TA0354
Technical article

Thermal design calculations for integrated stepper motor driver solutions

Introduction

One constant trend in the automotive world is the tendency to reduce the size of electronic components and the ECUs (Electronic Control Unit). While this development has many benefits for the car manufacturer as well as for the end customer, there are also challenges for the developers of these systems: especially for power drivers the design of robust applications requires an accurate estimation of the thermal power dissipation on a system level.

In this article a method to calculate the thermal power dissipation of a stepper motor driver is derived from a simple example to a model that includes the various configuration options and modes of a state of the art stepper driver, like that of ST Microelectronic's L9942.

This class of motor driver features:

- PWM based current regulation,
- integrated programmable waveform generation,
- configurable current decay modes, and
- motor state and failure diagnosis.

The benefit of these features is that the effort to control a stepper motor is reduced to providing the desired step frequency and direction.

Contents

List of figures

1 Thermal power dissipation for generic power drivers

In order to calculate the thermal performance of an integrated power driver as shown in *Figure 1*, two main power dissipation sources must be considered individually. These are:

- Conduction losses
  Every MOS transistor based switch has a drain source resistance when switched on (RDSON). It causes a thermal power dissipation during ON-state:

Equation 1

$$P_{RDSON} = U_{SW} \times I_{LOAD} = (R_{DOSON} \times I_{LOAD}) \times I_{LOAD}$$

Equation 2

$$P_{RDSON} = R_{DSON} \times I_{LOAD}2$$

- Switching losses
  There are intrinsic parasitic capacitors and for every switch transition there is a charging- or discharging required -time for these capacitors.
  Consequently the power switch needs a finite time for the transition from non-conductive state to conductive state and vice versa.
  This is especially the case for driving methods based on pulse width modulated (PWM) signals - the switching losses may have a significant impact on the overall thermal power dissipation.
  Furthermore, the switch transition times are often prolonged by slew rate options to avoid fast rising and falling edges and thus improve EMC performance, often at the cost of higher thermal switching losses.
  To simplify the calculation of the switching losses for an inductive load, it can be assumed that the voltage over the switch will change linearly and the current is constant – as shown in *Figure 2*.

