, resulting in a smooth and constant movement of the motor shaft.

Table 2 Drive mode: Full step with one phase on

Step	A	B	A'	B'	C	CW
1	ON	-	-	-	+ V_{BAT}	↓
2	-	ON	-	-		
3	-	-	ON	-		
4	-	-	-	ON		

Table 3 Drive mode: Full step with two phase on

Step	A	B	A'	B'	C	CW
1	ON	ON	-	-	+V_{BAT}	↓
2	-	ON	ON	-		
3	-	-	ON	ON		
4	ON	-	-	ON		

Table 4 Drive mode: Half step/one and two phase on

Step	A	B	A'	B'	C	CW
1	ON	-	-	-	+V_{BAT}	↓
2	ON	ON	-	-		
3	-	ON	-	-		
4	-	ON	ON	-		
5	-	-	ON	-		
6	-	-	ON	ON		
7	-	-	-	ON		
8	ON	-	-	ON		

3.2 Simulation

Infineon provides a ready to use online tool for simulating different application scenarios with the SPIDER+. This tool is called Infineon Designer *[1]* and provides standard components such as resistors, inductors, and capacitors. The SPI communication cannot be used directly in the tool therefore, the required registers are exposed and their values are set directly via voltage sources. Values such as ambient temperature are also set by applying an appropriate analog voltage step, for example. 25°C = 25 V.

As can be seen in ***Figure 10***, the individual phases of the stepper motor are connected to separate SPIDER+ output channels. Each phase has a resistance of 30 Ω and an inductance of 14 mH. Since each phase of the stepper motor has a nominal current of 400 mA, an appropriate series resistor has to be used when the supply voltage V_S is higher than 12 V.

To switch the outputs on or off, the pin, OUTN_REG representing the OUT register, has to be used. A voltage corresponding to the decimal interpretation of the OUT register's bit pattern for bits 7 to 0 can be used to switch each channel on or off individually.

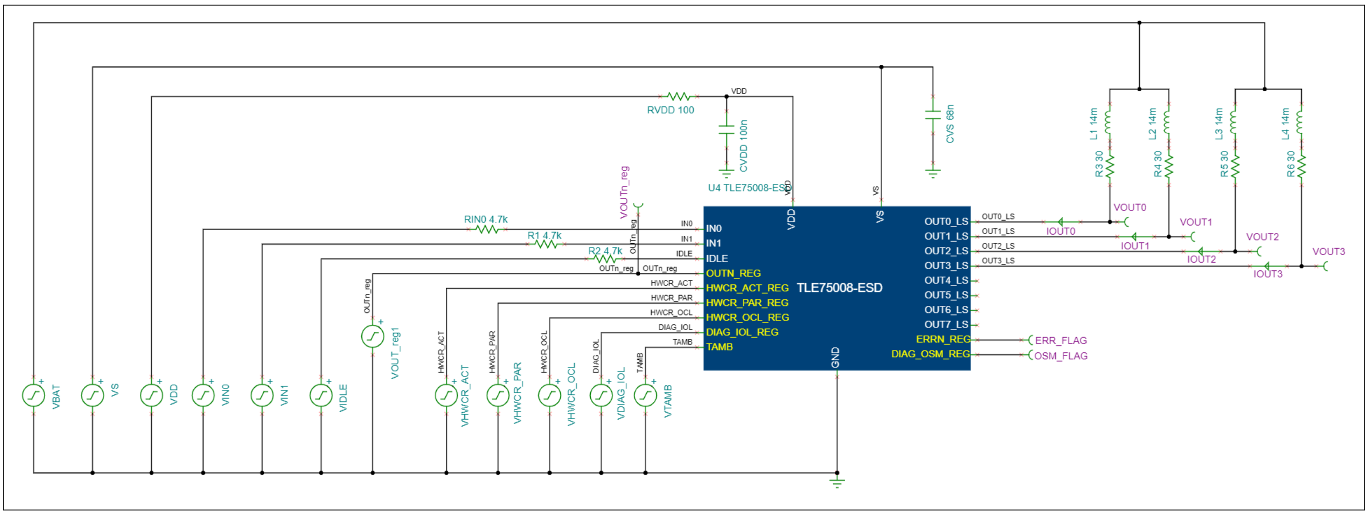


Figure 10 **Circuit diagram in the Infineon Designer environment**

A first simulation of the stepper motor with two phases on, shows the typical behavior of the current and voltage, seen in ***Figure 11***. The voltage at the output channels drops down to 0 V when switching on the channel. Switching off the channel introduces a reverse voltage of approximately 50 V which is within the value range for the reverse voltage of inductive loads. For more information please refer to the datasheet ***[2]***.

