A methodology based on electro-thermal simulations for designing over-temperature protection of linear and switch-mode power management ICs

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Summary: Over-temperature protection (OTP) is an essential feature for modern power management integrated circuits (PMICs); it prevents overheating that can impair operation and lead to irreversible damage. The methodology for designing OTP circuits described here involves running iteratively electrical, thermal and electro-thermal simulations and comprises three main design steps. A first-pass design is completed based on electrical-only simulations and a rough estimate of die temperature; next, thermal-only sims provide the temperature distribution within the die, that allows the designer to place the OTP sensor properly and to adjust the OTP activation point by taking into account the difference between the sensed temperature and the highest temperature developed within the die – the hotspot. The design is fine-tuned by using electro-thermal simulations to assess the circuit behaviour over time for extreme use cases. Two OTP design examples are presented: a BJT linear voltage regulator, which also includes over-current protection, and a MOS switched-capacitor DC-DC converter that employs a power mirror.

Keywords: over-temperature protection, electro-thermal simulations, LDO, SC DC-DC converter

OTP circuits designed by using electro-thermal simulations

Generally, the over-temperature protection (OTP) comprises a temperature sensor - which provides information on the die temperature at its location, a reference to compare the sensor output against and an execution element able to change the operating condition of the IC when an OTP event occurs. One can recognize these elements in Fig.1, which depicts a BJT LDO. The OTP circuitry can be fairly simple: a diode as the OTP sensor and a voltage comparator that shuts down Q_{DRIVER} when the CTAT voltage across the diode goes below a set threshold – the OTP trigger point. However, standard electrical- and thermal-only simulations are not sufficient: they should be used in conjunction with electro-thermal sims, within a clear design methodology, as shown in Fig.2. A first-pass design can be completed by using electrical-only simulations; as they assume a constant temperature across the die, the designer has to set the OTP trigger point below the required T_{MAX}.

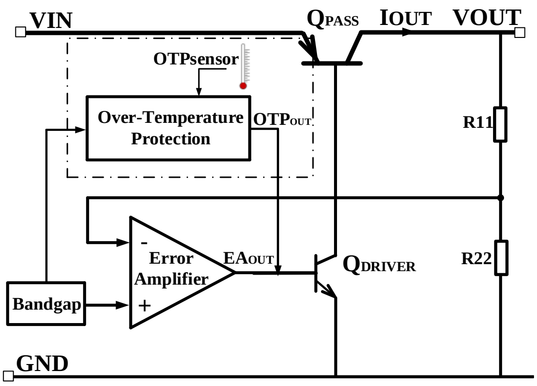

Fig.1 Block Diagram of an LDO with OTP

The pass transistor Q_{PASS} is controlled by the driver Q_{DRIVER}, in turn driven by the Error Amplifier that gains up the difference between the reference voltage provided by the bandgap and a fraction of the output voltage fed back by the network R11-R12

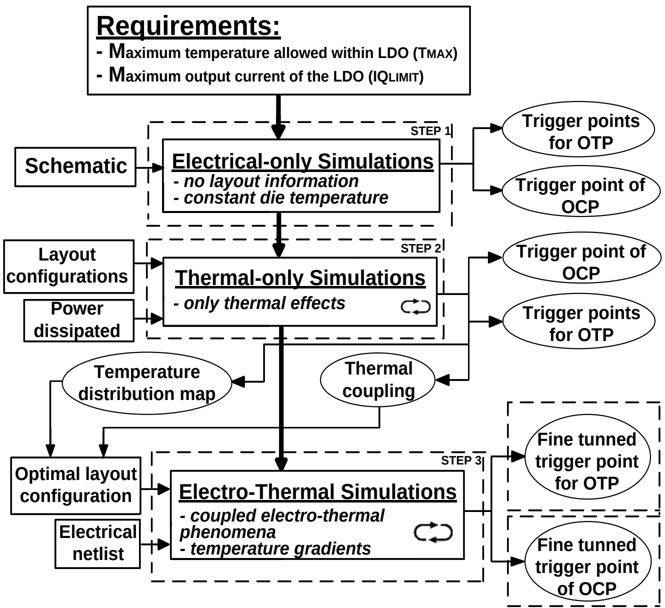

Fig.2 Flow-chart of the proposed methodology for designing the OTP and OCP circuits for an LDO [1].

