AN6477

Application note

Introduction to Capacitive Charging Mode (CCM) across ST eFuse families

Introduction

This application note provides a general introduction to the Capacitive Charging Mode (CCM) implemented in ST eFuse products. It describes the purpose of CCM, identifies the ST eFuse families that support it, and summarizes the main differences among the corresponding implementations.

CCM is available across three ST eFuse families:

- Monolithic eFuses
- Hybrid eFuses
- eFuse controllers

Although the CCM concept is common across these families, its practical implementation, configurability, and interaction with protections depend on the underlying device architecture.

In a monolithic eFuse, the high-side power switch and the related control circuitry are integrated in a single silicon die. In a hybrid eFuse, the high-side power switch stage and the related control circuitry are implemented in two separate silicon dice within the same device. In an eFuse controller, only the control and protection functions are integrated, while the external high-side power switch is implemented in the application.

This note is intended as an overview document and as an introduction to the family specific application notes:

- AN6395 for the monolithic eFuse family.
- AN6396 for the hybrid eFuse family.
- AN6392 for the eFuse controller family.

Together, this document and the related family-specific application notes show how the same CCM concept is implemented across different product architectures, each optimized for specific current levels, integration approaches, and application constraints.

1 CCM features description

In automotive power distribution systems, many loads connected to the battery rail exhibit a significant input capacitance. Examples include electronic control units, sensor modules, domain controllers, downstream DC-DC converters, and other smart loads connected behind an eFuse. When these loads are switched on, the charging of the input capacitor can generate a high inrush current. If not properly managed, this transient can lead to unwanted current limitation, premature intervention of protection functions, voltage disturbances on the supply rail, or unnecessary electrical and thermal stress on both the power switch and the load.

To address this condition, ST has developed CCM (Capacitive Charging Mode), a proprietary control algorithm implemented across multiple eFuse product families. CCM is available, for example, in:

- Monolithic eFuses, such as VNF9D5SF and VNF9Q20SF
- Hybrid eFuses, such as VNF9D1M2Q, VNF9D1M5Q and VNF9D3Q
- eFuse controllers, such as VNF1248F

The purpose of CCM is to improve the management of capacitive loads during turn-on. Instead of handling capacitor charging as a standard overload event, CCM applies a dedicated control strategy that allows the output capacitor to be charged in a controlled manner while maintaining device protection and preserving overall application robustness. This helps distinguish a legitimate capacitive inrush from fault conditions such as short circuit or persistent overload.

From the application point of view, CCM provides several benefits. It can:

- Support the startup of loads with high input capacitance.
- Reduce unnecessary shutdown or retry behavior during power-up.
- Limit electrical and thermal stress on the switching element.
- Improve system stability during hot-plug or load activation events.
- Simplify system design by extending the usable operating range of protected load driving.

Although the implementation details differ among product families, the CCM concept remains the same: to enable reliable charging of downstream capacitive loads while keeping the eFuse protection framework active. This is especially important in modern automotive architectures, where a protected high-side switch is often required not only to isolate faults, but also to power complex electronic subsystems with nonnegligible input capacitance.

2 Main differences in CCM management among the eFuse families

The main differences in CCM management among eFuse families are:

- Architectural
- Protection strategy
- System design perspective

2.1 Architectural differences

While CCM addresses the same application need across all three product families, namely the controlled charging of downstream capacitive loads during turn-on, its implementation reflects the different architectures of the devices in which it is embedded. As a result, the CCM behavior, available control options, and system-level implications are not identical for eFuse controllers, monolithic eFuses, and hybrid eFuses.

In the monolithic eFuse family, the power stage and control logic are integrated in the same silicon. In this case, CCM benefits from a high degree of integration and simplified application design, since no external pass element is required. The CCM behavior is therefore more tightly linked to the internal characteristics of the device, including the integrated power transistor, internal protection thresholds, and thermal management capability. Compared with a controller-based solution, the monolithic implementation typically offers less external flexibility, but provides a compact and straightforward way to manage capacitive charging with reduced design complexity and a limited number of external components. The detailed operation of CCM for monolithic eFuses is described in AN6395.

