AN4250
Application note

Fishbone diagram for power factor correction

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Introduction

This report aims to show through a Fishbone diagram, all possible causes of failure of the Power MOSFET mounted on a PFC.

This work is divided into 5 sections:

- The first one describes the power factor
- The second describes the Boost converter
- The third describes the PFC system
- The forth paragraph shows all critical conditions causing the failure of the Power MOSFET and builds up the Fishbone diagram
- Last paragraph presents a specific Fishbone parallel configuration

Contents

1 Power factor

In the power electrical circuit, the power factor represents an index measuring the available main power used.

The general power factor definition is given by the ratio between the active power and the apparent power:

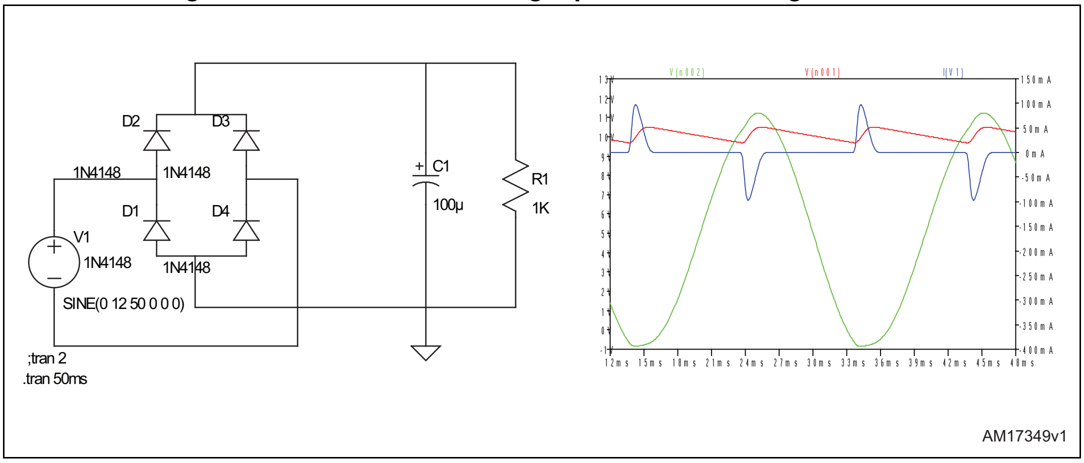
Equation 1

$$P.F. = \frac{P}{S} = \frac{P.Active}{P.Apparent}$$

Its value varies from 0 to 1. In the efficient system, the value of the power factor should be equal to 1.

In the classic Graetz rectifier with capacitive filter, the voltage and current waveforms are not sinusoidal.

Figure 1. Schematics of a single phase diode bridge rectifier



The sinusoidal voltage main is expressed by the following equation:

Equation 2

$$V_{mains} = \sqrt{2} V_{eff}\, sen(\omega t + \varphi)$$

The current expression, not being sinusoidal, can be represented in fourier series:

Equation 3

$$I_{mains} = \sqrt{2}\, I_1 \sin(\omega t + \varphi 1) + \sqrt{2}\, I_3 \sin(3\omega t + \varphi 3) + \sqrt{2}\, I_5 \sin(5\omega t + \varphi 5) + ...$$

The active power is given by the following formula:

Equation 4

$$P = V_{eff}\, I_1 \cos\varphi$$

While the apparent power:

Equation 5

$$S = V_{eff} I_{eff}$$

Due to equations *4* and *5*, the power factor is:

Equation 6

$$P.F. = \frac{I_1}{I_{eff}} \cos\varphi = \cos\vartheta \cos\varphi$$

The power factor depends on the phase displacement due to the contribute of the factor φ and on the harmonic content due to the contribute of the factor ϑ.

2 Boost converter

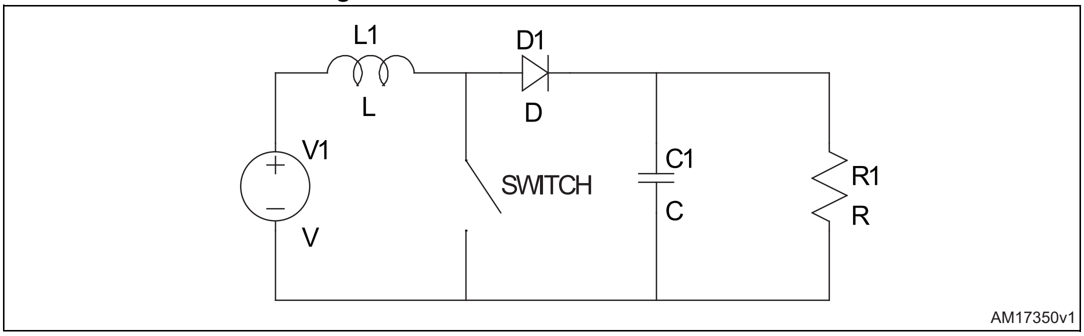
The Boost converter is generally used in the SMPS as a PFC.