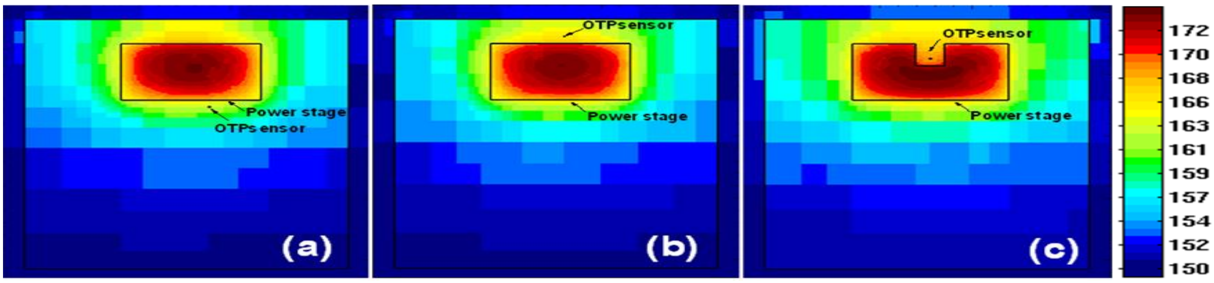

Figure 3: Temperature maps for three LDO design cases – OTP sensor placed bellow (a) and above (b) the rectangular-shaped power-stage and the OTP sensor placed in the gap of a re-shaped power-stage (c) [1]

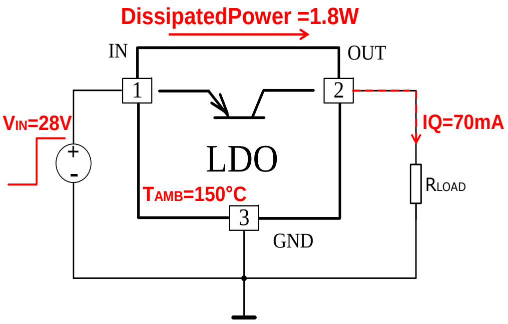

Figure 4: Test scenario considered for sizing & measuring the OTP trigger point. The larger-than-normal dissipated power, caused by the heavy load, pushes the hotspot temperature up to the limit T_{MAX}, when the OTP is activated and shuts down the LDO. The LDO cools down and it is re-enabled when the sensor temperature gets below a threshold.

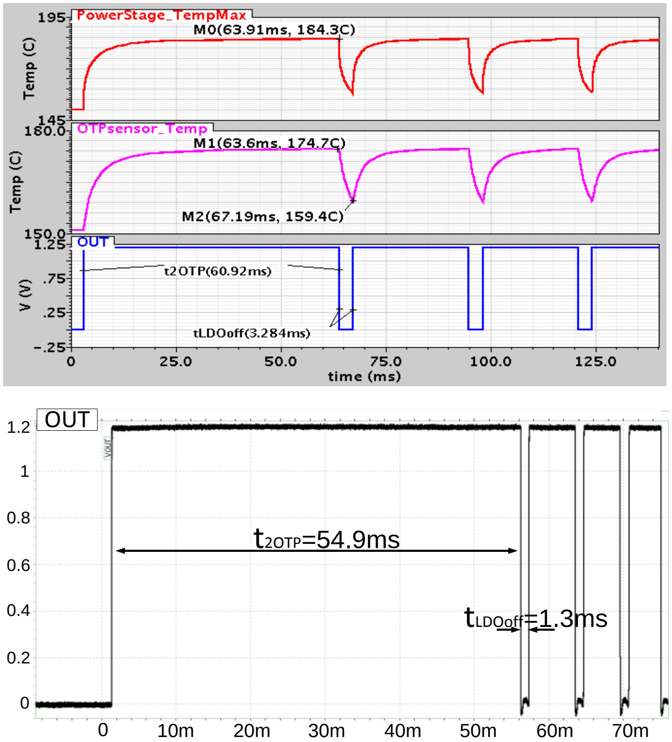

Figure 5. Simulated (top) and measured (bottom) LDO output voltage for the use case shown in Fig. 4

Next, thermal-only simulations are run to obtain temperature distribution maps such as those shown in Fig.3. They are first used to optimize the shape of the power-stage, in order to minimize the temperature of its hot-spots, then to optimize the OTP sensor location, and finally to derive the thermal coupling between it and the worst hotspot. The design is completed by employing electro-thermal simulations to assess the LDO dynamic behaviour in various use-cases, including extreme real-life operation scenarios, as shown in Fig. 4. Fig. 5 presents simulated and measured results for a BJT LDO developed using this design methodology.

In general, switched-mode DC-DC converters have far larger efficiency than linear regulators. However, they still need OTP to prevent thermal runaway which can appear in particular use cases. For example, the standard switched-capacitor DC-DC converter based in a power current mirror overheats when powered-up with a large input voltage and the output shorted to ground. The design methodology for OTP shown in Fig. 2 can be extended to DC-DC converters but first all use cases and extreme conditions which can result in over-temperature events have to be identified [2].

References

[1] C.-S. Plesa, M. Neag, C. Boianceanu and A. Negoita; – "Design methodology for over-temperature and over-current protection of an LDO voltage regulator by using electro-thermal simulations", Microelectronics Reliability, Volume 79, December 2017, pages 509-516

[2] C.-S. Plesa, M. Neag, C. Boianceanu - "Design of Over-Temperature Protection for Switched-Capacitor DC-DC Converter Based on Electro-Thermal Simulations", Romanian Journal of Information Science and Technology, Volume 22, Number 2, 2019, pages 144–157