The eFuse controller family offers the highest level of flexibility. In this architecture, the control and protection functions are implemented in the controller, while the external power MOSFET defines the main current handling capability and power dissipation. As a consequence, CCM management can be tuned in a way that better matches the application requirements, because the external MOSFET and surrounding circuitry contribute significantly to the overall charging behavior, thermal performance, and safe operating area. This makes the controller-based family particularly suitable for applications requiring scalability, customization, or optimization for higher current and energy levels. The detailed operation of CCM for eFuse controllers is described in AN6392.

The hybrid eFuse family can be considered an intermediate approach between the previous two. It combines a protected and partially integrated architecture with application-level advantages in terms of robustness and integration, while retaining some characteristics that differentiate it from both the fully monolithic and the controller-based solutions. In this family, CCM management is shaped by the hybrid partitioning of functions and by the intended use case of the device. As a result, the charging profile, protection interaction, and achievable capacitive load management may differ from both the monolithic and controller families, even though the CCM objective remains the same. The detailed operation of CCM for hybrid eFuses is described in AN6396.

2.2 Protection strategy differences

A second major difference among the families concerns the interaction between CCM and the protection strategy. In all cases, CCM is intended to support capacitor charging without misinterpreting the inrush current as a fault. However, the way in which the device supervises current, power dissipation, timing, and thermal stress during this phase depends on the internal architecture.

In a controller-based solution, part of the design trade-off is transferred to the choice of the external MOSFET and to the dimensioning of the application. In a monolithic device, these trade-offs are more strongly embedded in the silicon design. In a hybrid device, the balance is application-dependent and follows the product architecture adopted for that family.

2.3 System design perspective

Another key difference lies in the system design perspective. With an eFuse controller, the designer typically has more freedom to optimize the external stage for the target capacitive load, but this also requires a deeper understanding of the application environment and of the component selection criteria. With monolithic and hybrid eFuse devices, CCM can be used in a simpler and more compact design flow, because the main switching element is already integrated and characterized by the device itself.

3 CCM User Parameters

The following tables summarize the main CCM-related parameters for the three eFuse families discussed in this note. Depending on the device architecture, these parameters may be directly programmable by the user, used as control and status indicators, or fixed by the internal CCM implementation and therefore relevant mainly for application dimensioning.

Note: *Reported CMAX values are application-dependent and shall always be interpreted together with the corresponding datasheet conditions, such as supply voltage, junction temperature, timing constraints, ESR, and, where applicable, the selection of the external MOSFET .*

Table 1. CCM parameters for the monolithic eFuse family

Symbol	Parameter	Role	Register field/source	Min.	Typ.	Max.	Unit
CAPCRx	CCM enable for channel x in Normal mode	Control	SOCR[5:2]	—	—	—	—
EXIT_CAPCRx	CCM exit for channel x in Normal mode	Control	SOCR[15:12]	—	—	—	—
CCR	Channel mode prerequisite for CCM	Configuration/ prerequisite	OUTCFGRx[3]	—	Bulb mode required	—	—
MCUext	Fail-safe CCM entry path selection	Configuration	FSITCRx[9]	—	—	—	—
DIx toggling sequence	CCM enable in Fail-safe mode	Control condition	5 rising edges within tCCM_EN	—	—	—	—
CAPCSRx	CCM status bit	Status	OUTSRx[13]	—	—	—	—
ICCM	Charging current	Characteristic	Electrical specification	—	0.4 × ILIMH	—	A
tCCM_DIS	Timing needed to leave Capacitive charging mode	Characteristic	Electrical specification	—	100	—	ms
tCCM_EN	Timing needed to enter Capacitive charging mode	Characteristic	Electrical specification	—	240	—	μs
ΔTPLIM_CCM	Junction-case temperature difference triggering power limitation in CCM	Characteristic	Electrical specification (VNF9Q20SF)	—	30	—	°C
ΔTPLIM_CCM	Junction-case temperature difference triggering power limitation in CCM	Characteristic	Electrical specification (VNF9D5SF)	—	35	—	°C
CMAX	Max. capacitive load	Characteristic	Electrical specification (VNF9Q20SF)	—	2.2	—	mF
CMAX	Max. capacitive load	Characteristic	Electrical specification (VNF9D5SF)	—	3.3	—	mF