Figure 1. Simplified power driver example

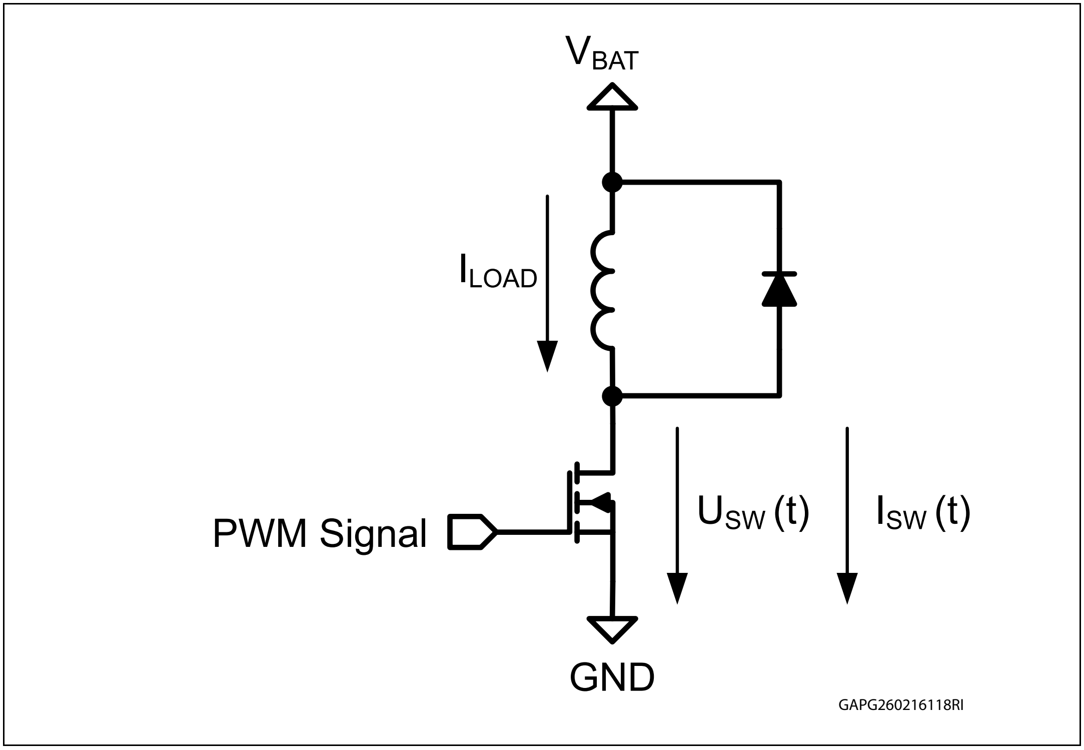
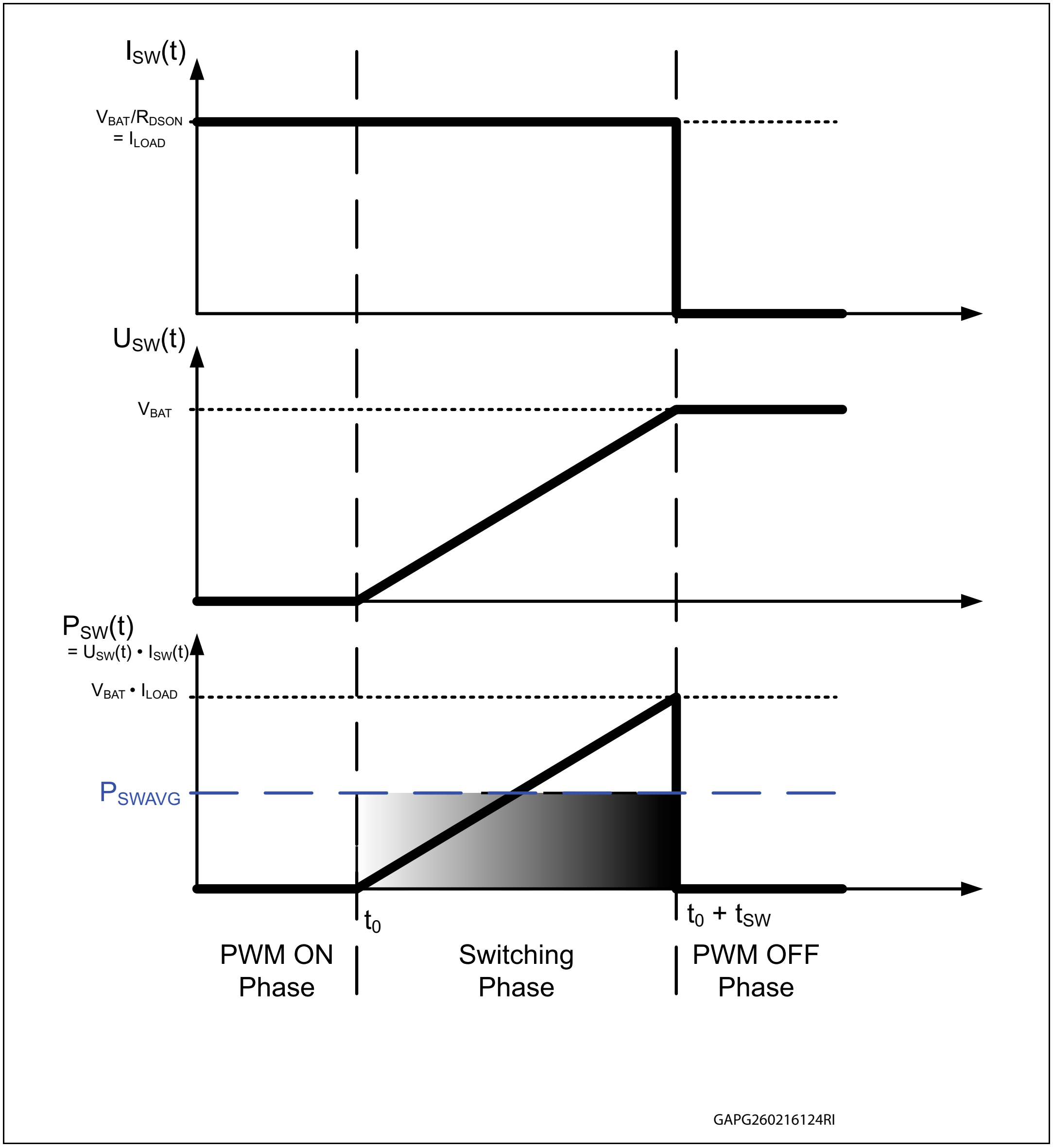


Figure 2. Switching losses (Thermal Power Dissipation)



It simplifies the formula to calculate the average thermal power dissipation during a switching phase to:

Equation 3

$$P_{SWAVG} = \frac{1}{t_{SW}} \int_{t_0}^{t_0 + t_{SW}} P_{SW(t)DT}$$

Equation 4

$$P_{SWAVG} = I_{LOAD} \times \frac{V_{BAT}}{t_{SW}} \times \frac{1}{t_{SW}} \int_{t_0}^{t_0 + t_{SW}} t\,dt$$

