Application Note

Two Coil Fan Driver - Power Dissipation

1. Scope

This application note provides a method to determine the power dissipation in Melexis Two Coil fan driver ICs. Rather than giving complex formulas requiring long calculations which increase the risk of errors this application note provides practical and usable solutions to perform accurate estimations. General theory and steps of simplification are explained, so that the reader keeps the understanding of the contents and formulas.

The method described here is completed with two concrete examples based on Two-Coil fan driver:

- US91A – High Voltage Fan Driver
- US65 – Low Noise High Output Current Fan Driver

To use this document, it is recommended to the reader to prepare in advance some information and data based on the application:

- Latest datasheet of the Melexis Two-coil fan driver used (www.melexis.com)
- Oscilloscope pictures showing OUT1 or OUT2 voltage and the fan current consumption I_{DD} during normal rotation of the fan
- Average current consumption of the fan during rotation

2. Related Melexis Products

Two-Coil Fan Drivers IC:

- Using "VDD" design
    - US65 / 66 – Low Noise High Output Current Fan Driver

- Using "No-V_{DD}" Melexis patented design
    - US79 – Smart Fan Driver
    - US62 / US63 – Generic Fan Driver
    - US890 / US891 – High Output Current Fan Driver
    - US90A / US91A – High Voltage Fan Driver

3. Contents

4. Power Dissipation factors

The total IC power dissipation in a Two-coil fan driver is the sum of four major factors:

- ☐ Static input supply
- ☐ Output driver “ON” state
- ☐ Output switching loss
- ☐ Logic output driver (depends on device – FG, RD or none)

4.1. P_{SUP} – static input supply

P_{SUP} represents the “static” power dissipated by the IC itself.

- ☐ V_{DD} design

The static input power P_{SUP} is equal to the voltage applied on the V_{DD} pin multiplied by the static supply current flowing through the V_{DD} pin:

$$P_{SUP} = V_{DD} \cdot I_{DD} \qquad \textbf{(1)}$$

- ☐ No-V_{DD} design

In No-V_{DD} design, there is no direct V_{DD} pin on the IC because the supply voltage is recovered through the switched off output driver. This enables to fit the device into a smaller package.
During normal rotation of the fan, the output voltage when the driver is switched off is the sum of the V_{DD} voltage (applied on the coil common node) plus the electro-motive force (EMF) voltage naturally induced by the fan coil. The EMF is a sinusoidal voltage with amplitude proportional to the rotation speed.

Fig.1 illustrates the output voltage shape during normal rotation and shows the EMF effect:

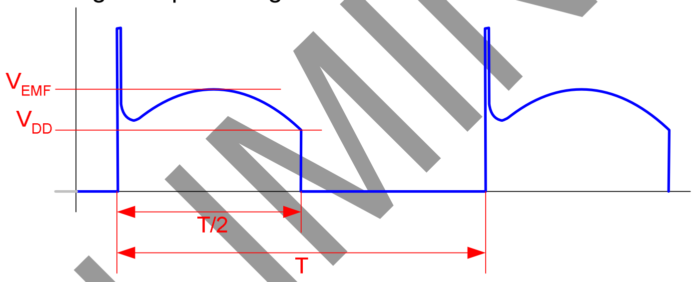
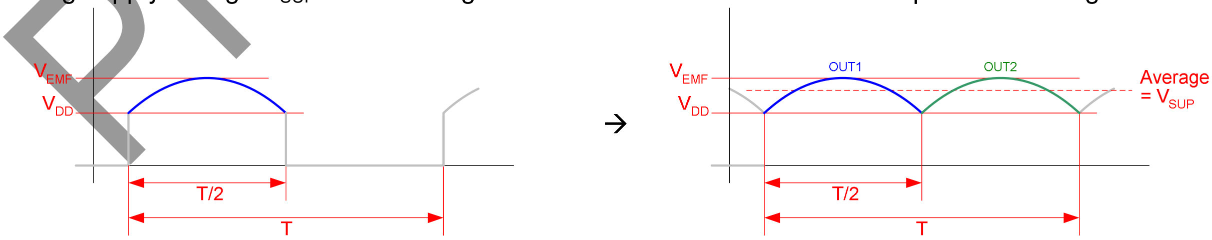