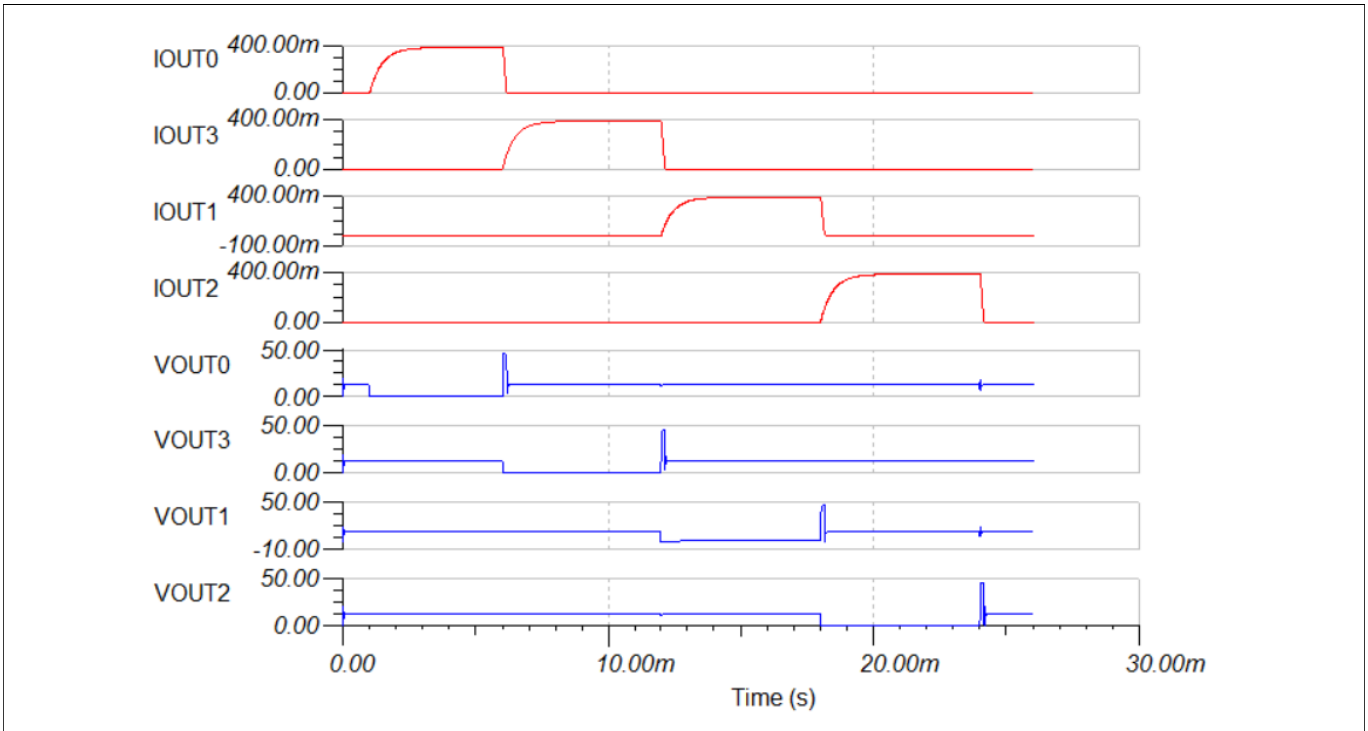


Figure 11 **Simulation of the stepping of the stepper motor (two phase on)**

By inspecting the current and voltage of only one phase in ***Figure 12***, the inductance of the phase can be roughly estimated by the formula τ = L/R . The charging curve of the coil current can be mathematically represented by the equation:

$$i_L(t) = I_0 \cdot \left(1 - e^{-\frac{t}{\tau}}\right) \quad (1)$$

Using a resistance of 30 Ω and the measured time constant of 498 µs, the inductance of the phase is 14.94 mH which is close to the value of 14 mH stated in ***Table 1***.

