AN5499

Application note

How to implement adaptive synchronous rectification in flyback converters using STM32 MCUs

Introduction

Synchronous Rectification (SR) is widely used in power supply converters to improve efficiency, reduce conduction losses and thermal dissipation, improving user experience in high power applications as well as in portable or hand-held devices.

Flyback converters have relatively high peak and RMS currents, which may cause high conduction losses in the output diode rectifier. Synchronous Rectification can reduce these losses and improve the efficiency of the overall power supply.

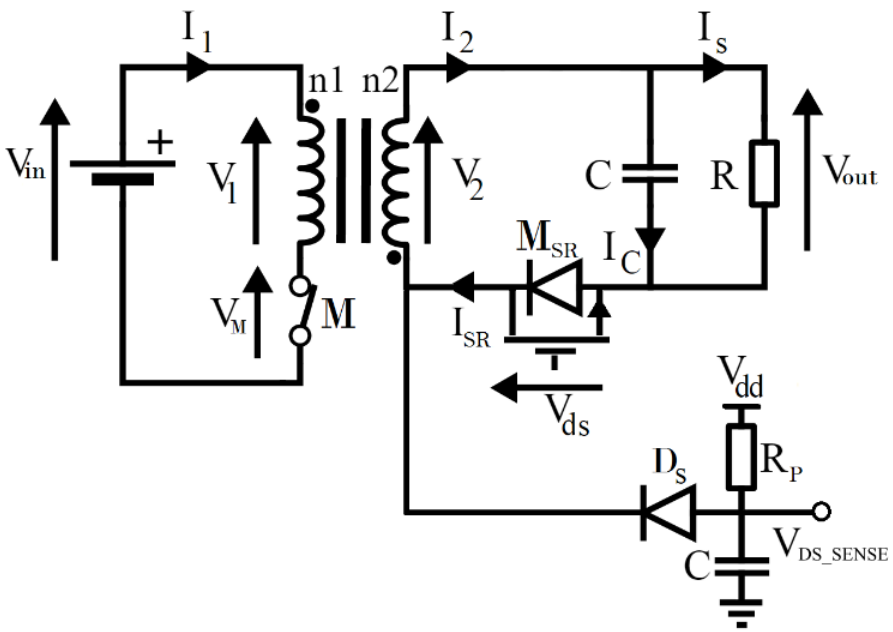
Substituting diode rectifiers with power MOSFETs in SR reduces power losses and thermal heating in converters because of their very low R_{DSON} compared with the voltage drop across diodes, including Schottky diodes.

SR, however, requires additional electronics to drive the MOSFETs: a sensing network to detect when the MOSFET must be turned on or a dedicated IC to control MOSFET switching, and an on-board microcontroller for digital solutions.

1 Synchronous rectification in flyback topology

The following figure shows the synchronous rectification technique applied in flyback topology, using a power MOSFET as the rectifier and corresponding V_{DS} sensing circuitry with a filter capacitor.

Figure 1. Synchronous rectification and V_{DS} sense circuitry operating principle



When the flyback converter primary switch is turned off, the voltage across the transformer reverses, the M_{SR} drain voltage drops quickly decreases to negative and the M_{SR} body diode starts conducting.

The synchronous rectification control logic is triggered by the falling edge of the M_{SR} V_{DS} and generates a signal to turn M_{SR} on, thus reducing conduction losses as the current flows through the MOSFET channel with a lower impedance path. After MOSFET turn-on, the V_{DS} signal changes from the body diode forward voltage to the drop across the MOSFET channel resistance R_{DS_ON}.

When the current flowing through the MOSFET channel decreases to zero, the V_{DS} voltage rises again and triggers the MOSFET turn-off.

Noise sources such as spikes from active components or flyback transformer leakage inductance can interfere with the V_{DS} signal and consequently trigger undesired transitions in the SR MOSFET. To increase reliability and avoid short-circuits, a delay is generated before turning the MOSFET on to ensure a safe diode conduction time. Similarly, the MOSFET is turned off to allow the diode conduct briefly before V_{DS} voltage inversion.

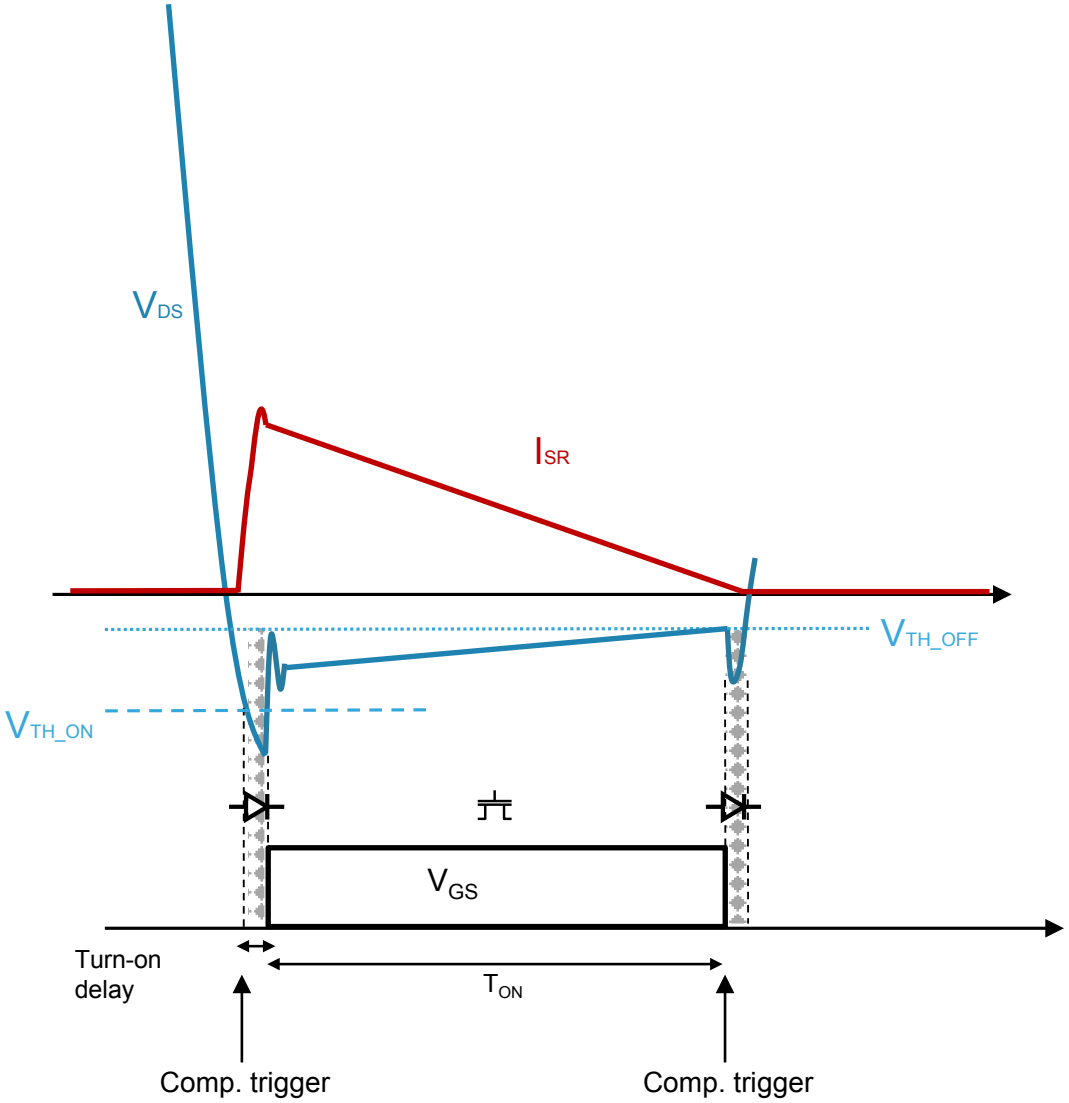
The MOSFET T_{ON} period should be maximized to reduce the diode conduction time and increase the overall converter efficiency. In this way, SR conduction losses are significantly reduced as the output current flows through the MOSFET channel instead of the rectification diode for most of the time. The power loss therefore decreasea from $P_{loss\_diode} = V_d \cdot I_{out}$ to $P_{loss\_MOSFET} = R_{ds\_on} \cdot I_{out}^2$, where R_{ds_on} is very low for SR MOSFETs.