Figure 1 – illustration of one output voltage with a Two-coil fan driver

The formula to calculate P_{SUP} should be an integral as the resulting supply voltage varies in time. However, we can simplify it and avoid the use of integral by determining with a simple method the resulting supply voltage.
To do so, we assume the resulting supply voltage on one output during half a period T/2 is a half sinusoidal shape with amplitude equal to V_{EMF} and offset by V_{DD}, as shown in Fig.2a. Taking into account that we have two outputs where the supply voltage is recovered and that they are complementary, the resulting supply voltage V_{SUP} is the average value of the rectified sinusoidal shape shown in Fig.2b.



(a) – resulting supply voltage with one output

(b) – resulting supply voltage with both outputs

Figure 2 – Simplification to calculate the supply voltage V_{SUP}

That is, the resulting supply voltage V_{SUP} over time can be written as:

$$V_{SUP}(t)=V_{DD}+\left|\left(V_{EMF}-V_{DD}\right)\cdot\sin\left(\frac{2\pi\cdot t}{T}\right)\right|$$

We can now calculate the resulting average supply voltage V_{SUP}.
Given that the average value of a rectified sinusoidal shape with offset ***y(t) = offset + |A sin(2πt / T)|*** over its period **T** is roughly equal to (***0.64 x A) + offset***, or:

$$\frac{1}{T}\cdot\int_0^T\left[\left|A\cdot\sin\left(\frac{2\pi\cdot t}{T}\right)\right|+offset\right]\cdot dt=\frac{2}{T}\cdot\int_0^{T/2}\left[A\cdot\sin\left(\frac{2\pi\cdot t}{T}\right)+offset\right]\cdot dt$$

$$=offset+\frac{2}{\pi}\cdot A\approx offset+0.64\cdot A$$

We can thus calculate V_{SUP} by using the same principle and replacing ***offset = V_{DD}*** and ***A = (V_{EMF} - V_{DD})***

Therefore, the resulting average supply voltage V_{SUP} is:

$$V_{SUP}=V_{DD}+0.64\cdot\left(V_{EMF}-V_{DD}\right)\qquad\textbf{(2)}$$

The EMF amplitude depends on the stator construction: in general it would look as Fig.1, but on some fans it might be very flat. The latter is not a problem as the formula uses difference V_{EMF} – V_{DD}, if this is close to zero, the resulting average voltage V_{SUP} is equal to about the supply voltage V_{DD}.

The performance graph given in the device datasheet needs to be used to know the average supply current I_{SUP} at an input voltage V_{SUP}.
The power dissipation P_{SUP} is so:

$$P_{SUP}=V_{SUP}\cdot I_{SUP}\qquad\textbf{(3)}$$

4.3. P_{SAT} – output driver “ON” state

P_{SAT} represents the power dissipated due to the continuous current flowing through the switched on output driver. This is calculated by knowing either the output saturation voltage or the output driver resistance. Using the output driver resistance is generally easier as it is directly given in the performance graph of the device’s datasheet.

$$P_{SAT}=V_{SAT}\cdot I_{FANcont}\qquad\textbf{(4)}$$

or

$$P_{SAT}=R_{DSON}\cdot I_{FANcont}{}^{2}\qquad\textbf{(5)}$$

4.4. P_{SWITCH} – output switching loss

P_{SWITCH} represents the power dissipated when the output switches its state.

☐ Typical Two-coil design

When the output switches from on to off, the rapid change of the coil current generates a high voltage spike on the output voltage (which could easily reach more than 100V) due to the inductance characteristics:

$$U_L=L\cdot\frac{di}{dt}$$

However, the fan driver includes a voltage clamp which limits this voltage spike at a much lower value. This value is defined by the output clamping voltage parameter in the datasheet. The above formula also means that the output voltage is clamped until the derivative of the coil current is null.
Since the current during the clamping event varies in time, we should theoretically use an integral calculation to obtain the power dissipated in one output driver, as:

$$P = \frac{1}{T} \cdot \int_0^{t_{CLAMP}} \left[V_{CLAMP} \cdot I_O(t) \right] \cdot dt$$