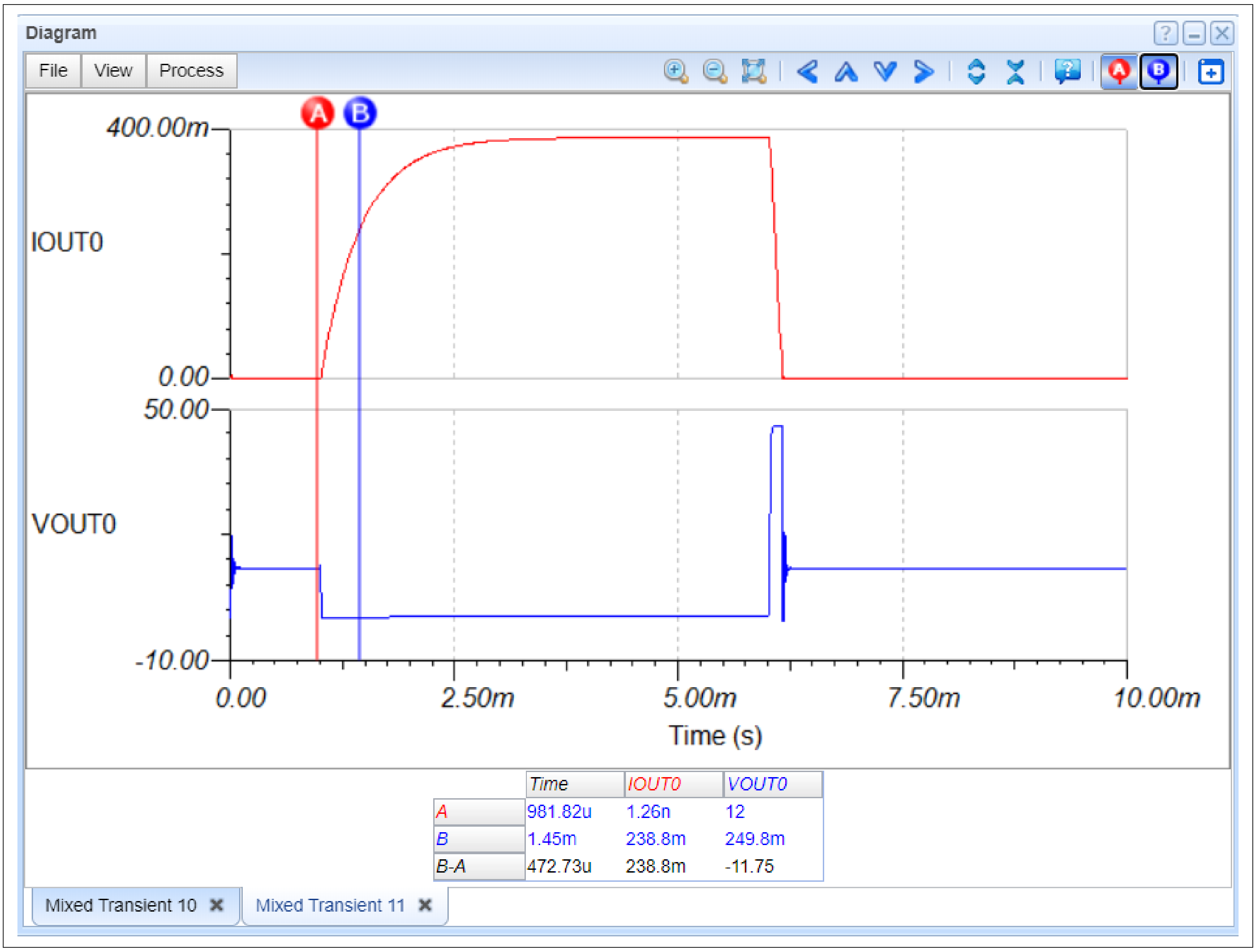


Figure 12 Behavior of one phase by controlling the motor in full step mode

3.3 Config Wizard for IPD

To simulate the serial communication, the Config Wizard for IPD can be used which is available in the Infineon Toolbox *[3]*. An Infineon µIO-stick is required for the connection between the SPIDER+ and the computer. The Infineon Toolbox offers several programs, one of them is the IPD Config Wizard.

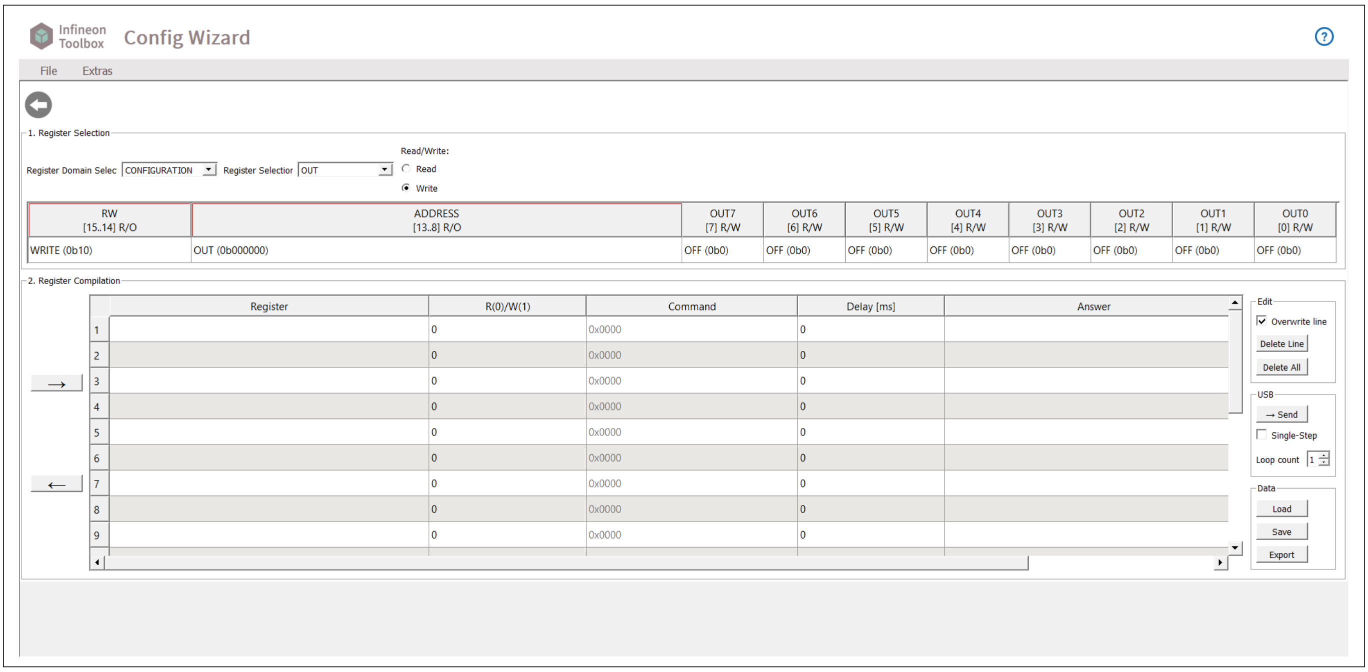


Figure 13 Config Wizard Layout (Infineon Toolbox)

The layout consists of different fields, as shown in ***Figure 13***, which are explained below:

- Register selection
  - Register domain selection: The register domain selection is used to set up the proper register group to address
  - Register selector: Addressing the relevant register name is essential in order to communicate with the device, for example, the register name OUT controls the 8 output channels.
- Register compilation

The generated commands can be sent to the device sequentially and can also be sent in a loop where the total loop iterations can be set manually. A single-step mode is also available, where the user can step through the commands one by one. Furthermore, each command can be delayed before the next command is executed.

3.3.1 TLE75008-ESD register description

Hardware Control (HWCR) - Register

If the HWCR.ACT bit is set to “high”, the device enters active mode. This is done to ensure that the device is always in active mode. Setting this bit to “low” allows the device to return to idle mode when all outputs are off, resulting in reduced power consumption. Setting the HWCR.ACT bit to “high” forces the chip to enter the active mode, using its full potential of resources. ***Figure 14*** illustrates, the serial clock and the command. The command is defined as “write” or “read” command in the first two clock cycles. The hexadecimal representation of the command for entering the active mode is 0x8C80.