Section 3 gives a complete description of the PFC block and the Boost converter.

The Boost circuit is a DC-DC converter providing a higher output voltage than input voltage.

Here below the classic Boost topology.

Figure 2. Boost converter schematic



The circuit is composed of:

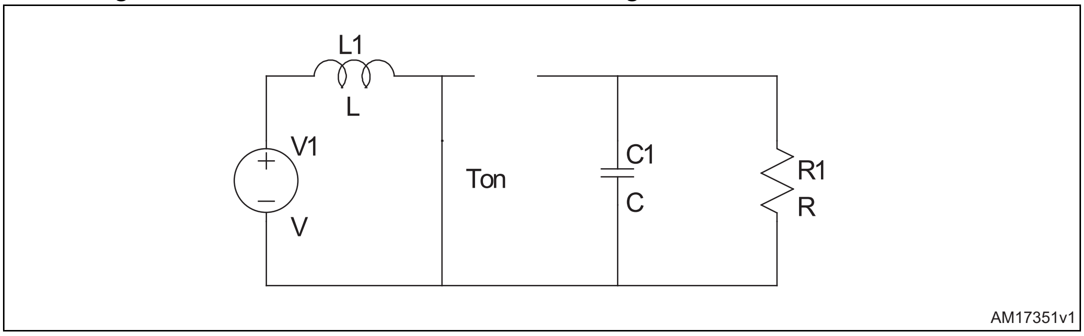
- Inductor
- Switch (Power MOSFET)
- Boost diode
- Capacitor and load

The functioning of the circuit can be divided into two steps depending on the conduction state of the switch: on-state, off-state.

On-state

During the on-state, the switch can be considered as a short-circuit, thus from the initial topology two meshes can be derived:

Figure 3. Boost converter schematic during the Power MOSFET turn-on

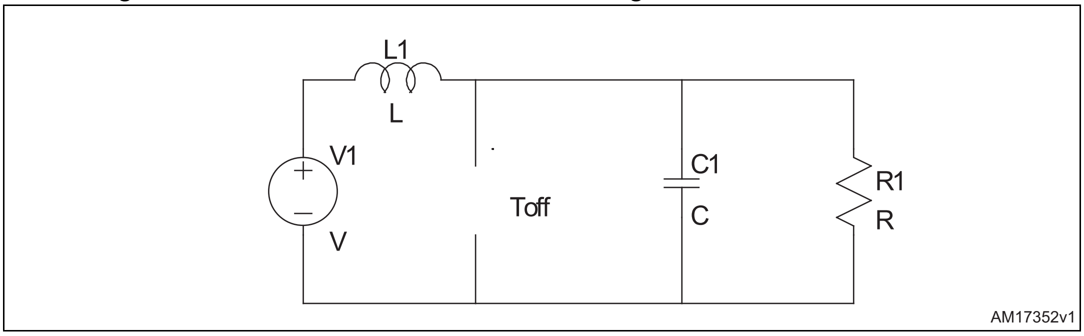


$$V_L = V_{IN}$$

Off-state:

During the off-state the switch is open, thus the electrical schematic of the converter is:

Figure 4. Boost converter schematic during the Power MOSFET turn-of



Owing to the energy accumulated by the inductance during the previous phase (ON), the current, through the inductor, cannot go to zero instantaneously. The consequence of this phenomenon is an extra voltage with a sign, which can oppose to the decreasing current. Due to the extra voltage, the anode of the Boost diode has a higher voltage than the output one, allowing the current to flow through it.

Below equation describes the above concept:

Equation 7

$$V_{IN} t_{on} + (V_{IN} - V_O) t_{off} = 0$$

Dividing the equation by the commutation period (T_s) we obtain:

Equation 8

$$\frac{V_O}{V_{IN}} = \frac{T_S}{t_{off}} = \frac{1}{1-D}$$

(D is the duty cycle= t_{on}/T_s)

The above two formulas have to be considered valid only if the converter works in the continuous mode.