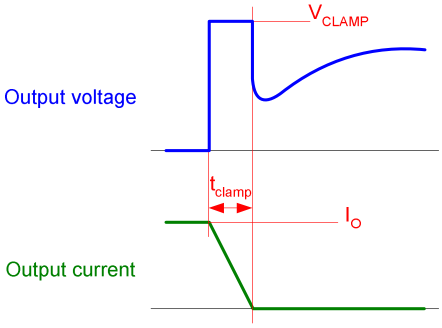


Figure 3 – Output clamping event

Fig.3 illustrates the output clamping event, showing output voltage and current.

To calculate this power dissipation, we can make the approximation that the output current decreases linearly from a maximum value I_O to zero for an output clamping duration of t_{CLAMP}. During this period, the output voltage is clamped to the "output clamping voltage" V_{CLAMP}.

This approximation enables to re-write the power dissipated in one output driver as:

$$P = V_{CLAMP} \cdot \frac{I_O}{2} \cdot \frac{t_{CLAMP}}{T}$$

Because of the two output drivers, the clamping event occurs twice in total over a period T.
Hence, the total output switching loss P_{SWITCH} is:

$$P_{SWITCH} = V_{CLAMP} \cdot I_O \cdot \frac{t_{CLAMP}}{T} \qquad \textbf{(6)}$$

- ☐ "Soft Switching" Two-coil design

In Two-coil fan driver using the soft switching techniques, the rise and fall times of the output voltages are increased. It reduces the voltage spikes on the output because the current value is smoothly changed.

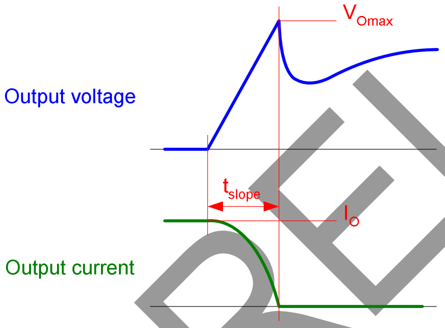


Figure 4 – Soft switching event without reaching the output clamping voltage

Soft switching the fan coil by using a linear ramp voltage shape proportional to time t makes the output current not decreasing following a linear shape as in Fig.3 but with a square factor t^2, because of the integration by the inductance. It is illustrated in Fig.4.

When the output clamping voltage is not reached, the output current equals to zero when the output voltage peaks to its maximal value V_{Omax}.

The formula of the coil current during the duration t_{slope} is :

$$i_{slope}(t) = I_O - \frac{V_{O\max}}{R \cdot t_{slope}} \cdot \left(\frac{L}{R} \cdot \left(e^{\frac{-t \cdot R}{L}} - 1 \right) + t \right)$$

The integral of this formula is obviously complicated. Moreover, even if measuring the DC resistance R of the fan coil is an easy task with a simple multimeter, it is unlikely to know the inductance L as it necessitates the use of an inductance meter, rarely available.
It is however possible to find a close and simple approximation of the current shape by using a cosinusoidal function:

$$i_{slope}(t) \approx I_O \cdot \cos\left(\frac{2\cdot\pi}{4\cdot t_{slope}}\cdot t\right)$$

In the above approximation, the motor time constant is discarded from the calculation. In fact, the simplified formula is very close to the original formula when the motor time constant $\frac{L}{R}$ is greater than 300us. This is generally the case for low and medium speed fans using ferromagnetic core in the stator construction.
For high speed fans without ferromagnetic core, the motor time constant tends to be much less. In this case, the current shape would be much a linear decrease than exponential.
In this sense, the given formula can be seen as a worst case.