The power converter continues to work even if the SR MOSFET is not driven, as rectification is ensured by the MOSFET body diode.

Appropriate MOSFET driving when the body diode is forward biased can generally improve system peak efficiency by 3% to 4%.

The figure below shows the relative V_{DS} and I_{SR} waveforms involved in SR driving, as well as the V_{GS} signal used to drive M_{SR}.

Figure 2. **Synchronous rectification driving signal waveforms**



1.1 V_{DS} sensing circuit

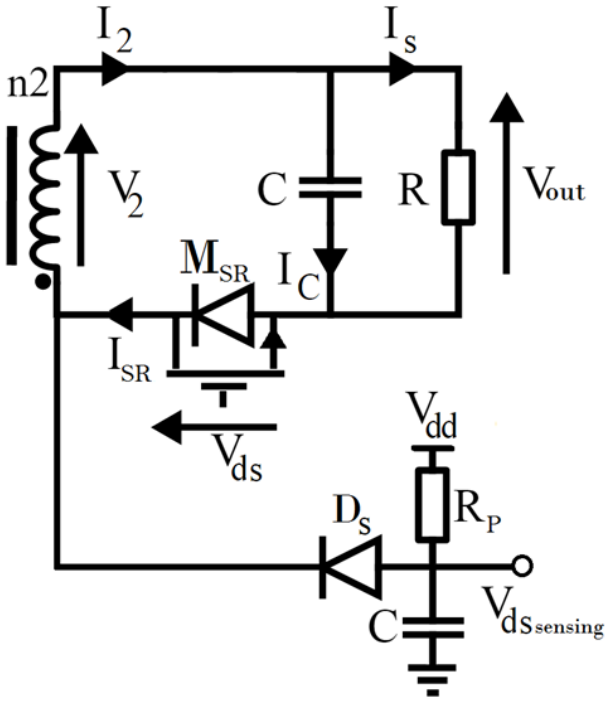
A sensing circuit for V_{DS} voltage is required to properly drive the MOSFET:

- when the current flows through the body diode and the V_{DS} voltage goes negative, the MOSFET must be turned on;
- when the current falls to zero and the V_{DS} increases again, the MOSFET must be turned off.

The sensing network shown below can be implemented with a fast Schottky diode and a pull-up resistor connected to the MCU supply voltage:

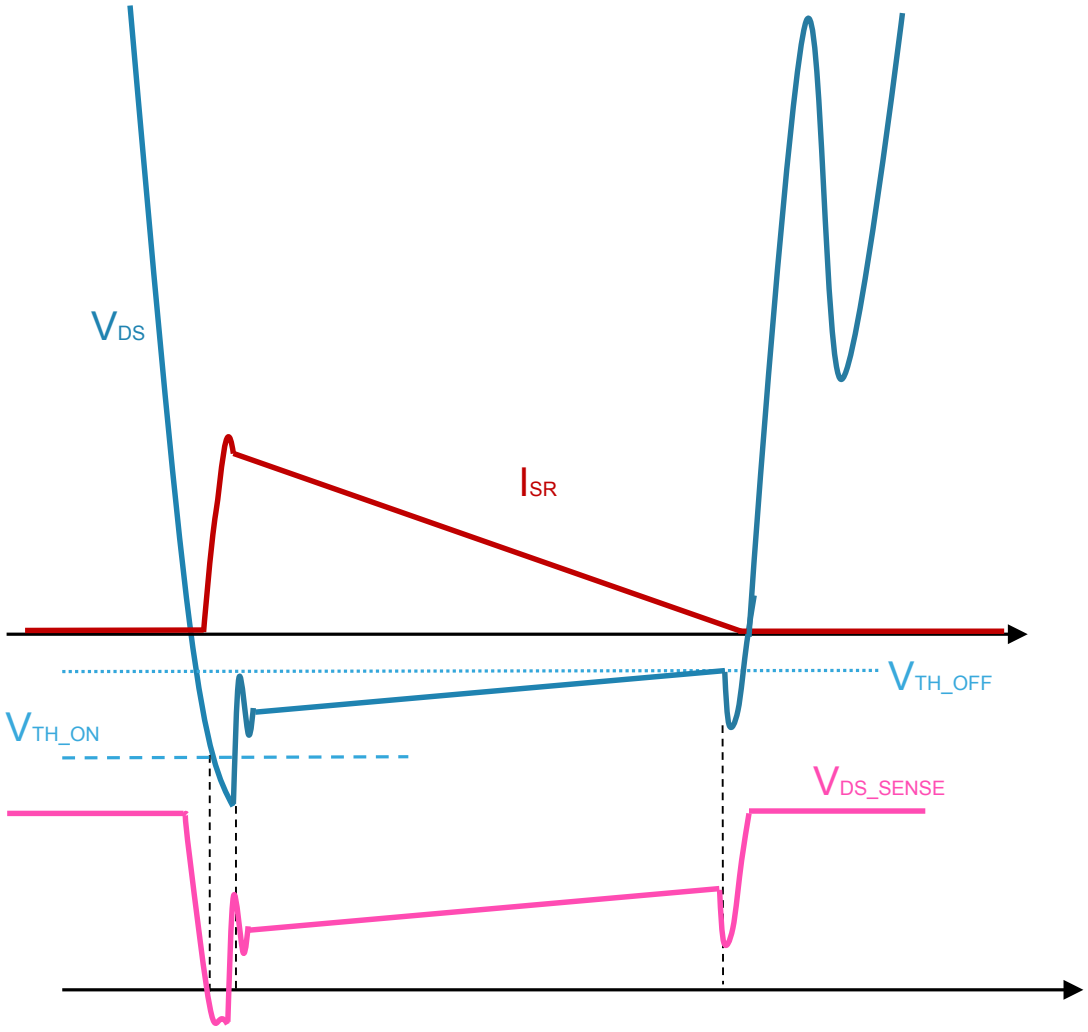
- when the SR MOSFET drain voltage is greater than V_{DD} (the MCU operating voltage), the Schottky diode is reverse biased and the sensed voltage is pulled up to V_{DD}
- when the drain voltage is below V_{DD}, the Schottky diode is forward biased and the sensed voltage is equal to V_{DS} plus the diode voltage drop that generates a positive voltage shift