Equation 5

$$P_{SWAVG} = \frac{I_{LOAD} \times V_{BAT}}{2}$$

The switching losses considering the switching time and the PWM frequency can then be calculated with:

Equation 6

$$P_{SWPWM} = \frac{I_{LOAD} \times V_{BAT}}{2} \times t_{SW} \times f_{PWM}$$

Figure 3. PWM cycle with ON-, OFF-, and Switching phase

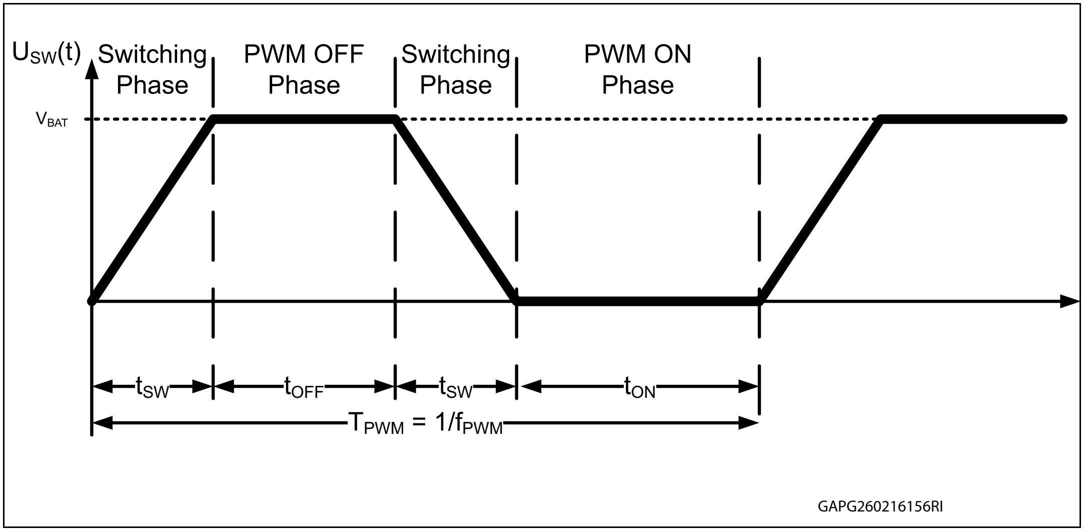


Figure 3 shows a complete PWM period. It consists of two switching cycles (when the switch is turned on and turned off again), an ON period (conduction losses formula can be applied here) and an OFF period when there is no current in the switch and thus no power dissipation in the switch itself.

The formula to calculate the overall power dissipation for this setup considering the on and off cycles is consequently:

Equation 7

$$P_{thdis} = 2 \times (t_{SW} \times f_{PWM}) + P_{RDSON} \times (t_{on} \times f_{PWM})$$

Just to recapitulate the above steps as preparation for the stepper driver calculation, this is the procedure that has just been applied:

The thermal power dissipation is calculated by the average thermal power dissipation in a PWM period. This is calculated by differentiating the PWM period into switch states, calculating the power dissipation for each individual switch state and then applying a weighting according to the switch state duration.

1.1 Challenges in stepper motor driver applications & Prerequisites

For a bipolar stepper motor driver the calculation conditions seem to be rather complex:

- The motor consists of two phases and these are driven with an H-bridge instead of a single MOS switch (see Stepper motor a and c)
- The motor current is not constant and consists – in the case of a bipolar motor – of two sine shaped currents in each motor phase that have a relative phase shift of 90° to each other (see Stepper motor b)
- When the motor is stopped, the current will not be completely set to zero, but rather be reduced – this is commonly referred to as “hold current”, which is needed to provide a minimum force to maintain a rotor position(a)
- The motor phase currents are permanently regulated using a PWM signal.
  The switching states and the number of transitions in this current regulation loop are depending on the selected current decay mode and may vary in one electrical revolution. This implies that the PWM switching states as well as the number of state transitions in one PWM cycle may vary, which is directly influencing the switching losses.
- There are many application oriented configuration options that are commonly used to optimize the system but in return directly affect the thermal power dissipation like slew rates, cross current protection delay and filter times