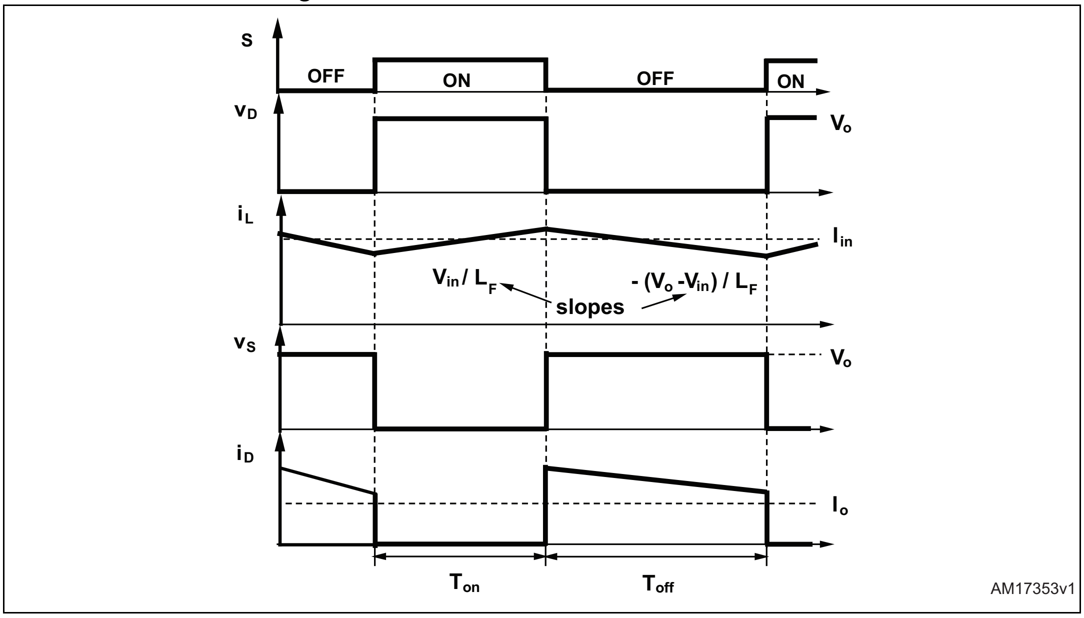
In fact, the Boost converter can work in two modes of conduction: CCM (continuous conduction mode), DCM (discontinuous conduction mode).

The shape of the current, flowing through the switch, distinguishes these two modes:

CCM

In the continuous conduction mode the current, through inductor during an entire period, does not reach the zero value; the Boost diode starts its conduction phase with a positive current value.