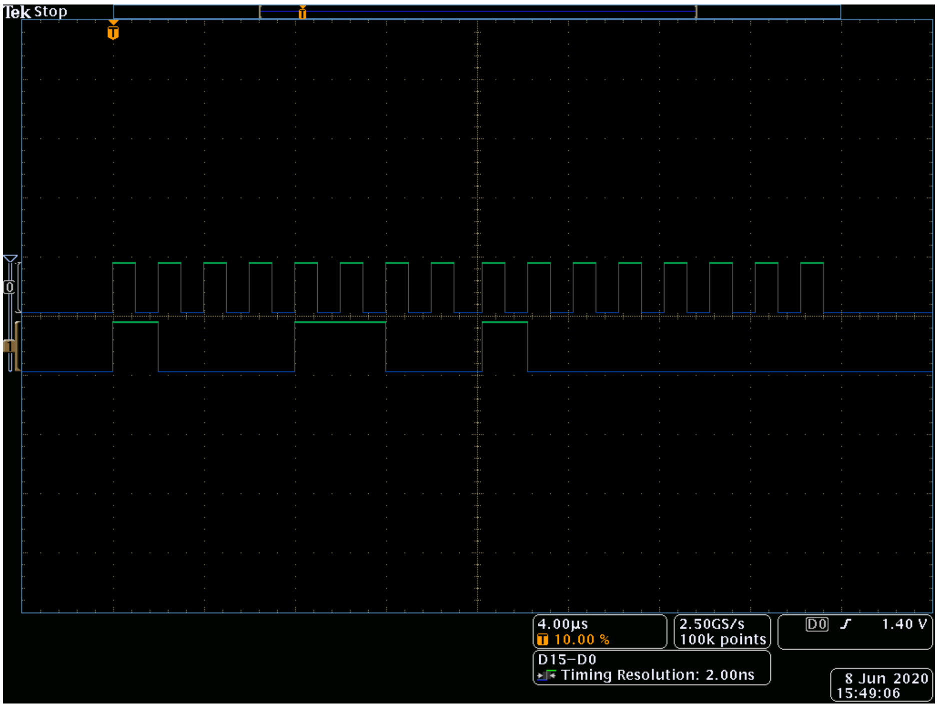


Figure 14 **SPI command to enter active mode (HWCR register)**

OUT - Register

The "OUTn" register switches the channels on or off. The lowest 8 bits are used to control the output channels. ***Figure 15*** shows the SPI command for switching off all channels by writing to the OUT register. The hexadecimal representation of the command for switching all channels off is 0x8000.

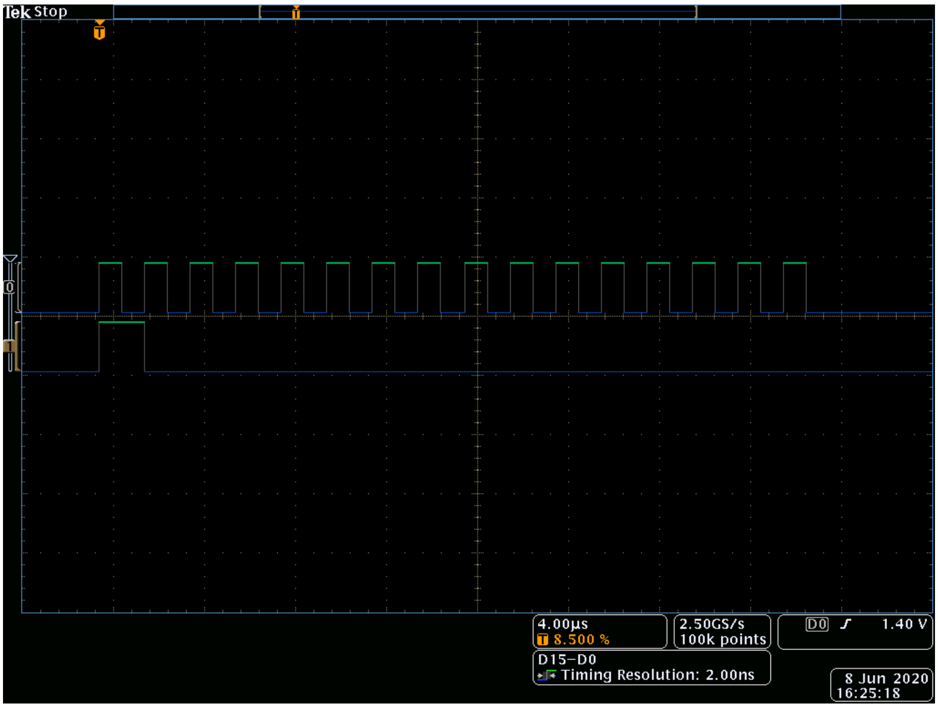


Figure 15 **SPI command for switching off all channels (OUT register)**

3.4 Lab set up

To verify the simulation results, the set up for controlling the stepper motor was recreated in the lab. Therefore the stepper motor, a laptop, a µIO Stick, an SPI driver board from Infineon Technologies and some wires were required which can be seen in ***Figure 16***. The main component is the SPIDER+ TLE75008-ESD, which is shown as a plausible SPI driver for this application. A power supply is used to supply V_S = 12 V and V_{DD} = 3.3 V. A Tektronix MDO4104C oscilloscope was used for measurements.