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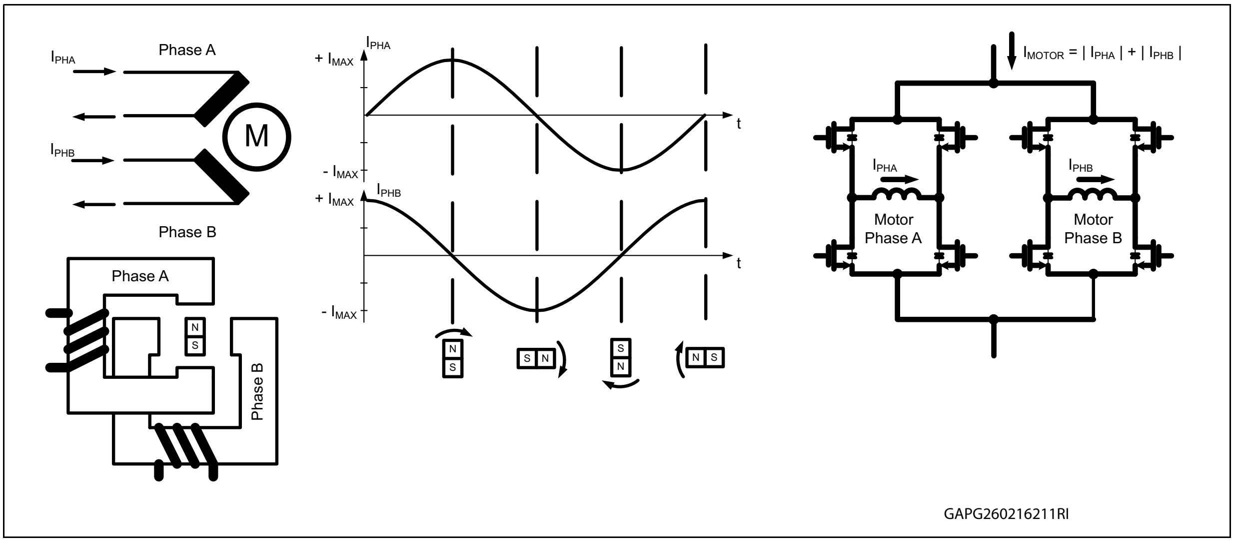
a. Typically the lowest possible current for the application is being used here because due to the missing back electromotive force in standstill the only active load is the ohmic resistance of the motor coil and the electrical energy is directly converted into thermal power losses in the motor

Figure 4. Stepper motor



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a) Symbol and Model
b) Current Waveform for one electrical revolution
c) Dual Full Bridge Driver Implementation

The procedure to create a thermal evaluation of a stepper motor driver system is very similar to the initial calculation example, considering these requirements and prerequisites:

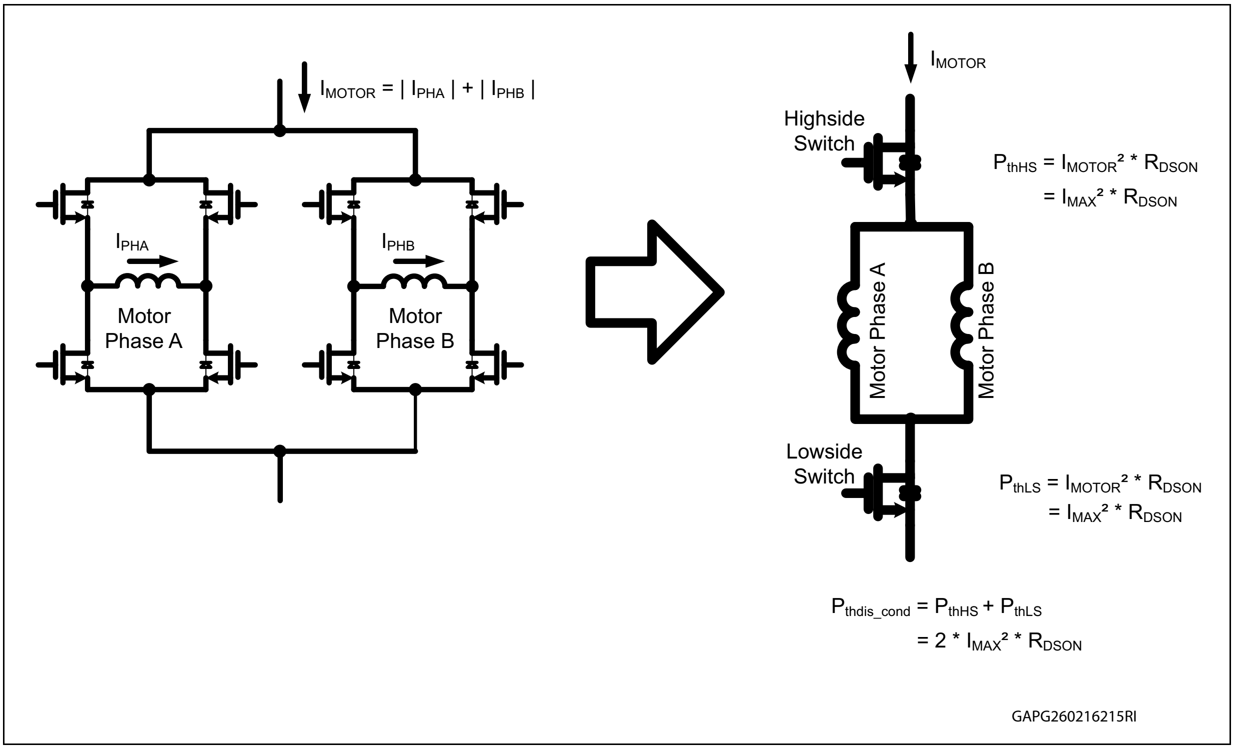
- An application load profile is required to consider the ratio in between nominal driving current and hold current. Generally *Equation 8:* can be used.