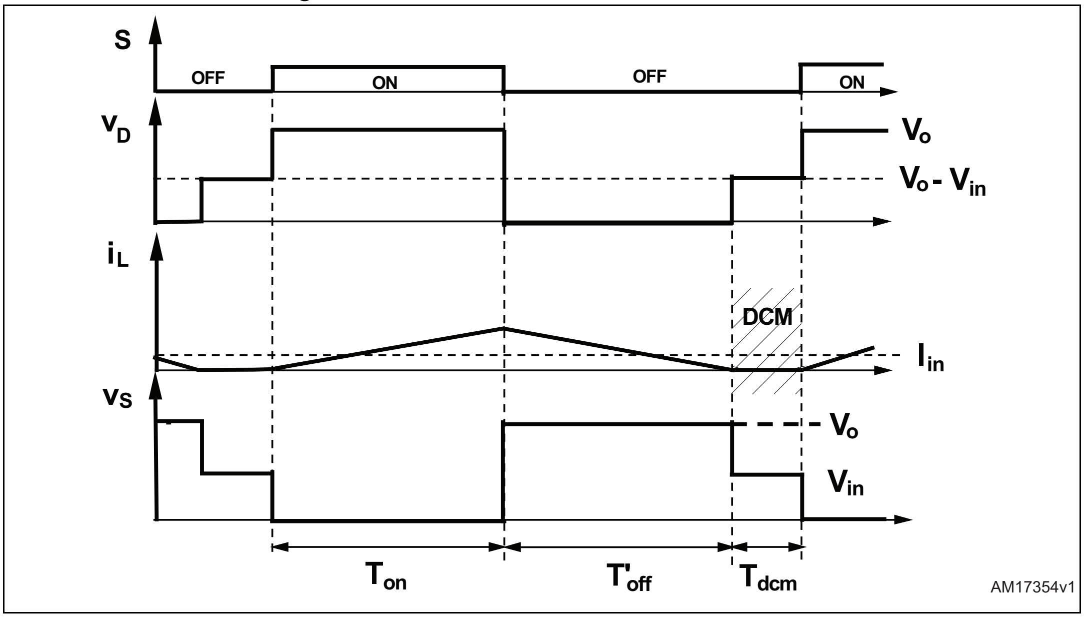
Figure 5. CCM Boost converter waveforms



DCM

In the discontinuous transition mode the current, through the inductor during an entire period, reaches the zero value, so the diode and the switch start their conduction phase from zero.

Figure 6. DCM Boost converter waveforms



As it is possible to notice, during the discharge phase of the inductor, the current reaches zero.

3 Power factor correction

The PFC is a power stage, which can correct the power factor. The circuit target allows the input current in phase with the main voltage to reduce the harmonic distortion. PF values are close to 1.

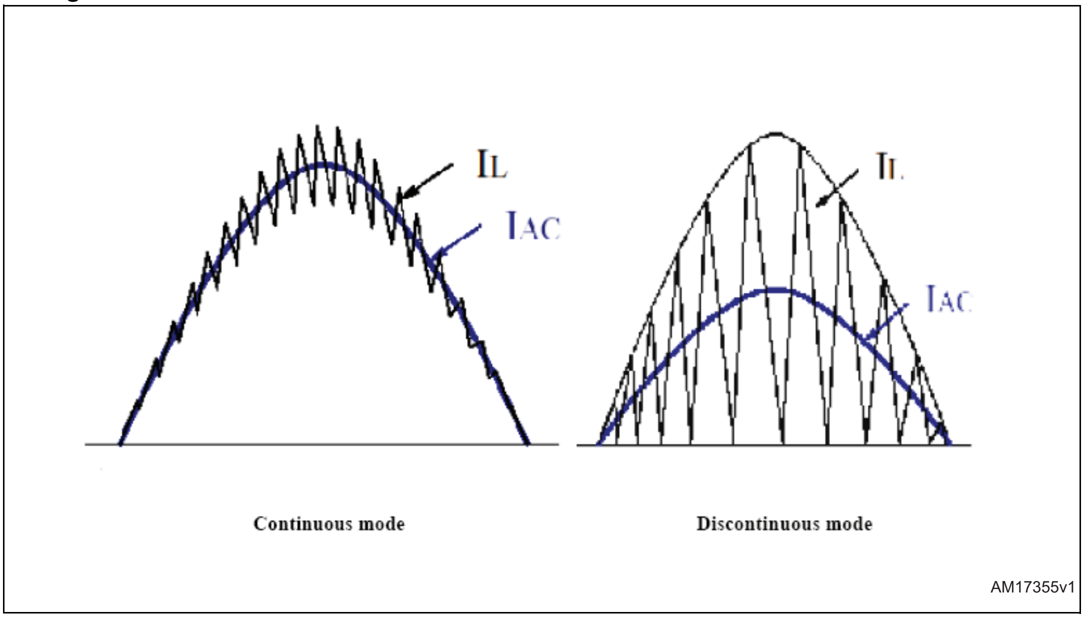
Working on the duty cycle or on the frequency of the switch commutation, the sinusoidal current shape can be built. The entire system is managed by a microcontroller, which compares the input main voltage with the output voltage and acts on the duty cycle.

Boost converter features two conduction modes; current waveforms depend on them.

In the DCM, the Power MOSFET of the Boost converter turns on when the inductor current reaches zero, and turns off when the inductor current meets the desired value.

In the CCM, the Power MOSFET of the Boost converter turns on when the inductor current is not zero.

Figure 7. Current waveforms on the inductor for the CCM/DCM Boost converter



4 Fishbone diagram

In this section most common critical conditions, affecting the Power MOSFET mounted as switch on the Boost converter, are described. Besides, they are reported in a fishbone diagram.