Table 2. CCM parameters for the hybrid eFuse family

Symbol	Parameter	Role	Register field/ source	Min.	Typ.	Max.	Unit
CAPCRx	CCM trigger for channel x in Normal mode	Control	SOCR[5:4]	—	—	—	—
EXIT_CAPCRx	CCM exit for channel x in Normal mode	Control	SOCR[3:2]	—	—	—	—

Symbol	Parameter	Role	Register field/ source	Min.	Typ.	Max.	Unit
CAPFSSRx	Automatic CCM start after POR to Fail-safe transition	Configuration/ status	OUTSRx[5]	—	—	—	—
DIx toggling sequence	CCM enable in Fail-safe mode	Control condition	at least 5 rising edges within t_di_mon	—	—	—	—
CAPCSRx	CCM status bit	Status	OUTSRx[10]	—	—	—	—
t_ccm_cycle (TCCM_MAX)	Time to exit from CCM	Characteristic	Electrical specification	200	250	300	ms
t_di_mon	Time window to enter CCM in Fail-safe	Characteristic	Electrical specification	198	300	402	µs
t_filter_ipeak	Filtering time of IPEAK detection	Characteristic	Electrical specification	0.95	1.2	1.45	µs
tLF	Period for low frequency charging mode	Characteristic	Electrical specification	3.4	4.0	4.6	ms
tHF	Period for high frequency charging mode	Characteristic	Electrical specification	0.85	1.0	1.15	ms
MAX_COUNTER_LF	Maximum number of autorestart pulses allowed in short-circuit	Characteristic	Electrical specification	—	—	30	—
VOUT_THR	VOUT threshold for CCM	Characteristic	Electrical specification	-9□	3	9□	V
CMAX	Max. capacitive load	Characteristic	Electrical specification (VNF9D1M2Q, VNF9D1M5Q)	—	10	—	mF
CMAX	Max. capacitive load	Characteristic	Electrical specification (VNF9D3Q)	—	4.7	—	mF

Table 3. **CCM parameters for the eFuse controller family**

Symbol	Parameter	Role	Register field/ source	Min.	Typ.	Max.	Unit
CCM_CTRL_ON	CCM start trigger	Control	CR#1[18]	—	—	—	—
CCM_CTRL_OFF	CCM stop trigger	Control	CR#1[19]	—	—	—	—
CCM_VOUT_THR	VOUT threshold to switch from start charging phase to standard charging phase	Configuration	CR#3[16:14]	1	—	5	V
CCM_PWM_TON_MF	PWM T_on multiplying factor	Configuration	CR#3[19:18]	1	—	8	—
CCM_TIMEOUT	Maximum duration of standard charging phase	Configuration	CR#5[23:22]	200	—	400	ms
CCM_PWM_SC_T_NB	Maximum number of low frequency PWM pulses during start charging phase	Configuration	CR#5[21:17]	5	—	50	pulses

Symbol	Parameter	Role	Register field/ source	Min.	Typ.	Max.	Unit
CCM_PWM_SC_T	PWM period during start charging phase		CR#5[16:14]	2.0	—	4.0	ms
CCM_PWM_TON	PWM T_on setting	Configuration	CR#5[13:8]	1	—	50	µs
CCM_PWM_T	PWM period during standard charging phase	Configuration	CR#5[7:2]	50	—	4000	µs
CCM_STATUS	CCM operation status	Status	SR#1[23:22]		See note (1)		—

(1): *CCM status coding = 00_b: IDLE; 01_b: RUN; 10_b: CHARGED; 11_b: CHARGE INCOMPLETE*

Table 4 provides a compact comparison of the main CCM implementation differences across the three eFuse families.