Figure 3. V_{DS} sensing circuit



The output of this sensing stage is shown below: the $V_{DS\_SENSING}$ amplitude is limited to V_{DD} range and the section where the body diode is forward biased is appropriately shifted and suitable for being sensed.

Figure 4. V_{DS} sensing signals



The pull-up resistor limits the current during the diode forward biasing: the pull-up and its associated capacitor (see Figure 1) create a discrete low pass filter that can be used to filter noise on the sensing network.

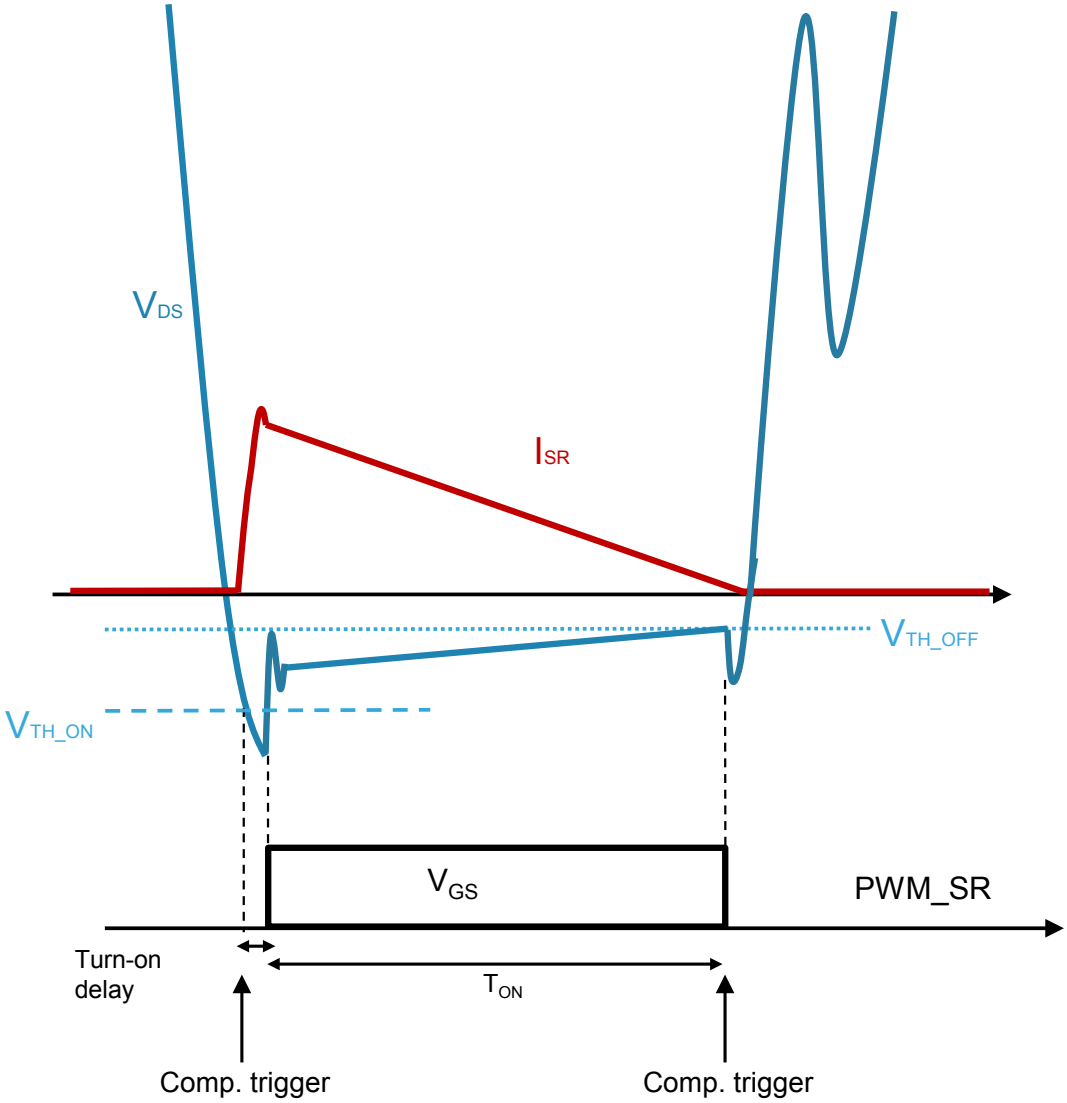
Two comparators are usually used to detect the beginning and the end of body diode conduction: the first is triggered by the falling edge of V_{DS} voltage and the second is used to detect the V_{DS} rise due to a falling I_{SR}.

As a result, two thresholds could be defined to correctly drive the power MOSFET:

- when V_{DS} decreases below the V_{TH_ON} threshold, the first comparator is triggered
- when the second comparator rises above the V_{TH_OFF} threshold, the MOSFET turns off

During the turn-on time, $V_{DS} = I_{SR}*R_{DS\_on}$ and is linear for a flyback converter.

Figure 5. **Comparator thresholds**



1.2 Blanking windows

Once the first comparator has been triggered, the V_{GS} gate drive output rises to turn M_{SR} on and performs active rectification. Undesired noises from spikes or oscillations due to commutation can trigger the second comparator and cause erroneous MOSFET switch-off events. A blanking window on the second comparator responsible for M_{SR} turn-off can be added to avoid false triggering after MOSFET turn-on due to rising voltage, ensuring a minimum turn-on time of the MOSFET.

Similar behavior can occur after MOSFET turn-off: the V_{DS} may fall due to the body diode activation, and voltage ringing could trigger an undesired turn-on due to discontinuous conduction mode at light load, causing the output capacitor to discharge. A blanking window on the first comparator (responsible for M_{SR} turn-on) can be added after the second (turn-off) trigger event, ensuring a minimum turn-off time.