Equation 8

$$P_{thdis} = P_{thdis\_drive} \times \left(\frac{t_{drive}}{t_{drive} + t_{hold}}\right) + P_{thdis\_hold} \times \left(\frac{t_{hold}}{t_{drive} + t_{hold}}\right)$$

- P_{thdis_drive} and P_{thdis_hold} represent the thermal power dissipation for one specific target current (nominal driving current and hold current). Both values include:
  - Conduction losses (P_{thdis_cond})
  - Switching losses (P_{thdis_sw})
  - Cross conduction protection losses (P_{thdis_cc})
- In order to calculate P_{thdis_drive} and P_{thdis_hold} the motor current instead of the phase currents is used (see Alternative calculation model for conduction loss calculation). In this way only one time independent average current is being used for the calculation instead of two time-depending currents with trigonometric functions.

Figure 5. Alternative calculation model for conduction loss calculation



Equation 9

$$P_{thHS} = P_{thHSA} + P_{thHSB}$$

Equation 10

$$P_{thHS} = (I_{PHA})^2 \times R_{DSON} + (I_{PHB})^2 \times R_{DSON}$$

Equation 11

$$P_{thHS} = R_{DSON} \times ((I_{PHA})^2 + (I_{PHB})^2)$$

Equation 12

$$P_{thHS} = R_{DSON}((I_{MAX} \times \sin(t))^2 + ((I_{MAX} \times \mathrm{cost}(t))^2)$$

Equation 13

$$P_{thHS} = R_{DSON} \times (I_{MAX})^2 \times (\sin((t)^2 + \cos(t))^2)$$

Equation 14

$$P_{thHS} = R_{DSON} \times (I_{MAX})^2$$

- The simplified calculation in *Figure ·* is only valid for the conduction loss calculation because the current is here calculated with a power of 2 and thus the term ($\sin^2(t) + \cos^2(t)$) is eliminated. For the other cases (switching loss and cross current protection loss) the motor current has to be calculated by the formula:

Equation 15

$$I_{MOTOR}(t) = |I_{PHA}(t)| + |I_{PHB}(t)| = I_{MAX} \times |\sin(t)| + \cos(t)|)$$

The calculation with $I_{MOTOR}(t)$ can be simplified by using the time independent value (see *Equation 16*):

Equation 16

$$RMS(I_{MOTOR}(t)) = \frac{1}{T_{PWM}} \int_0^{T_{PWM}} I_{MAX} \times (|\sin(t)| + |\cos(t)|)dt$$