Table 4. Cross-family comparison of CCM implementation

Feature	eFuse controller family	Monolithic eFuse family	Hybrid eFuse family
Reference device	VNF1248F	VNF9Q20SF/VNF9D5SF	Hybrid eFuse family VNF9D1M2Q/ VNF9D1M5QVNF9D1M5Q/ VNF9D3Q
CCM entry in Normal mode	SPI trigger	SPI trigger	SPI trigger
CCM entry in Fail-safe mode	DIN toggling sequence	DIN toggling sequence	DIN toggling sequence
CCM exit in Normal mode	SPI trigger or completion	SPI trigger or automatic timeout	SPI trigger or automatic timeout
CCM exit in Fail-safe mode	Automatic termination/DIN-dependent CCM stop	Automatic timeout	Automatic timeout
CCM status visibility	Dedicated status field	Dedicated channel status bit	Dedicated channel status bit
User programmability	High	Low	Low
Main CCM tuning items	PWM timing, duty-cycle related parameters, thresholds, timeout	Entry/exit and mode conditions; core CCM behavior internally defined	Entry/exit and mode conditions; core CCM behavior internally defined
Short-circuit discrimination during CCM	Yes, through dedicated start and standard charging phases	Implicit through internal CCM behavior	Yes, through low-frequency to high-frequency charging sequence
Representative max. capacitive load	Depends on external MOSFET and configuration	Up to 2.2 mF / 3.3 mF depending on device	Up to 4.7 mF / 10 mF depending on device
Architectural implication	Highest flexibility, application-dependent dimensioning	Highest integration, reduced tuning freedom	Intermediate approach, algorithm fixed but application-visible

The comparison highlights that the eFuse controller family provides the highest degree of freedom in CCM configuration. For example, in the VNF1248F, the user can tune several CCM timing and threshold parameters through dedicated SPI fields, including PWM period, PWM on-time, multiplying factor, start-phase pulse count, VOUT transition threshold, and time out. This makes the CCM implementation highly adaptable to the selected external MOSFET and to the target capacitive load profile.

The monolithic eFuse family exposes a different philosophy. In devices such as VNF9Q20SF, the user can enable or abort CCM and can select the operating conditions under which CCM is allowed, but the charging current, thermal threshold, entry/exit timing, and maximum supported capacitive load are mostly intrinsic to the device design. As a consequence, the user interacts with CCM mainly as an operating function rather than as a strongly tunable algorithm.

The hybrid eFuse family follows an intermediate approach. In devices such as VNF9D1M5Q, the user can trigger CCM, abort it, observe its status, and rely on a clearly documented charging sequence based on low-frequency and high frequency IPEAK pulses. However, the key CCM behavior remains largely fixed by the internal implementation. Compared with the monolithic family, the hybrid family exposes more detail on the internal CCM sequence, such as the low-frequency and high-frequency charging periods, the IPEAK filtering time, the maximum number of short-circuit retry pulses, and the VOUT threshold used for phase transition.

Overall, the three implementations reflect the architecture of the corresponding product family:

- The monolithic eFuse family emphasizes integration and eases of use
- The hybrid eFuse family emphasizes a predefined but application-visible charging algorithm
- The eFuse controller family emphasizes configurability

4 Conclusions

Although CCM serves the same functional purpose across all three eFuse families, namely the controlled charging of capacitive loads while preserving device and system robustness, the degree of user interaction with the feature is substantially different. For this reason, CCM should not be viewed as a single implementation replicated unchanged across the product portfolio, but rather as a common concept realized through architecture-specific methods.

When selecting a device family, the application designer should therefore consider not only the current and thermal capability of the target solution, but also the expected level of CCM flexibility. Applications requiring strong control over the charging profile are better aligned with the eFuse controller family, while applications prioritizing integration and reduced design complexity can benefit from the monolithic or hybrid approaches.

For implementation details, configuration flow, and application-specific recommendations, the reader should refer to:

- AN6395 for the monolithic eFuse family
- AN6396 for the hybrid eFuse family
- AN6392 for the eFuse controller family

Revision history

Table 5. Document revision history

Date	Revision	Changes
16-Jun-2026	1	First release.

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