If blanking windows are properly defined, the same threshold value can be used for both comparators (V_{TH_ON}=V_{TH_OFF}=$V_{TH\_ON\_OFF}$).

2 Adaptive SR algorithm

If the turn-off threshold is too low, V_{GS} is turned off too early and the positive current causes body conduction to lower the efficiency.

If the turn-off threshold is too high, V_{GS} is turned off too late and the MOSFET is forced to conduct even if the diode is reverse biased, causing shoot-through and voltage ringing that can cause the diode to turn on again (as well as an undesired PWM turn-on if the blanking time is not properly set) and possible damage to the devices involved.

Figure 6. V_{GS} turned off too early

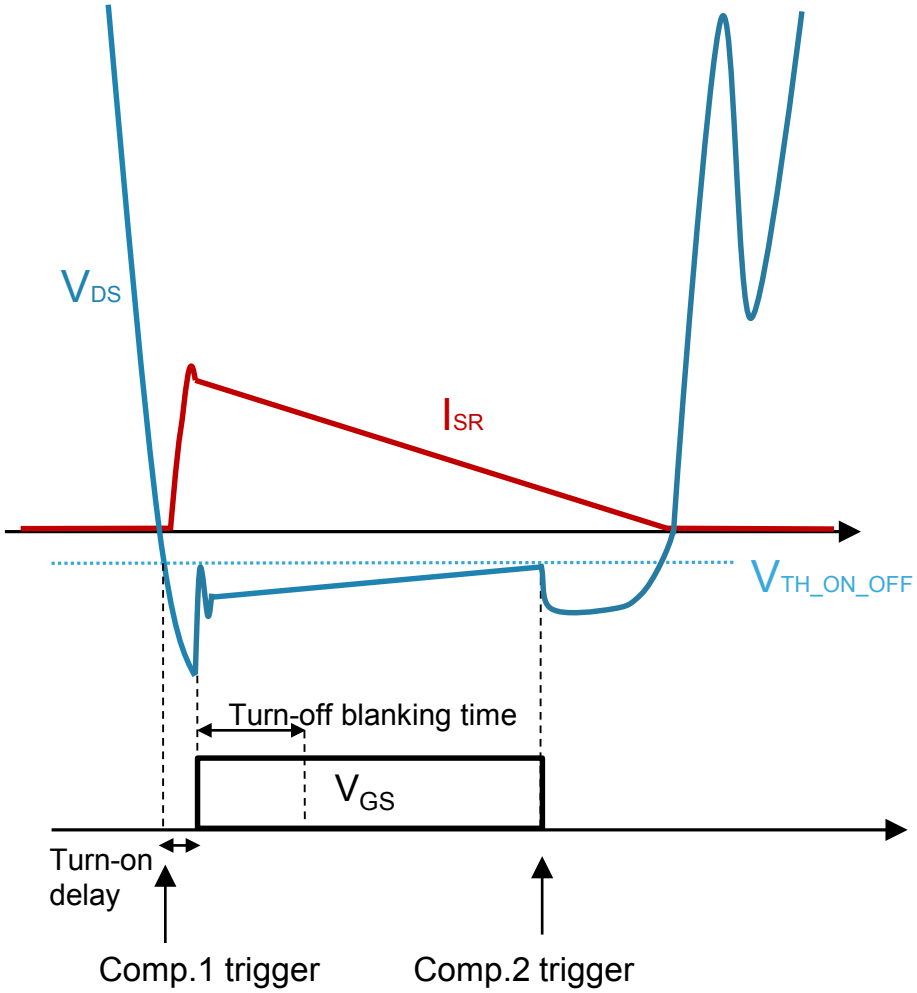
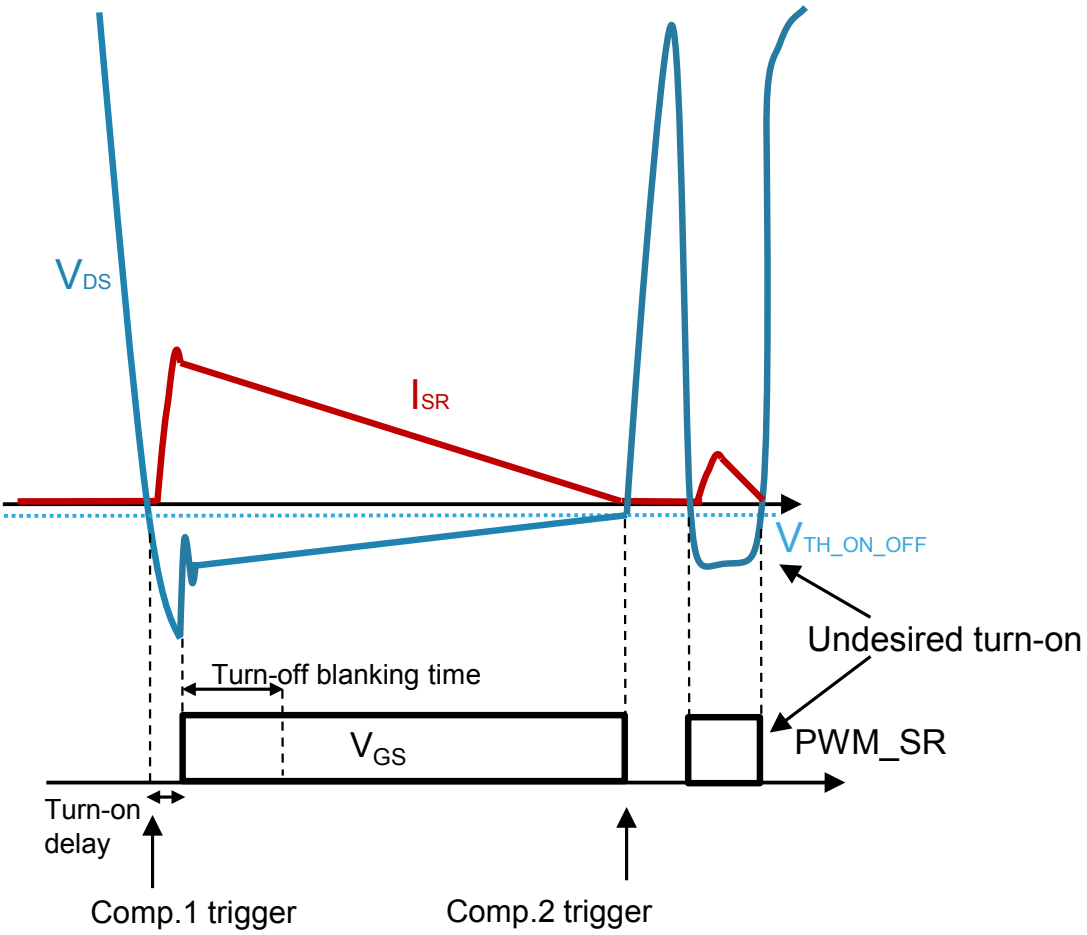


Figure 7. V_{GS} turned off too late



In flyback converters, signal shapes and timing may vary according to many parameters, including output load and voltage, input voltage and switching frequency. Fixed frequency flyback converters may change operation from discontinuous conduction mode (DCM) operation at light loads to continuous conduction mode (CCM) operation at heavier loads. Variable frequency converters during quasi resonant (QR) operation (with or without valley skipping) are subject to resonance due to primary inductance and total parasitic capacitance across the primary switch after transformer demagnetization.