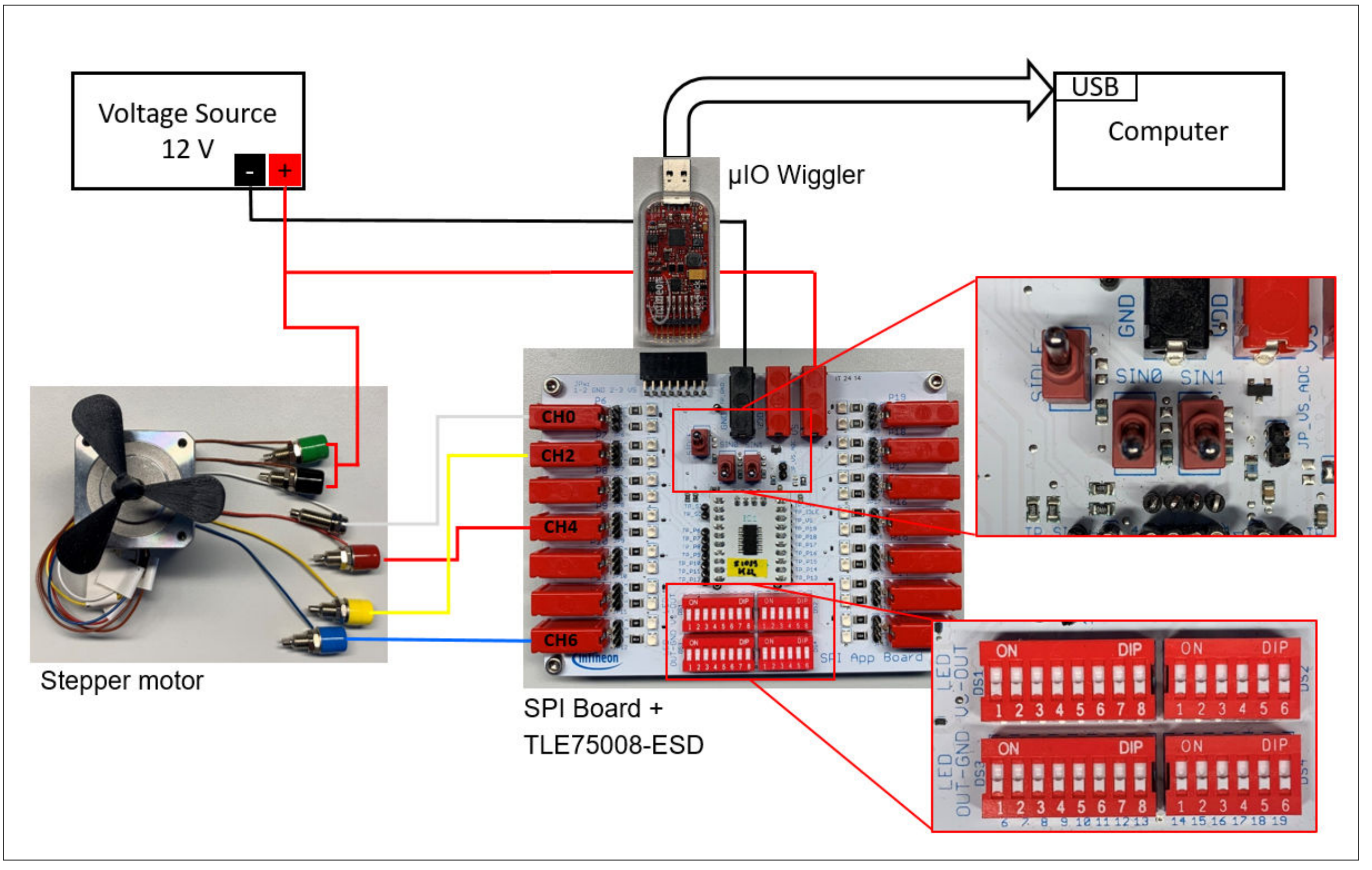


Figure 16 **Lab set up**

3.4.1 Wire management

The SPI driver board uses outsourced pins to connect wires to the pins of the SPIDER+. Since the SPIDER+, used in this instance, is an 8-channel low-side switch, the phases of the stepper motor are connected to V_S on the one side and to four SPIDER+ output channels on the driver board on the other side. See ***Figure 16***. The µIO stick provides the SPI connection from the laptop to the driver board.

3.4.2 Commands

The Config Wizard provides the possibility to write commands to the SPIDER+ and also has a single step function, see ***Chapter 3.3***. The wires of the stepper motor are connected to the SPI driver board as follows:

- Channel 0: white (A)
- Channel 2: red (A')
- Channel 4: yellow (B')
- Channel 6: blue (B)

The brown wires (C) of the stepper motor are directly connected to the supply voltage V_S (***Figure 16***). Considering ***Table 5*** the following commands let the stepper motor rotate by four steps:

Table 5 Command list for every step

Step	Command									
	Write/ Read	Address	OUT7	OUT6	OUT5	OUT4	OUT3	OUT2	OUT1	OUT0
1	10	000000	0	1	0	0	0	0	0	1
2	10	000000	0	1	0	0	0	1	0	0
3	10	000000	0	0	0	1	0	1	0	0
4	10	000000	0	0	0	1	0	0	0	1

This command order has to be sent to the stepper motor in order to let the motor rotate in clockwise direction. For counterclockwise rotation, the order of the commands has to be reversed. The rotational speed can be adjusted by selecting an appropriate frequency for writing the commands to the SPIDER+.

At the beginning, the command to enter active mode (***Table 6***) is sent once in order to ensure the device stays in active mode all the time.

Table 6 Hardware control command - Enter Active Mode

Command									
Write/Read	ADDR	HWCR.ACT	HWCR.RST	(reserved)		HWCR.PAR			
10	001100	1	0	0	0	0	0	0	0

4 Calculations

As far as this example is concerned, all calculations are done only for one phase of the stepper motor, being one channel. The results gathered in this section can be used for all other phases.

4.1 SPIDER+ power stage and power dissipation considerations

The power stage is standard across SPIDER+ family; with a typical $R_{DS(ON)}$ of 1 Ω at 25°C and a maximum of 2.2 Ω guaranteed across temperature and operational voltage. The power stage is protected for over current, over temperature, over voltage, loss of ground, loss of battery and electrostatic discharge (ESD) and it can also be diagnosed for over temperature, over current and open load.

As SPIDER+ integrates multiple channels in the same package, it is important to consider the power dissipation for the whole device at each usage profile to ensure that maximum junction temperature T_J is kept below its maximum rating of 150°C and the current for each individual channel does not reach the over load threshold $I_{L(OVL)}$ under any circumstance. Even though each individual channel has over current and over temperature protection as a safety mechanism, it is important to keep the device within operational ratings to ensure long term reliability.