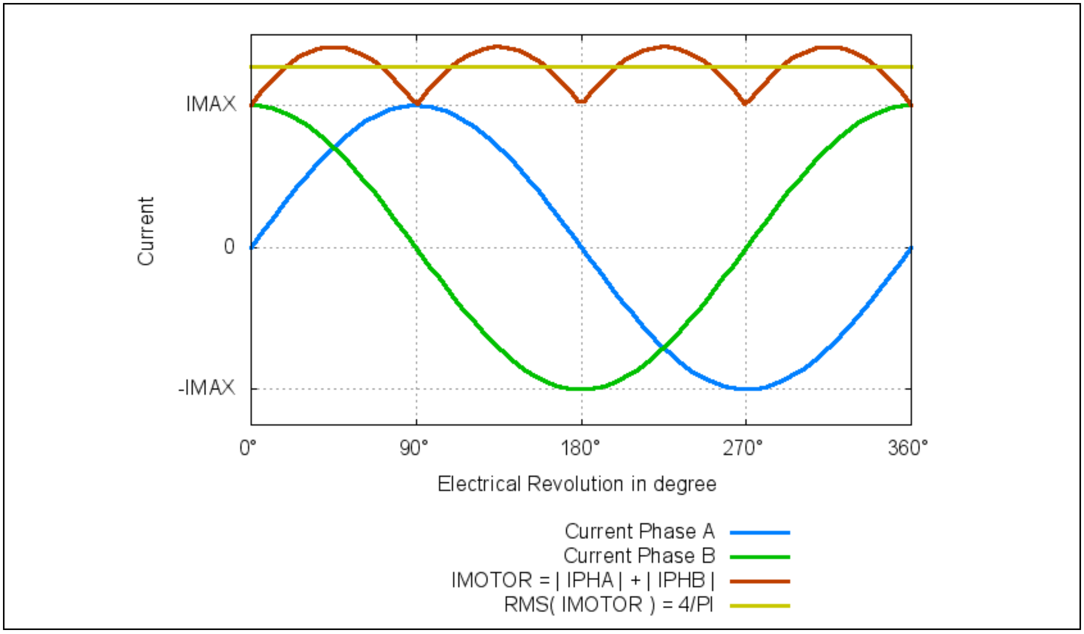
Equation 17

$$\mathrm{RMS}(I_{MOTOR}(t)) = \frac{1}{T_{PWM}} \times 4 \times \int_0^{\frac{T_{PWM}}{4}} (\sin(t) + \cos(t))dt$$

Equation 18

$$\mathrm{RMS}(I_{MOTOR}(t)) = \frac{4 \times I_{MAX}}{\Pi}$$

Figure 6. Phase Currents and Motor Current



1.2 Calculation of the thermal power dissipation

The first step is to differentiate the switching states in one PWM period. Therefore an in depth look in the switching sequence is mandatory:

Figure 7. Switching sequence "Slow Decay" for a single motor phase

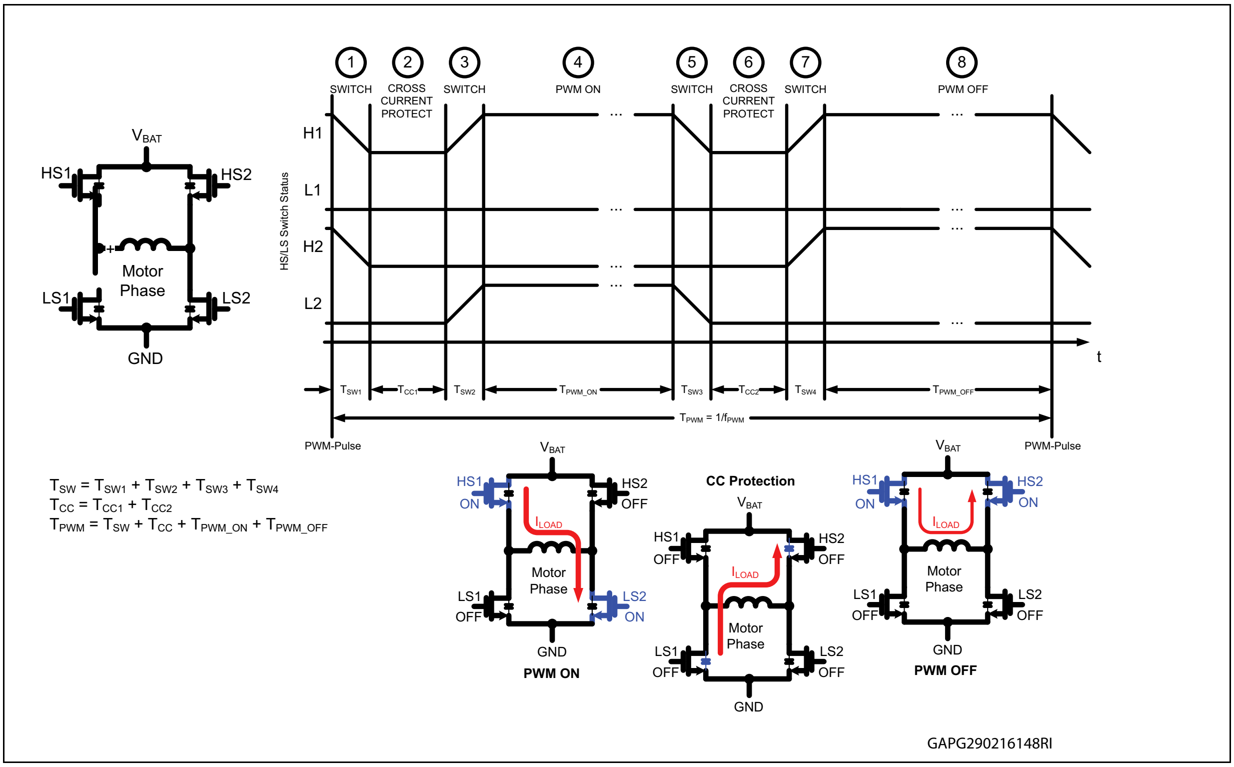


Figure 7 shows an example of a typical “slow decay” PWM period and the referring states. At the beginning of the PWM period the H-Bridge has to be set to a defined state, therefore all switches are deactivated first (1). Before any switch can be activated again, a cross current protection time (2) has to be passed. Then the switches are activated again (3) and the PWM ON state (4) is reached. This state persists until the current limit for this motor step is reached in the motor phase or a new PWM period starts. If the current limit has been reached then there is another switch transition (5) followed by a cross current protection time (6). Then the switches are activated again to enter the PWM OFF (8) state until a new PWM period starts.

For the PWM OFF state there are several user configurable options possible:

- Slow Decay
  Both High Side Switches are active so that the current in the motor phase has a freewheeling path in the H-Bridge high side
- Fast Decay
  In PWM OFF state the opposite switches as in PWM ON state are active. In this way the motor phase is driven in the contrary current direction as in PWM ON state, which has the benefit that the phase current can be decreased faster than in Slow Decay setup.
- Mixed/Auto Decay Variants
  There is another configuration that starts with a fast decay and switches in the slow decay configuration after a predefined time or when current limit underrun occurs. These cases are not considered in the calculation below, but this can be calculated in a similar way as described herein by adapting the switching times and cross current protection times of one PWM period accordingly.

Now that the switching states in a period are defined, the next step is to calculate the power dissipation for the integrated circuit in each of these states:

- PWM ON / PWM OFF state (Conduction Losses)
  With the model described in Alternative calculation model for conduction loss calculation and the calculation in The simplified calculation in Figure · is only valid for the conduction loss calculation because the current is here calculated with a power of 2 and thus the term ($\sin^2(t) + \cos^2(t)$) is eliminated. For the other cases (switching loss and cross current protection loss) the motor current has to be calculated by the formula: the thermal power dissipation for the PWM ON state can be calculated by only using the peak current I_{MAX} for the electrical motor revolution and the R_{DSON} values for the power switches.
  The same model and calculation can be applied to the PWM OFF state, because in each of the two PWM OFF switching states (Fast Decay and Slow Decay) two switches are active and the whole motor phase current will pass these two switches.
  This means that the thermal power dissipation generated in PWM OFF state and PWM ON state is equal for the stepper motor driver and can be calculated as conduction loss for the motor with:

Equation 19

$$P_{thdis\_cond} = 2 \times R_{DSON} \times I_{MAX^2}$$

- Switching states (Switching Losses)
  For the switching transition the same formula as in the initial example in Simplified power driver example will be used. This is possible because it is assumed that the linearly increasing voltage in this example is divided equally to the two switches in the high and low side. Using the current value RMS(I_{MOTOR}) and the previously derived formula this results in

Equation 20

$$P_{thdis\_sw} = \frac{V_{BAT} \times RMS(I_{MOTOR})}{2}$$

- Cross Current Protection Time
  In this state all power switches are deactivated. However, there is thermal power dissipation in the integrated circuit, caused by the freewheeling current in the motor coils, which will bypass the power switches over internal reverse diodes in the high side and low side.
  The thermal power dissipation in this state can be calculated by the formula.