Knowing that:

$$P = \frac{1}{T}\cdot\int_0^{t_{slope}}\left(V_{O\max}\cdot\frac{t}{t_{slope}}\right)\cdot\left(I_O\cdot\cos\left(\frac{2\cdot\pi}{4\cdot t_{slope}}\cdot t\right)\right)dt = V_{O\max}\cdot I_O\cdot\frac{t_{slope}}{T}\cdot\frac{2\cdot(\pi-2)}{\pi^2}$$

We conclude that the power dissipation generated by the soft switching for the 2 output drivers:

$$P_{SWITCH} = V_{O\max}\cdot I_O\cdot\frac{t_{slope}}{T}\cdot\frac{4\cdot(\pi-2)}{\pi^2} \approx V_{O\max}\cdot I_O\cdot\frac{t_{slope}}{T}\cdot\frac{1}{2.15} \qquad \textbf{(7)}$$

Note that the equation 7 is only taking into account the power dissipated during the rising edge of the output voltage. To be accurate, we should also include the power dissipated during the falling edge of the output voltage as well.

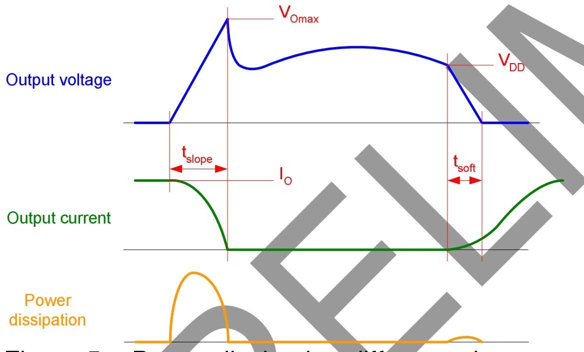


Figure 5 – Power dissipation difference between rising and falling edge of the output voltage

However, the power dissipated during the falling edge of the output voltage can generally be neglected as it quite small compared to the power dissipated during the rising edge of the output voltage, as illustrated in Fig.5.

This is mainly explained because of the motor time constant which makes the current rising relatively slowly. Therefore, the multiplication of output voltage by output current during this period leads to very small power dissipation.

The power dissipated during the falling edge of the output voltage would be greater when the ratio slope over motor time constant becomes rather important. It can occur with high speed fans without magnetic core (i.e. low inductance = low motor time constant) but is unlikely with typical medium and low speed fans.

4.5. P_{LOGIC} – logic output driver

- ☐ RD (Rotation Detection) output version

During rotation, the RD output driver is kept on. Hence, the power dissipated by the RD output driver equals the RD output saturation voltage multiplied by the RD output current, defined by the pull-up voltage and pull-up resistor:

$$P_{LOGIC} = V_{RDsat}\cdot I_{RD} \qquad \textbf{(8)}$$

- ☐ FG (Frequency Generator) output version

During rotation, the FG output pin follows the Hall signal and alternates between the on and off state. The

FG driver is switched on for half the period. Therefore, the power dissipated is 2 times lower than when using an RD output driver:

$$P_{LOGIC} = \frac{V_{FGsat} \cdot I_{FG}}{2} \qquad \textbf{(9)}$$

In practise, we could neglect the power dissipation P_{LOGIC}. Assuming the worst case where V_{RDsat} = 0.5V and I_{RD} = 20mA, which represents a power dissipation of just P_{LOGIC} = 10mW. Using the FG output, it would be even 5mW.

5. Calculating the IC power dissipation

With the different equation depicted in the section 4, it is now easy to calculate the IC power dissipation and thus to determine the IC junction temperature.

It was mentioned that consulting the performance graph of the device's datasheet is required for several IC parameters like Supply Current I_{DD} and Output Driver ON Resistance R_{DSON}. However, these parameters also vary with the junction temperature. Therefore, the calculation is more likely to be done by several refining steps. This effort can be minimized by taking from the beginning some worst case condition:

- ☐ the Supply Current I_{DD} decreases with the temperature so the worst case is at lower temperature
  → use the value at the operating ambient temperature without need to refine the calculation

- ☐ the Output Driver ON Resistance increases with temperature
  → use the R_{DSON} value for a higher temperature than the operating ambient one as the junction is always higher

For example, if the IC operates at 50 degree ambient temperature with a large output current, it is expected that the IC junction temperature would be much higher. To reduce the time needed for the calculation, we should use the supply current I_{DD} at 50 degree and the output resistance R_{DSON} at higher temperature like 75 degree for example.