Power dissipation calculations should encompass static characteristics or conduction losses, given by the $R_{DS(ON)}$ of the output stage and the current flowing through it by the following formula:

$$P_{\text{conduction}} = \sum_{\text{CH1}}^{\text{CHN}} I^2 \cdot R_{\text{DS(ON)}} \tag{2}$$

Maximum $R_{DS(ON)}$ at hot temperature (150°C) is 2.2 Ω for all members of SPIDER+ family.

As the stepper motor can be driven in different drive modes, the maximum load is reached using the full step mode with two phase on. Using Equation *(2)* the conduction loss of one phase is 352 mW. Regarding that two phases are switched on at the same time, the total conduction loss is two times higher, resulting in 704 mW.

4.2 PWM – Switching losses

As stepper motors are controlled by repetitive patterns for each phase, the channels need to switch on and off depending on the set frequency. In this case, switching losses also have to be considered, calculated by:

$$P_{\text{switching}} = \sum_{n=0}^{7} \frac{1}{2} \cdot I_{\text{CHn}} \cdot V_S \cdot f_{\text{PWM}} \cdot (t_{\text{rise}} + t_{\text{fall}}) \tag{3}$$

Where t_{rise} and t_{fall} are obtained from the slew rate values dV/dt_{ON} and dV/dt_{OFF} given in device datasheet *[2]*. Using the maximum value of 0.7 V/µs given in the specification, t_{rise} equals t_{fall} to 17.2 µs at 12 V. Assuming a maximum frequency of 900 Hz, each phase of the stepper motor is switched on with a frequency of 900 Hz. Using a current of 400 mA per phase, the switching loss per phase can be calculated with Equation *(3)* and results in 37.2 mW. As there are always two phases on, the switching loss is two times higher, resulting in 74.4 mW.

4.3 Operational power

The operational current required for the whole device to operate is usually neglected in the power calculations, but it can also be a significant contributor to the total power dissipation of the device. The maximum supply

current in active mode with all channels on, $I_{VS(ACTIVE)}$, is defined as 4.2 mA @13.5 V in the TLE75008-ESD datasheet *[2]*. The operational power, $P_{operational}$, is simply defined as:

$$P_{\text{operational}} = V_S \cdot I_{\text{VS(ACTIVE)}} \tag{4}$$

Evaluating Equation *(4)*, scaling the current from 4.2 mA to 3.73 mA at 12 V results in an operational power of 45 mW.

4.4 Total power dissipation

The total power dissipation for the device is given by the sum of the different sources of power dissipation from Equations *(2)*, *(3)* and *(4)*:

$$P_{\text{total}} = P_{\text{conduction}} + P_{\text{switching}} + P_{\text{operational}} \tag{5}$$

Calculating the total power loss at a supply voltage V_S = 12 V, the drive mode of the stepper motor has to be considered. As the full step mode with two phases on is considered, the total power loss is 823.4 mW.

4.5 Maximum junction temperature

To estimate the maximum junction temperature of the device, the maximum ambient temperature $T_{A(MAX)}$ has to be considered. In this specific example assume 85°C outside the electronic module, however, the temperature inside the module could be 10°C to 15°C degrees higher for the actual device mounted on the printed circuit board (PCB), given the influence of other drivers generating heat on the board. Simultaneously, this additional temperature has to be considered in the real application. In this example assume $T_{A(MAX)}$ = 100°C.

$$T_{J(\text{MAX})} = P_{\text{total}} \cdot R_{\text{thJA}} + T_{A(\text{MAX})} \tag{6}$$

Assuming the thermal resistance junction to ambient, R_{thJA}, given in the device specification of 28 K/W for a 2s2p type board (for further information please refer to the corresponding product datasheet *[2]*) and evaluating Equation *(6)*, the maximum device temperature $T_{J(MAX)}$ at 12 V is 123.1°C, which is below the 150°C maximum specified for the device.

4.6 Inductive output clamp

When switching off inductive loads with a low-side switch, the voltage across the power switch rises to $V_{DS(CL)}$ potential, because the inductance tends to continue driving the current. The voltage clamping is necessary to prevent device destruction.

Figure 17 shows a concept drawing of the implementation. Nevertheless, the maximum allowed load inductance is limited. The clamping structure protects the device in all operative modes (Sleep, Idle, Active, Limp Home).

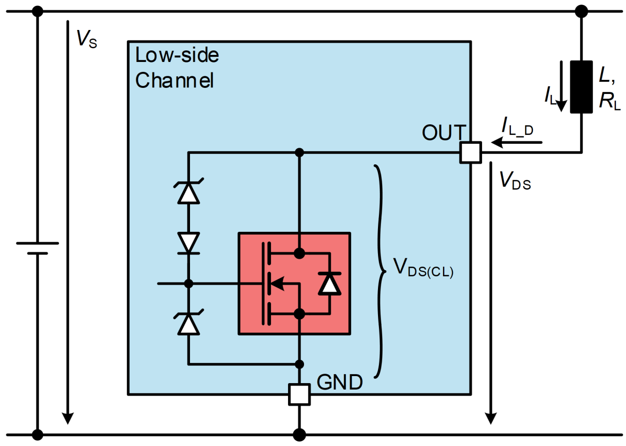


Figure 17 **Output clamp concept**

4.7 Considerations for inductive loads

When an inductive load is switched off, it generates a voltage across its terminals to oppose the reduction in current (the Lenz law) whose amplitude depends on the current slope and the inductance value; this might cause the drain-source voltage of the driver to exceed its maximum voltage and avalanche.