Most controllers on the market also use operating frequency modulation to optimize EMI filters.

An adaptive synchronous rectification (ASR) algorithm minimizes body diode conduction time and maximizes converter efficiency. In this ST patented adaptive algorithm, the MOSFET T_{ON} duration is automatically maximized regardless of the parametric tolerances and load variations.

It is possible to determine whether the turn-off threshold setting is appropriate by sampling the V_{DS} from V_{GS} turn-off, after a delay which is used to correctly sense the V_{DS} after the MOSFET turn-off. A threshold on the V_{DS} value can be used:

- if the acquired V_{DS} value is lower than the threshold, the SR MOSFET is turned off too early, allowing the diode conduct and consequently losing efficiency, as shown in Figure 8
- if the acquired V_{DS} value is higher than the threshold, the SR MOSFET is turned off too late, forcing it to conduct more than necessary, as shown in Figure 9

Figure 8. **SR MOSFET turned off too early**

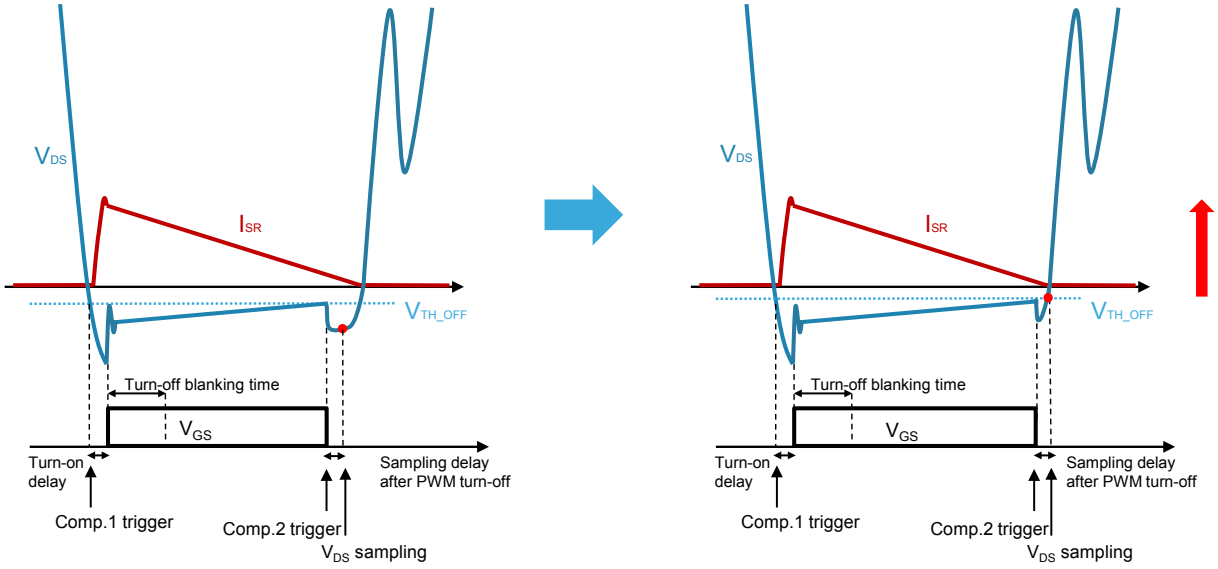
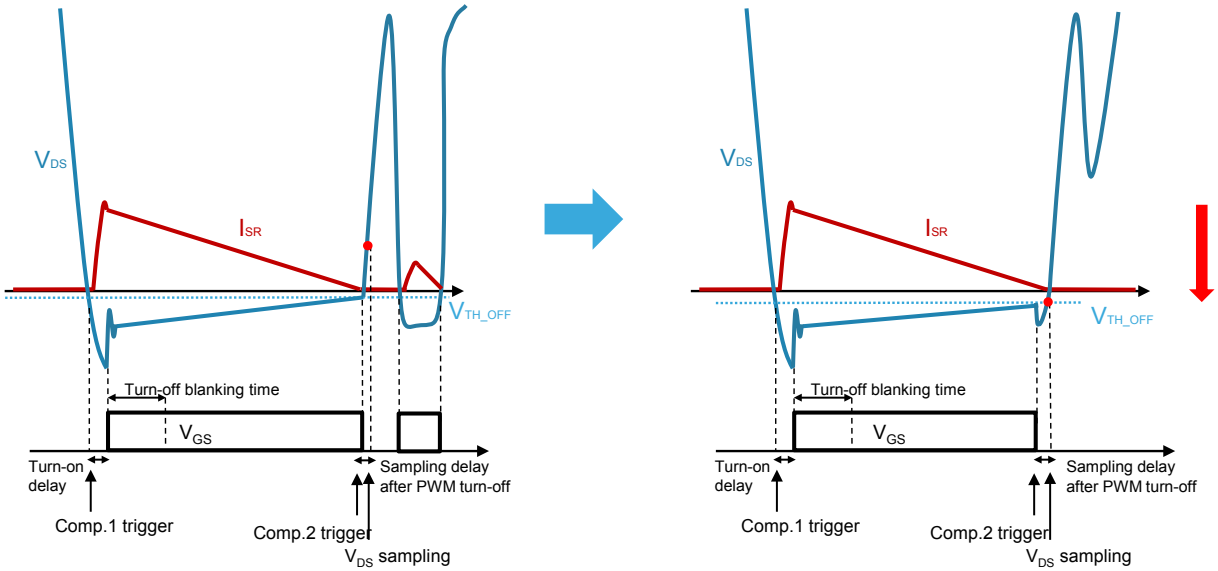


Figure 9. **SR MOSFET turned off too late**



3 Adaptive synchronous rectification setup

The SR algorithm requires several parameters, including thresholds, timing, MCU peripheral parameters, and V_{DS} sensing circuit components associated with the flyback configuration.

The steps below are general guidelines that should be adapted to your specific application.