5.1. P_D – Total IC power dissipation

The last operation to calculate the total IC power dissipation P_D is to sum the power dissipation factors:

$$P_D = P_{SUP} + P_{SAT} + P_{SWITCH} + P_{LOGIC} \qquad \textbf{(10)}$$

5.2. T_J – IC Junction temperature

The basic formula of an IC power dissipation calculation is:

$$P_D = \frac{T_J - T_A}{R_{THja}}$$

where:

P_D is the total IC power dissipation
T_J is the IC junction temperature
T_A is the operating ambient temperature
R_{THja} is the package thermal resistance junction to ambient

Reversing this formula, we can determine the IC junction temperature:

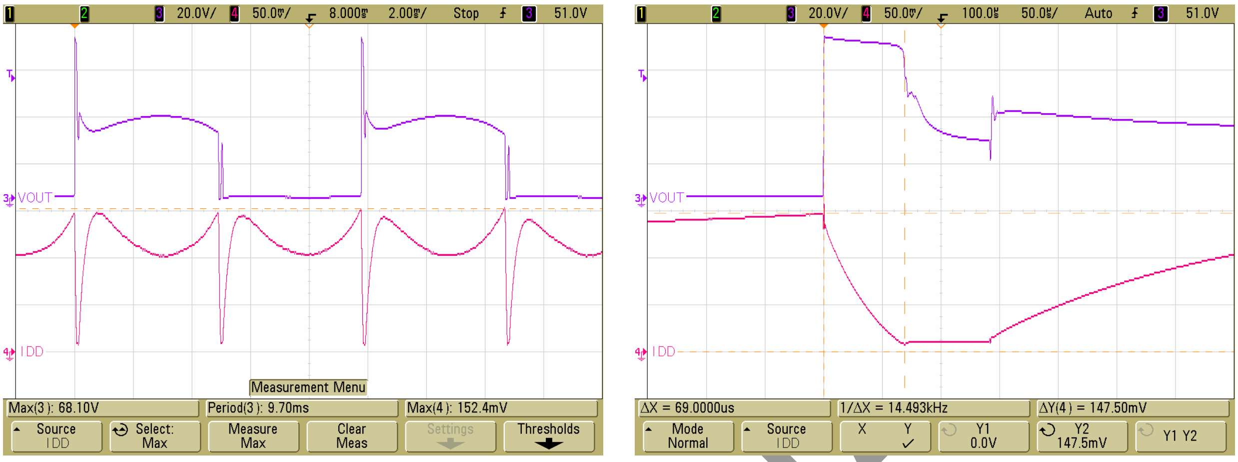
$$T_J = P_D \cdot R_{THja} + T_A \qquad \textbf{(11)}$$

Based on this result, it can be checked if the application is running under safe conditions, meaning below the maximum values given in Melexis product datasheets.

6. Calculation examples

6.1. US91A application – “No-V_{DD}” typical design

☐ Application-based data



(a) – V_{CLAMP}, Period T & I_O (b) – t_{clamp} & I_O

Figure 6 – US91A oscilloscope measurement

Nominal voltage	$V_{DD} = 24V$
Peak Current Consumption	$I_{FANpeak} = 220mA$
Nominal Current Consumption	$I_{FANcont} = 110mA$
Maximum Current when output switches off	$I_O = 150mA$
Operating Temperature	$T_A = 25$ degree
Output Switching Period	$T = 9.7ms$
Output Clamping Voltage	$V_{CLAMP} = 68V$
Output Clamping Duration	$t_{CLAMP} = 69\mu s$
EMF Voltage	$V_{EMF} = 35V$
VK Package Thermal Resistance	$R_{THja} = 200deg/W$
RD pull-up voltage	5V
RD pull-up resistor	10kΩ

☐ Calculation

Static Input Supply:

$$V_{SUP} = V_{DD} + 0.64 \cdot (V_{EMF} - V_{DD}) = 24 + 0.64 \cdot (35 - 24) = 31V$$

From the US91A datasheet → $I_{DD} \approx 1.7mA$ @ 31V & 25℃
We can observe that I_{DD} decreases with the temperature → the value given at 40℃ represents a worst case so we use it for the calculation.

$$P_{SUP} = V_{SUP} \cdot I_{SUP} = 31V \cdot 1.7mA = 53mW$$

Output Driver “ON” state:

As a first guess, let’s assume the US91A junction temperature is around 50 degree due to the 110mA current consumption.