SPIDER+ implements an active clamping circuit that is able to repetitively absorb the inductive energy for most automotive relays without the need for additional external protection circuitry (for example a recirculation diode). However, it is important to analyze each individual relay or inductive load driven by SPIDER+ to make sure it does not exceed the maximum rating given in the specification E_{AR} = 10 mJ for up to a 2 M cycles.

The inductive energy E_L stored in an inductive load is defined by the following equation:

$$E_L = \frac{1}{2} \cdot L \cdot I_L^2 \tag{7}$$

Where L is the inductance of the load and I_L is the load current.

The application note *Switching inductive loads* ***[4]*** gives additional details in Chapter 2.2, page 6, on how to calculate the inductive energy to be dissipated in the power stage of the device during an output clamping event. This is summarized by Equation ***(8)*** for a low-side channel.

$$E_{LS} = V_{DS(CL)} \cdot \left[\frac{V_S - V_{DS(CL)}}{R_L} \cdot \ln\left(1 - \frac{R_L \cdot I_L}{V_S - V_{DS(CL)}}\right) + I_L \right] \cdot \frac{L}{R_L} \tag{8}$$

Where:

- V_S = Supply voltage [V]
- R_L = Load resistance [Ω]
- I_L = Load current [A]
- $V_{DS(CL)}$ = Drain to source clamping voltage [V], typ. 46 V
- L = Load inductance [H]

As an example, the specification for one phase of the stepper motor is 400 mA at 12 V, with an inductance of 14 mH. The coil resistance can be calculated using Ohms law using the current I_L = 400 mA and the voltage

V_S = 12 V, resulting in 30 Ω. Evaluating Equation *(8)* for a low-side driver topology, the calculated energy to be dissipated by the device results in 1.23 mJ per channel, which is within the range of the device specification.

If the inductance is alternatively extracted from lab measurements, by applying a voltage step to one phase of the stepper motor and measuring the time constant $\tau = L/R$ for example, a more realistic value can be estimated. The time constant, τ, specifies the time it takes for the current to reach 62.3% of its steady state value.

Figure 18 shows an actual lab measurement made for the relay used in the previous calculation, specified in ***Table 1***. As it can be seen in ***Figure 18***, the steady state current (2, blue) is 420 mA to a step response of approximately 12 V (1, yellow) which results in a coil resistance that is very close to that specified by the relay supplier, with a quick calculation, the coil resistance results in 28.6 Ω.

In ***Figure 18*** it can also be seen that it takes approximately 508 µs to reach the 62.3% of the steady state value, resulting in an inductance of 14.5 mH, which is nearly equal to the inductance of 14 mH specified by the datasheet *[2]*. Reevaluating Equation *(7)* with the updated inductance value, the resulting inductive energy is 1.41 mJ per phase, which is also within device specification but a little higher than the previous calculation result.