Equation 21

$$P_{thdis\_cc} = 2 \times RMS(I_{MOTOR}) \times V_{forward}$$

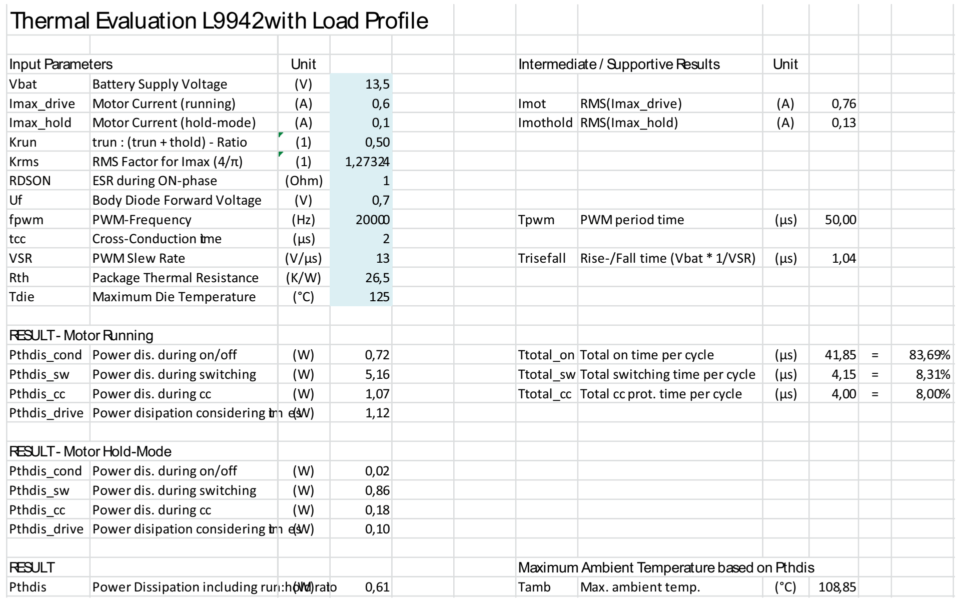
Now that the switching states are known and the power dissipation for each individual state can be calculated, the only remaining action is to apply a weighting to these values according to their duration in one PWM period.

Equation 22

$$P_{thdis} = t_{sw} \times f_{PMW} \times P_{thdis\_sw} + t_{cc} \times f_{PMW} \times P_{thdis\_cc} + \left(\frac{1}{f_{PMW}} - t_{sw} - t_{cc}\right) f_{PMW} \times P_{thdis\_ON}$$

Note: The times t_{SW} and t_{CC} are here used as accumulated values for all switching transitions and cross current protection times in one PWM period. All device related timings like the PWM frequency and the slew rate can be taken from the device datasheet.

Figure 8. Example calculation with L9942 and load profile



Thermal Evaluation L9942with Load Profile

Input Parameters		Unit	
Vbat	Battery Supply Voltage	(V)	13,5
Imax_drive	Motor Current (running)	(A)	0,6
Imax_hold	Motor Current (hold-mode)	(A)	0,1
Krun	trun : (trun + thold) - Ratio	(1)	0,50
Krms	RMS Factor for Imax (4/π)	(1)	1,27324
RDSON	ESR during ON-phase	(Ohm)	1
Uf	Body Diode Forward Voltage	(V)	0,7
fpwm	PWM-Frequency	(Hz)	20000
tcc	Cross-Conduction time	(µs)	2
VSR	PWM Slew Rate	(V/µs)	13
Rth	Package Thermal Resistance	(K/W)	26,5
Tdie	Maximum Die Temperature	(°C)	125
RESULT - Motor Running			
Pthdis_cond	Power dis. during on/off	(W)	0,72
Pthdis_sw	Power dis. during switching	(W)	5,16
Pthdis_cc	Power dis. during cc	(W)	1,07
Pthdis_drive	Power disipation considering times	(W)	1,12
RESULT - Motor Hold-Mode			
Pthdis_cond	Power dis. during on/off	(W)	0,02
Pthdis_sw	Power dis. during switching	(W)	0,86
Pthdis_cc	Power dis. during cc	(W)	0,18
Pthdis_drive	Power disipation considering times	(W)	0,10
RESULT			
Pthdis	Power Dissipation including run:hold ratio	(W)	0,61

Intermediate / Supportive Results		Unit			
Imot	RMS(Imax_drive)	(A)	0,76		
Imothold	RMS(Imax_hold)	(A)	0,13		
Tpwm	PWM period time	(µs)	50,00		
Trisefall	Rise-/Fall time (Vbat * 1/VSR)	(µs)	1,04		
Ttotal_on	Total on time per cycle	(µs)	41,85	=	83,69%
Ttotal_sw	Total switching time per cycle	(µs)	4,15	=	8,31%
Ttotal_cc	Total cc prot. time per cycle	(µs)	4,00	=	8,00%
Maximum Ambient Temperature based on Pthdis					
Tamb	Max. ambient temp.	(°C)	108,85		

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1.3 Conclusion

State of the art stepper motor drivers, such as STMicroelectronic’s L9942, feature various configuration options to optimize an application to specific system requirements. These include:

- Configurable slew rates
- Configurable PWM frequency
- Current regulation modes (current decay modes) for specific driver requirements
- Configurable timings (blanking time, cross current protection time)

The descriptions and calculation formulae presented in this article enable the reader to evaluate the thermal power dissipation of a complex motor driver system including the various options mentioned above. This is the basic requirement for an appropriate and robust thermal system design and allows the developer to evaluate and optimize application parameters with different device configurations.

2 Revision history

Table 1. Document revision history

Date	Revision	Changes
21-Jul-2016	1	Initial release.