→ $R_{DSON} \approx 1.5\Omega$ at 31V & 50℃

$$P_{SAT} = R_{DSON} \cdot I_O^{\,2} = 1.5\Omega \cdot 0.110^2 = 19mW$$

Output Switching Loss:

From the application data, V_{CLAMP} = 68V, t_{CLAMP} = 69µs and T = 9.7ms (measured on Fig.6).

$$P_{SWITCH} = V_{CLAMP} \cdot I_O \cdot \frac{t_{CLAMP}}{T} = 68V \cdot 150mA \cdot \frac{69\mu s}{9.7ms} = 73mW$$

Logic Output Driver:

With 10kΩ pull-up resistor tied to 5V, the maximum current flowing through the RD driver is 0.5mA.

$$P_{LOGIC} = V_{RDsat} \cdot I_{RD} = 0.5V \cdot 0.5mA = 0.25mW$$

As we can see, this value is even less than 1mW so it can easily be neglected.

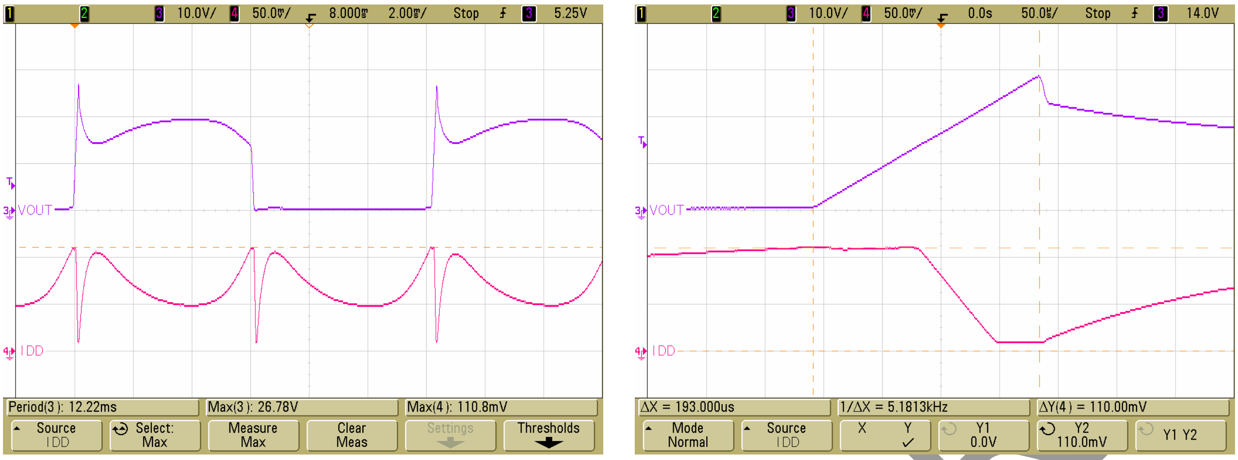
$$P_D = P_{SUP} + P_{SAT} + P_{SWITCH}\left(+P_{LOGIC}\right) = 53mW + 19mW + 73mW\left(+0.25mW\right) \approx 145mW$$
$$T_J = P_D \cdot R_{THja} + T_A = 145mW \cdot 200\deg/W + 25\deg = 54\deg$$

The calculation firstly leads to a junction temperature T_J = 54deg in the application.

At this step, using the value of R_{DSON} assuming T_J=54 degree instead of 50 degree would be needless as the goal of the formula is a fast and quite close estimation of the junction temperature to conclude the safe operating of the device and eventually anticipate parameters drift.
As a rule of thumb, performing any re-iteration should be done only if the difference between assumption and result is higher than 5 to 10 degree.

The result shows the US91A is safely used in this application.