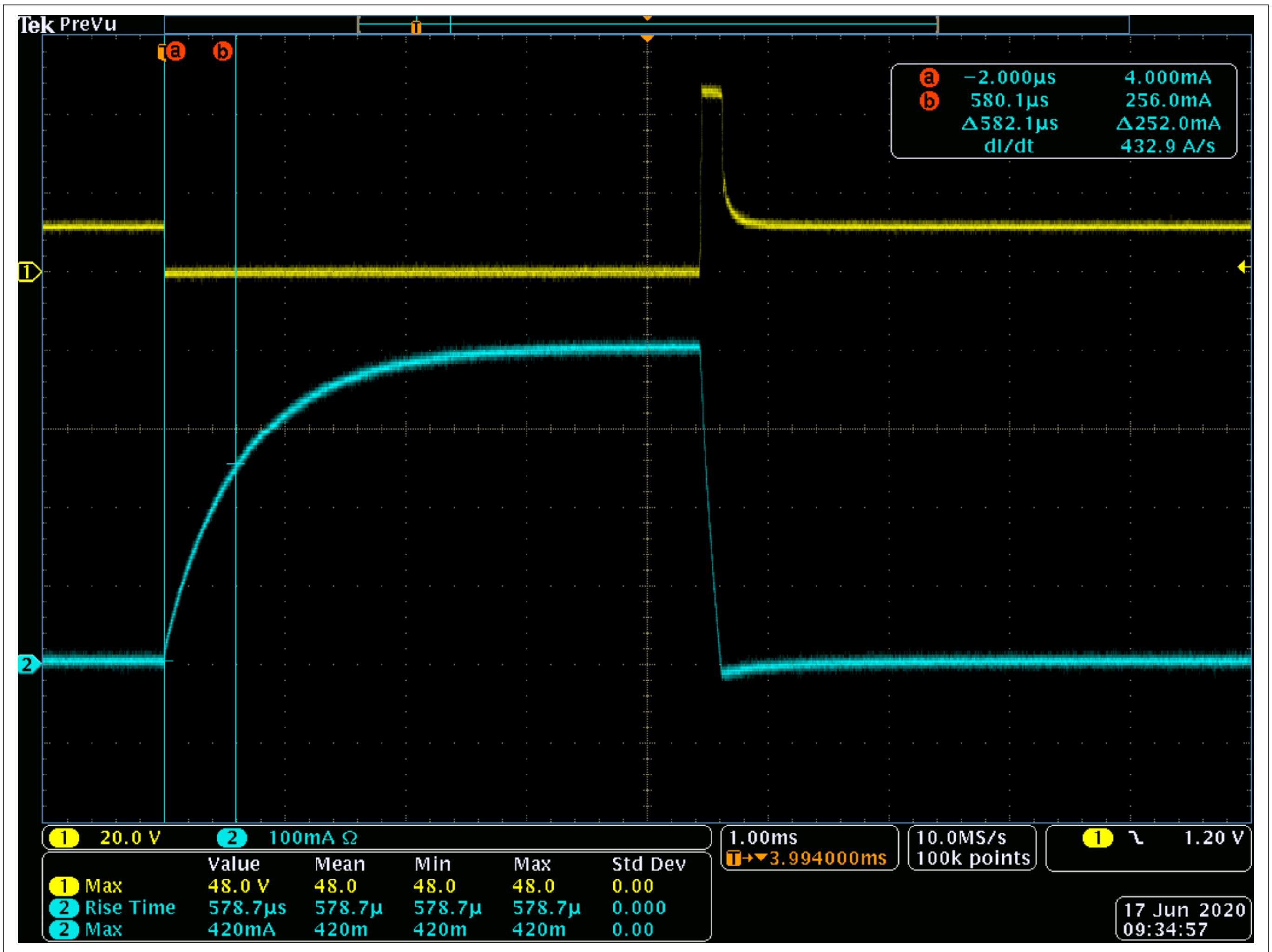


Figure 18 **Measuring time constant τ**

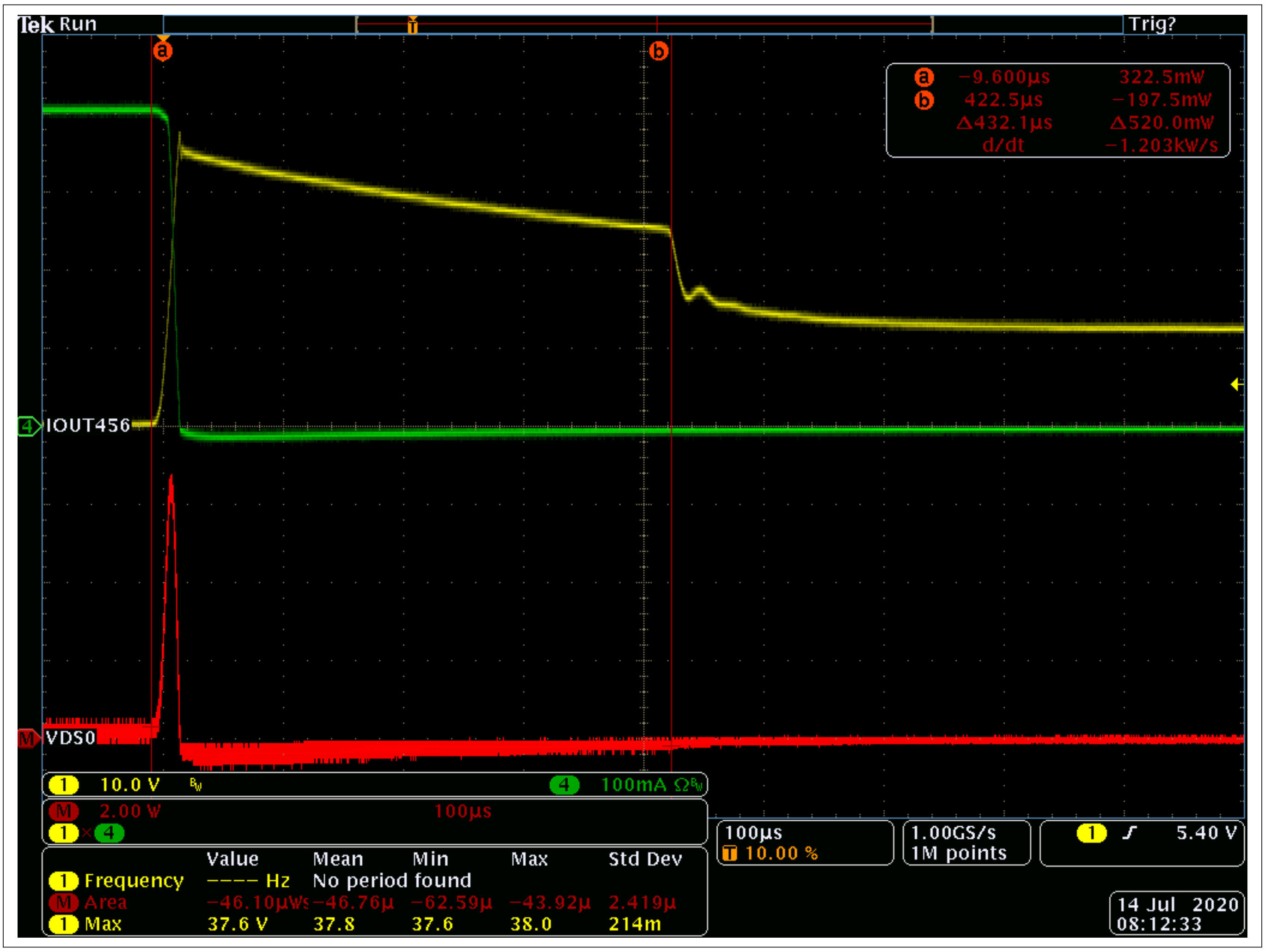


Figure 19 **Real inductive switch off energy measurement**

Where:

- 1: (yellow) = V_{OUT} [V]
  - (SPIDER+ pin OUTn_LS for fixed low-side)
- 4: (green) = I_{Load} [A]
- M: (red) = P_{switch} [W]
  - $P_{switch} = V_{OUT} \cdot I_{Load}$
- M: Area (measurement) = $E_{measured}$ [µWs]
  - integral (area) of P_{switch} between cursors (clamping event duration)

5 Conclusion

This application note shows the basic steps to control a stepper motor. In addition, power calculations are done in order to verify that the SPIDER+ is capable to be used in combination with the stepper motor.

Infineon Technologies SPIDER+ family is designed to support the automotive requirements in a safe, reliable and cost-effective manner.

6 List of references

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2. Infineon Technologies AG, 2017-11-23. Datasheet: *TLE75008-ESD Data sheet* Rev.1.0 [Online]
3. Infineon Toolbox [Online] ***https://www.infineon.com/toolbox***
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