Step 1. Set the flyback converter up according to required specifications (output voltage, current, etc.)

Step 2. Choose the same voltage rating of the Schottky diode of V_{DS} sensing network, as the maximum V_{DS} and the maximum MOSFET V_{DS} on the secondary side are fixed by the flyback topology.

Step 3. Turn the converter on without any load to determine V_{DS} and $V_{DS\_SENSING}$ voltages and to tune the sensing circuit (pull-up resistor and filter capacitor).

Note: Follow this step to also adjust RC parameters and estimate the comparator turn-on threshold and the turn-off blanking time according to V_{DS} residual ringing.

Step 4. Turn the TIM_SR timer on and set a maximum turn-on time equal to or lower than the turn-off blanking time.

The MOSFET is turned on for a short amount of time regardless of the turn-off threshold.

Step 5. Gradually increase the turn-on time to reach V_{DS}, as shown in Figure 2.

The turn-off threshold is identified.

Step 6. Activate the second comparator with the threshold identified in the previous step.

Step 7. Set the blanking time for the first comparator equal to the turn-off blanking time, taking the V_{DS} waveform as reference.

Step 8. Repeat steps 4-7 with a different output voltage, if available, and for different loads up to the maximum available to check all time parameters and identify turn-off threshold ranges, blanking times, T_{ON} range.

Step 9. Before turning off the adaptive algorithm, check the V_{DS} shape and set the time to trigger ADC conversions after MOSFET turn-off.

Important:
The adaptive SR algorithm must always start with the lowest turn-off threshold to ensure the safest operating condition, that is T_{ON} is not optimized and the body diode is conducting for a long period after MOSFET turn-off.

Note: The adaptive SR algorithm can periodically run.

4 Adaptive SR implementation with STM32

The sensing circuit shown in Figure 1 and described in Section 1.1 can provide a $V_{DS\_SENSING}$ signal with an amplitude suitable for an MCU domain. This signal must be connected to an analog pin and is connected to the MCU internal comparators, as shown in Figure 10. One or two comparators can be used on the basis of the STM32 comparator availability or user requirements.

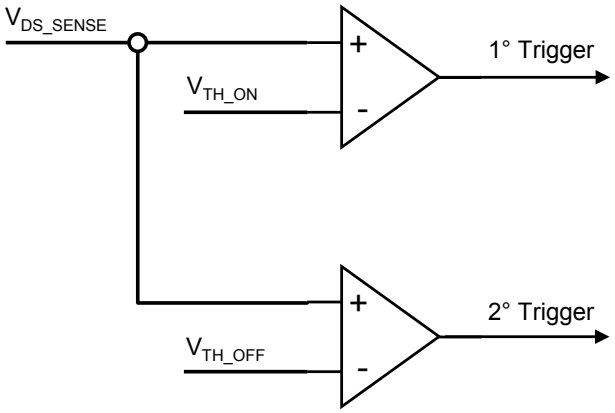
When using two comparators, assume the two relevant thresholds (V_{TH_ON} and V_{TH_OFF}) are translated into MCU V_{DD} domain.

The two comparators must be configured in window mode to share the same non-inverting input. The corresponding thresholds are applied to detect the two trigger conditions:

- the V_{DS} decreasing below V_{TH_ON}
- the V_{DS} increasing above V_{TH_OFF}, which means current falling to zero

As shown in Figure 10, the first comparator detects the falling edge and the second detects the turn-off condition.

Figure 10. Comparator setup



The two thresholds can be generated by the STM32 internal DAC as well as by the available internal reference voltage if suitable.

To actively control the SR MOSFET, the timer (TIM_SR) PWM output is used and configured in one-pulse mode (OPM). This mode allows starting the counter and generating a single pulse with a programmable length (maximum MOSFET turn-on time) after a programmable delay that corresponds to the turn-on delay.

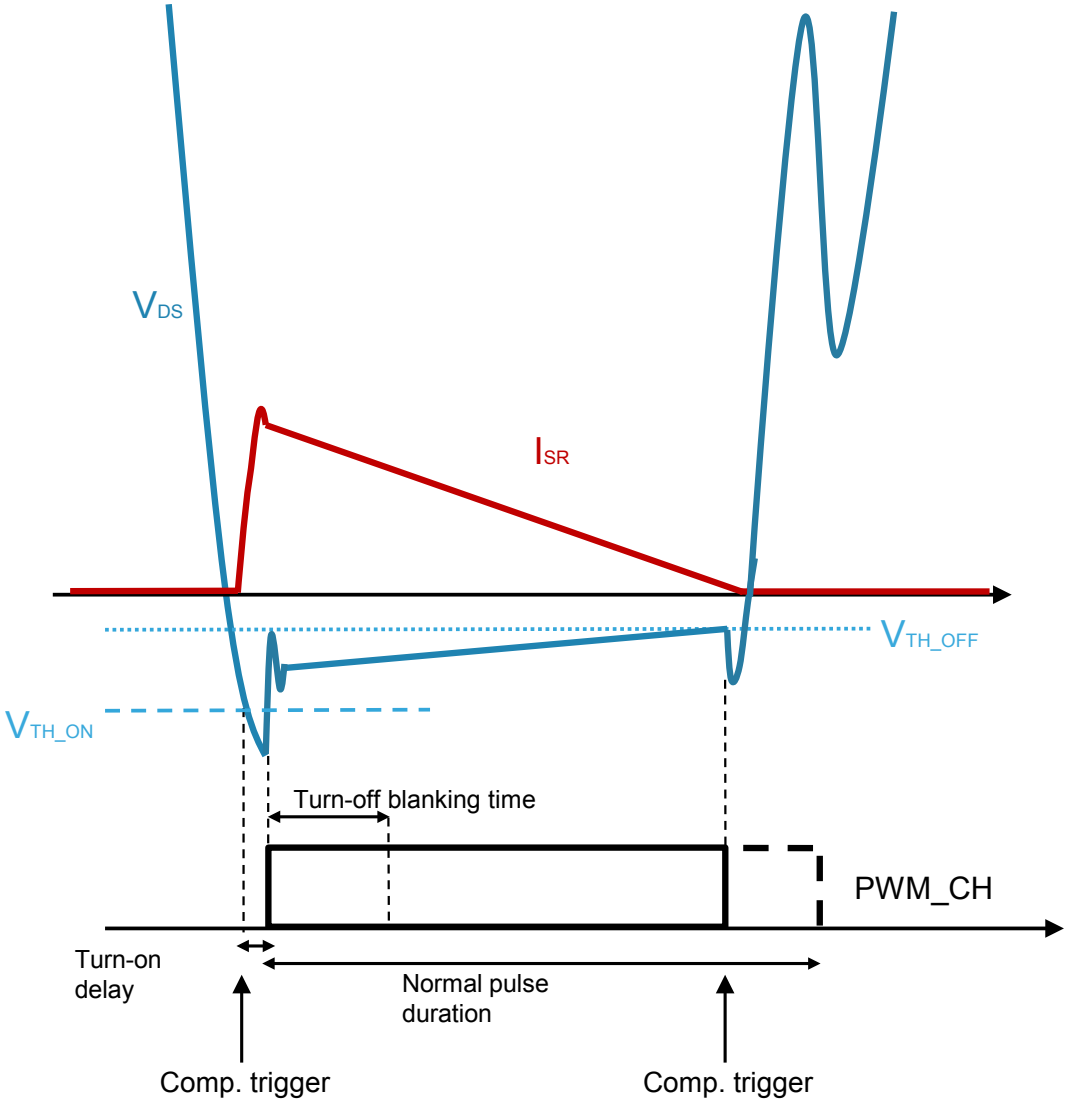
The first comparator resets and triggers the TIM_SR that works as the slave. [**Reset**] reinitializes the counter whereas [**Trigger**] starts it.