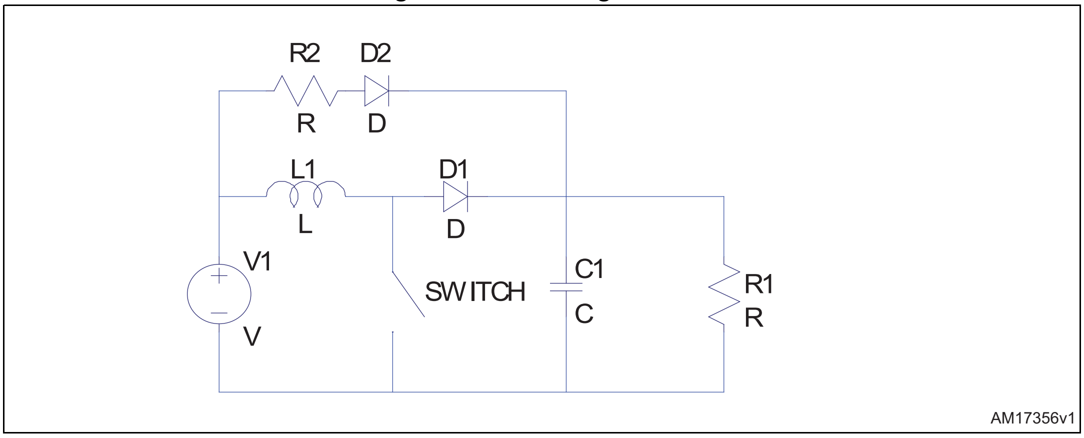
Causes linked to the application

Short-circuit of the startup

In the Boost topology above described, the “pre-charge” circuit has not been presented; this circuit works during the start-up phase when the output capacitor is not charged and the V_{IN} is greater than V_{OUT}. This condition forces the switch to absorb more current than the steady-state operation, therefore the switch could work with current exceeding the maximum ratings.

Using the “pre-charge” circuit, the current doesn't flow through the switch since it flows through the diode of the “pre-charge” circuit until $V_{IN} > V_{OUT}$.

Figure 8. Pre-charge circuit



Choke dimensions

Since coil saturation depends on the current flowing through it, if the coil is not dimensioned correctly, coil saturation can occur (the coil behaves as a simple short-circuit); a huge quantity of current can flow through the switch causing an overheating that, in some cases, causes the failure of the device.

Losses during the switching

If the MOSFET is not driven correctly, an overheating can occur. This phenomenon can cause the failure of the device.

Short-circuit of the load

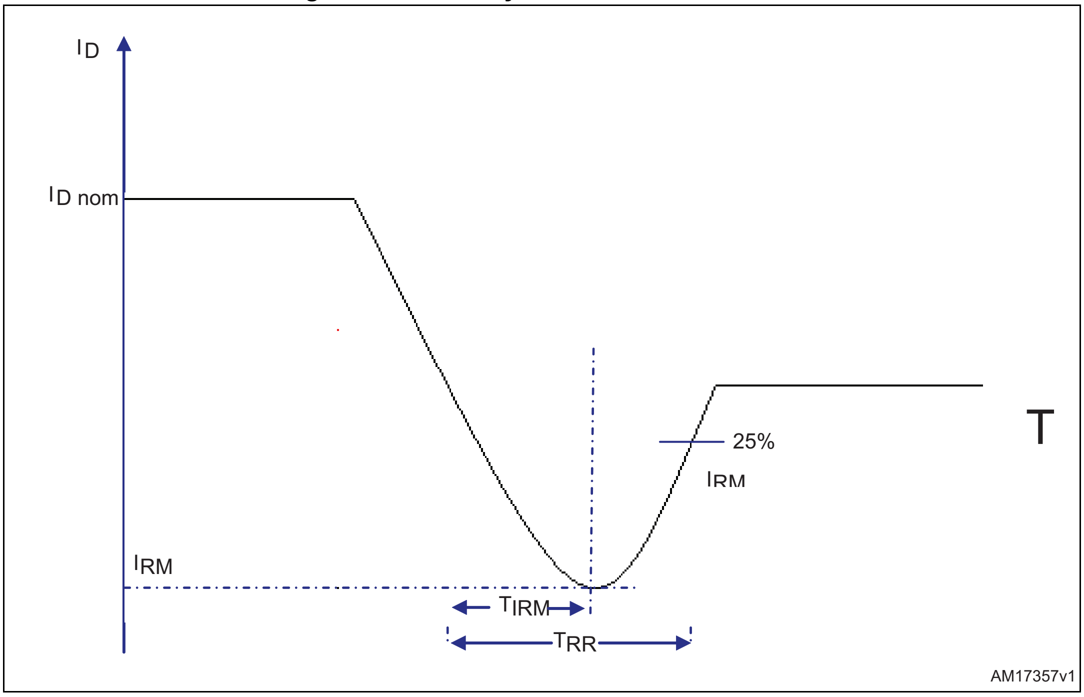
When the load is in short-circuit condition, if the short protection circuit is not present or if its operative time is too long, the following failures can happen:

1. If the “pre-charge” circuit is not present, the switch works in start-up phase with a huge quantity of current (refer to the start-up critical condition)
2. the “pre-charge” circuit is present till it works, then current flows onto the switch like the previous case

Switching diode recovery

In CCM as above written, during the commutation, the current, which flows through the diode, is not zero. In this case, both the coil current inside the switch and the diode current flow (current spike depends on the reverse recovery time t_{rr}). In relation to the intensity of the spike, the overall absorbed current could cause the failure.

Figure 9. Recovery current inside a diode



Causes linked to the material

Due to the intrinsic characteristics of the Power MOSFET device (V_{th}, R_g, C_{rss}), a spurious turn-on can happen during the turn-off commutation.

In detail, during the turn-off, spurious noise on the drain (like a fast d_v/d_t) generates with the C_{rss} capacitance a spurious current:

Equation 9

$$i_s = C_{rss}\frac{dV_{DS}}{dt}$$

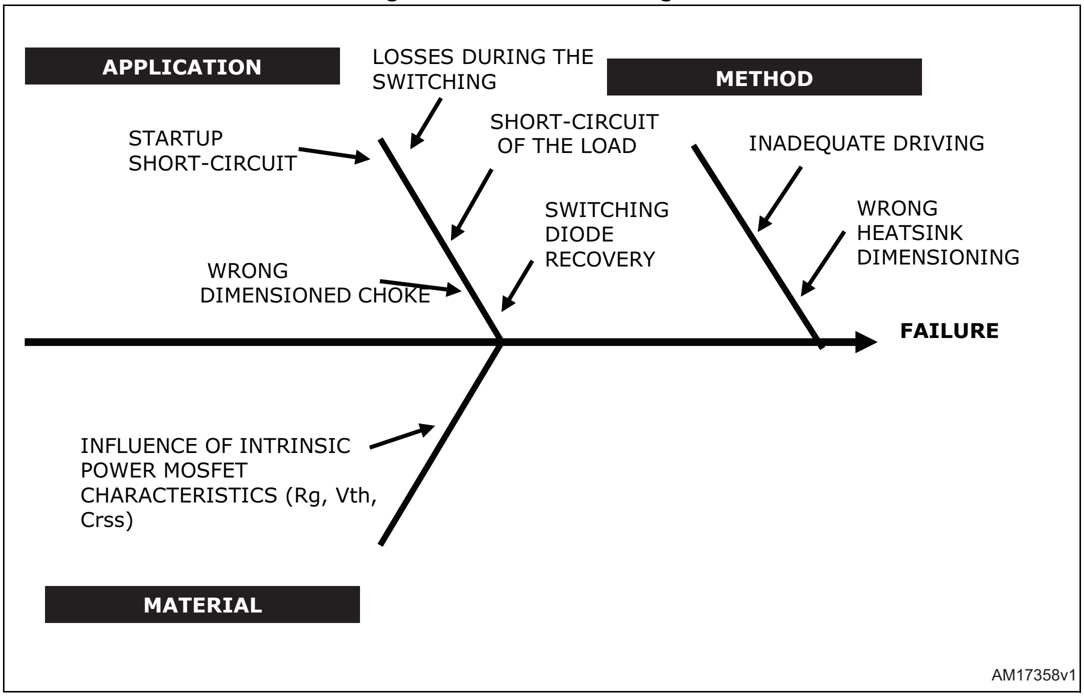
High values of C_{rss} can cause the undesired turn-on of the switch.

The above condition is better described when the intrinsic Power MOSFET R_g is much lower than the gate driver resistor R_d and the Power MOSFET threshold V_{th} is close to the lower datasheet limit.

Causes linked to the method

An improper thermal dissipation due to incorrect driving/heatsink, can cause an overheating of the device with failure.

Figure 10. Fishbone diagram



5 Fishbone diagram for Power MOSFET in parallel

When the power levels are very high, some PFC makers put in parallel two or more Power MOSFET devices. In this case, other aspects must be taken in account.