6.2. US65 application – “V$_{DD}$” & Soft Switching design



Period(3): 12.22ms | Max(3): 26.78V | Max(4): 110.8mV

ΔX = 193.000us | 1/ΔX = 5.1813kHz | ΔY(4) = 110.00mV

(a) – Period T, V_{Omax} & I_O

(b) – t_{slope} & I_O

Figure 7 – US65 oscilloscope measurement

Nominal voltage	V_{DD} = 12V
Peak Current Consumption	$I_{FANpeak}$ = 140mA
Nominal Current Consumption	$I_{FANcont}$ = 70mA
Maximum Current when output switches off	I_O = 110mA
Operating Temperature	T_A = 60 degree
Output Switching Period	T = 12.2ms
Maximum Output Voltage	V_{Omax} = 26.7V
Output Slope Duration	t_{slope} = 193µs
FG pull-up voltage	5V
FG pull-up resistor	10kΩ

☐ Calculation

Static Input Supply:

From the US65 datasheet → $I_{DD} \approx$ 3mA @ 12V & 60°C

$$P_{SUP} = V_{DD} \cdot I_{DD} = 12V \cdot 3mA = 36mW$$

Output Driver “ON” state:

Because of the small 70mA current consumption, let’s assume the US65 junction temperature to be around 70 degree.

→ $R_{DSON} \approx$ 1.2Ω at 12V & 70°C

$$P_{SAT} = R_{DSON} \cdot I_{DDcont}{}^2 = 1.2\Omega \cdot 0.070^2 = 6mW$$

Output Switching Loss:

From the application data, V_{Omax} = 26.7V, t_{slope} = 193µs and T = 12.2ms (measured on Fig.7).

$$P_{SWITCH} \approx V_{O\max} \cdot I_O \cdot \frac{t_{slope}}{T} \cdot \frac{1}{2.15} = 26.7 \cdot 110mA \cdot \frac{193\mu s}{12.2ms} \cdot \frac{1}{2.15} = 22mW$$

Logic Output Driver:

With 10kΩ pull-up resistor tied to 5V, the maximum current flowing through the FG driver is 0.5mA.

$$P_{LOGIC} = \frac{V_{FGsat} \cdot I_{FG}}{2} = \frac{0.5V \cdot 0.5mA}{2} = 0.12mW$$

As we can see, this value is even less than 1mW so it can easily be neglected.

$$P_D = P_{SUP} + P_{SAT} + P_{SWITCH}\left(+P_{LOGIC}\right) = 36mW + 6mW + 22mW\left(+0.12mW\right) = 64mW$$
$$T_J = P_D \cdot R_{THja} + T_A = 64mW \cdot 150\,\mathrm{deg}/W + 60\,\mathrm{deg} = 69.6\,\mathrm{deg}$$

The calculation leads to a junction temperature of 69.6deg in the application.
As in the previous example, it was used the value of R_{DSON} assuming T_J=70 degree and the initial result is 69.6 degree which is quite close so there is no need to perform any re-iteration.
The results shows the US65 is safely used in this application.

7. What to do if the results exceed the device specification ?

In case the calculation leads to a junction temperature higher than the device's absolute maximum ratings (generally 125 degree), it means the application is unsafe: the device may be damaged or there could be an important drift in some parameters leading to an application failure.

In order to operate within safe conditions, several possibilities can be explored:

- ☐ Reducing the operating temperature range
- ☐ Reducing the output current by increasing the number of turns on the coil windings or by using smaller wire diameter
- ☐ Improving the thermal resistance junction to ambient of the package

The two first points are directly related to the fan specification and design.

The third point could be achieved by using another package with better thermal performance or by more accurate measurement of the package thermal resistance in the customer system since it depends on some variable such as PCB type (single or multi-layer) and copper track design as the most important ones. However, this last option is rarely used as it requires long research and development phase.

8. Conclusion

A simple and practical method to estimate the power dissipation in two-coil fan driver has been presented in this application note. The goal is to determine if the device operates within safe limits in the application by checking if the junction temperature is below the value given in the datasheet.

Other operations can be performed by reversing several equations. For instance, the maximum output current could be determined where the maximum junction temperature would be reached.

If you have any question or need for application support, please do not hesitate to contact Melexis.

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