The second trigger output drives the OCxREF_clr signal to force PWM output to idle state until the end of the programmed period or the next update event: once the second trigger has occurred, the output channel is low until the next update event (SR MOSFET turn-off).

With this timer configuration, each time V_{DS} falls below V_{TH_ON}, it triggers a new PWM signal driving the SR MOSFET up to the second trigger event (see Figure 11. Timer output). The timer and output channel registers (Prescaler, Capture, etc.) must be configured to ensure the longest T_{ON} period exposed by the flyback converter.

Note: This PWM signal assures that the MOSFET is put in idle state even if comparator events are not detected.

Figure 11. **Timer output**



TIM_SR drives the SR MOSFET using:

- TRG_CH channel as a trigger to start the counter
- PWM_CH channel to drive the SR MOSFET
- OCxREF_clr signal to clear PWM_CH channel

If only one comparator is used, set the hardware up to use only one threshold for edge detection to avoid changing the threshold. The comparator output setup can be updated after each trigger event using the available DMA or IRQ as the comparator outputs are internally connected to the EXTI controller.

4.1 Blanking windows in the adaptive SR implementation

As described in Section 1.2 Blanking windows, blanking windows ensure overall robustness and damage prevention. Blanking action must be performed on comparators.

If the STM32 used has no blanking features on the comparators, IRQ handler function called by trigger interrupt must be activated to apply blanking features to the comparator through a dedicated code.

Note: Use a small amount of code (or DMA transfers) as these routines are called upon each trigger event.

If the on-board comparators offer blanking features, they are usually linked to timer channels: an additional channel of TIM_SR can be used for blanking features. You should set the appropriate period to perform blanking on the comparator by detecting the second trigger event as shown in Figure 11.

When using a channel from the same timer, the blanking time for SR MOSFET turn-on and turn-off are synchronized.

If TIM_SR also performs the second comparator blanking, it uses:

- TRG_CH channel as a trigger to start the counter
- PWM_CH channel to drive the SR MOSFET
- BLANK2_CH channel to blank the second comparator
- OCxREF signal to clear PWM_CH channel

Turning the blanking time on avoids undesired MOSFET activation due to V_{DS} ringing after MOSFET turn-off, by using a second timer (TIM_OFF).

Like the TIM_SR timer, the TIM_OFF timer should be configured in one-pulse mode (OPM). The trigger output of the second comparator should be used to reset and start it. One channel of this timer can perform a blanking window on the first comparator, focusing on the time duration to ensure the correct setup of turn-on triggers.

TIM_OFF uses:

- TRG_CH channel as a trigger to start the counter
- BLANK1_CH channel to blank the first comparator

4.2 Adaptive SR algorithm

As described in Section 2 Adaptive SR algorithm, MOSFET body diode conduction time must be minimized to ensure better performance. The optimum MOSFET T_{ON} duration can be achieved with an adaptive synchronous rectification (ASR) algorithm regardless of parametric tolerance and load variations.

In the patented ST implementation, MOSFET turn-off is driven by a second comparator using the turn-off threshold (V_{TH_OFF}). It is possible to determine whether turn-off threshold is set correctly by sampling the V_{DS} after a programmed delay from V_{GS} turn-off.

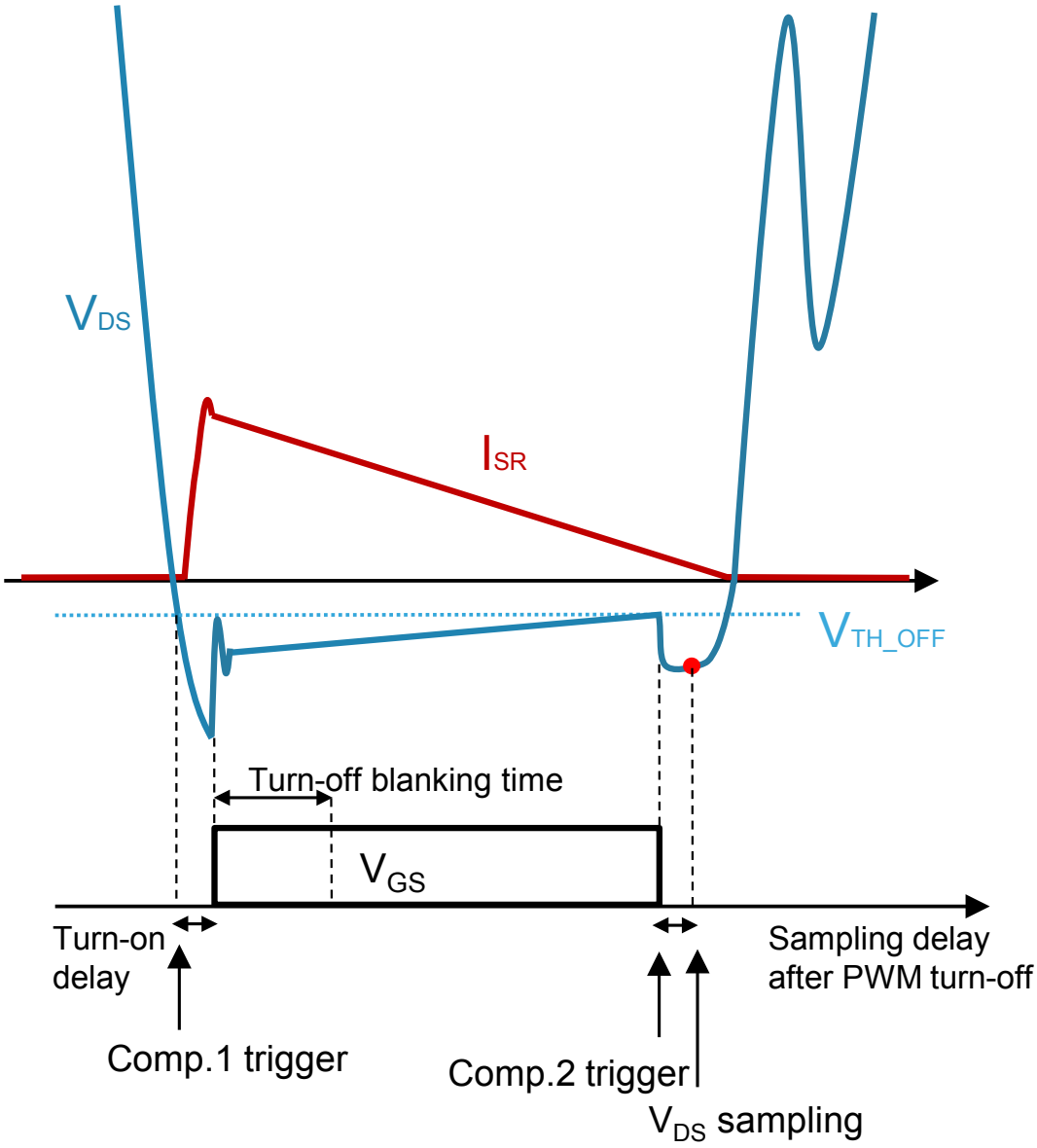
A third channel of the TIM_OFF timer can be used. The timer is triggered by the turn-off event, so you can set another channel to trigger ADC conversion after a specified amount of time. You have to set the appropriate time delay to obtain samples on the first rising edge of the V_{DS}, avoiding meaningless values sampled on the ringing V_{DS}. The V_{DS} voltage suffers from noise and oscillations whose amplitude and frequency depend on too many variables, including hardware setup, load conditions, voltage output, etc. Wrong V_{DS} samples may prohibit the adaptive algorithm from converging.