Causes linked to the application

Parasitic inductance

It is generated by interconnection wiring and discrete components. They cause delays and power losses which affect the balance of the current. It strictly depends on the PCB layout.

Temperature unbalance

A temperature rise causes a decrease of V_{th} and an increase of $R_{DS(on)}$.

Decrease of V_{th} -> switching loss rise -> thermal runaway.

Increase of $R_{DS(on)}$ -> conductive loss rise-> current limitation -> unbalance.

Several factors let two Power MOSFETs work according to different temperatures:

- Another device is mounted on the same heatsink
- Different air flow according to the fan

Boost diode

During the turn-on, it impacts on the current spike. If devices with different V_{th} are used (500 mV), a fast diode or a very fast diode involves a different peak current.

Gate circuitry

Decoupling resistor mismatch causes the current unbalance. The device with lower R_{gate} leads more current than other one and its temperature, as well as its $R_{DS(on)}$ increase.

Causes linked to the material

Different V_{th}

During the switching phase (turn-on, turn-off), the difference of V_{th} leads the device, with its lower value, to conduct earlier, causing an unbalance of the currents.

Different $R_{DS(on)}$

The difference of $R_{DS(on)}$ causes, during the conduction phase, an unbalance between two currents. In particular, if one of the two Power MOSFETs has a lower $R_{DS(on)}$, an increase of its I_D current is observed, causing an increase of the Power MOSFET temperature.

Gfs influence

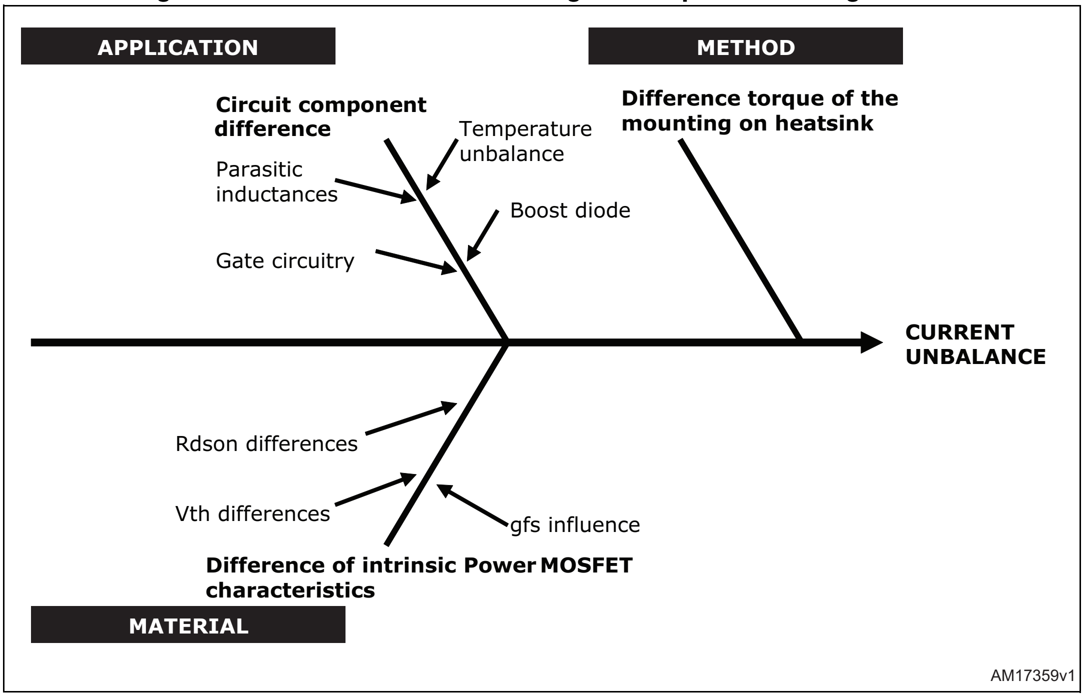
Different gfs values, during the commutation, cause substantial differences in relation to the two currents. This parameter is guaranteed by design and process.

Causes linked to the method

Different torque on heatsink

Different torque of the two devices causes different heat dissipation and the current unbalance.

Figure 11. Additional Fishbone diagram for parallel configuration



6 Revision history

Table 1. Document revision history

Date	Revision	Changes
11-Mar-2014	1	Initial release.