When the adaptive SR algorithm is running, the time delay represents the safe diode conduction time after MOSFET turn-off.

If TIM_OFF also triggers the ADC, it uses:

- TRG_CH channel as a trigger to start the counter
- BLANK1_CH channel to blank the first comparator
- ADC_TRG_CH channel to trigger ADC acquisition

Figure 12. V_{DS} sampling



5 Example of implementation

Figure 13 shows an SR cycle of V_{DS} and V_{GS} signals in a real use case implementation.

When the $V_{DS\_SENSING}$ is falling, the TIM_SR starts and, after the turn-on delay, the PWM signal (in yellow in the figure below) turns the SR MOSFET on. When the MOS is turned on, the voltage drop is lower than the forward voltage drop of the internal body diode. After that, the V_{DS} and the $V_{DS\_SENSING}$ (in blue in the figure below) decrease.

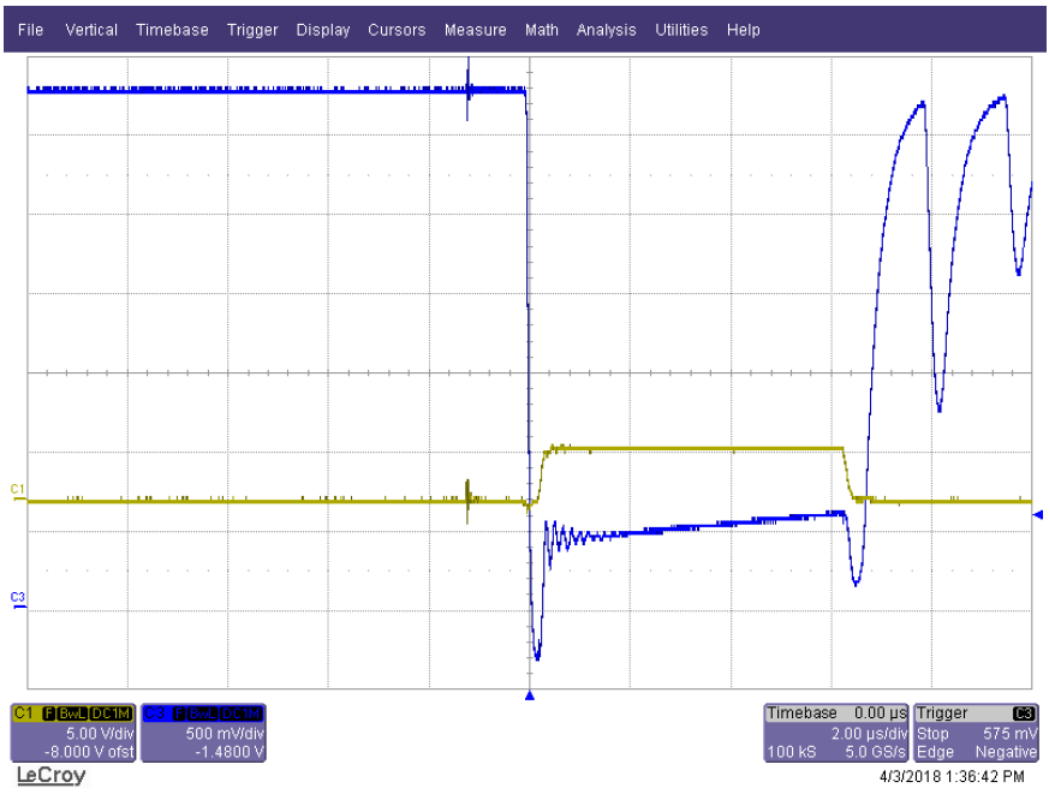
To prevent slight oscillation from causing undesired turn-off, the first blanking window is applied.

The current flowing through the device decreases and lowers V_{DS} and $V_{DS\_SENSING}$, approaching the turn-off threshold that drives the TIM_SR to stop the PWM.

Once the MOS is turned off, enabling the body diode to conduct again, a glitch occurs in the $V_{DS\_SENSING}$ signal, due to the diode forward voltage.

To avoid MOS turn-on by the glitch and other oscillations in the V_{DS}, a blanking window at turn-off is applied.

Figure 13. Experimental results: $V_{DS\_SENSING}$ and V_{GS}



6 Conclusions

The implementation of the Synchronous Rectification algorithm on specific STM32 MCUs with appropriate peripherals can help deliver higher power efficiency, and lower conduction losses and thermal dissipation in end applications.

To fulfill all operating conditions, an adaptive algorithm ensures the best possible performance.

The following elements are key to successful implementation:

- V_{DS} sensing stage used to monitor MOSFET operating conditions
- appropriate comparators used to get triggering events
- the timer driving the SR MOSFET
- blanking windows to protect the application against malfunction

Revision history

Table 1. **Document revision history**

Date	Version	Changes
23-Jun-2020	1	Initial release.

Contents

List of figures