



# Dual Intelligent High-current Self-protected Silicon High Side Switch (8.0 mOhm)

The 33988 is a dual self-protected 8.0 mΩ silicon switch used to replace electromechanical relays, fuses and discrete devices in power management applications. The 33988 is designed for harsh environment and includes self-recovery features. The device is suitable for loads with high inrush current, as well as motors and all types of resistive and inductive loads.

Programming, control and diagnostics are implemented via the serial peripheral interface (SPI). A dedicated parallel input is available for alternate and pulse-width modulation (PWM) control of each output. SPI-programmable fault trip thresholds allow the device to be adjusted for optimal performance in the application.

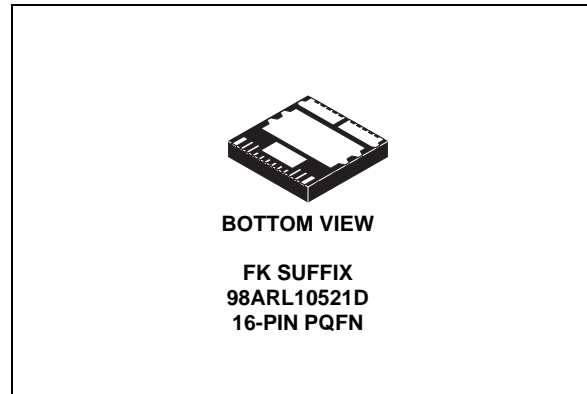
The 33988 is packaged in a power-enhanced 12 x 12 mm nonleadless PQFN package with exposed tabs.

## Features

- Dual 8.0 mΩ max high side switch with parallel input or SPI control
- 6.0 V to 27 V operating voltage with standby currents < 5.0 μA
- Output current monitoring with two SPI-selectable current ratios
- SPI control of over-current limit, over-current fault blanking time, output OFF open load detection, output ON/OFF control, watchdog timeout, slew-rates, and fault status reporting
- SPI status reporting of over-current, open and shorted loads, over-temperature, under-voltage and over-voltage shutdown, fail-safe pin status, and program status
- Enhanced -16 V reverse polarity V<sub>PWR</sub> protection

**33988**

**HIGH SIDE SWITCH**



ORDERING INFORMATION		
Device (For Tape and Reel, add an R2 Suffix)	Temperature Range (T <sub>A</sub> )	Package
MC33988CHFK	-40 °C to 125 °C	16 PQFN

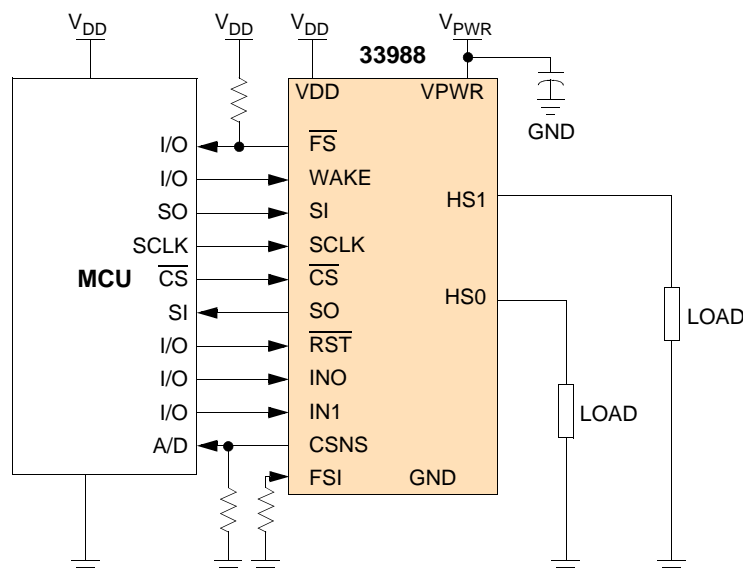


Figure 1. 33988 Simplified Application Diagram

Freescale Semiconductor, Inc. reserves the right to change the detail specifications, as may be required, to permit improvements in the design of its products.

© Freescale Semiconductor, Inc., 2010-2012. All rights reserved.



### INTERNAL BLOCK DIAGRAM

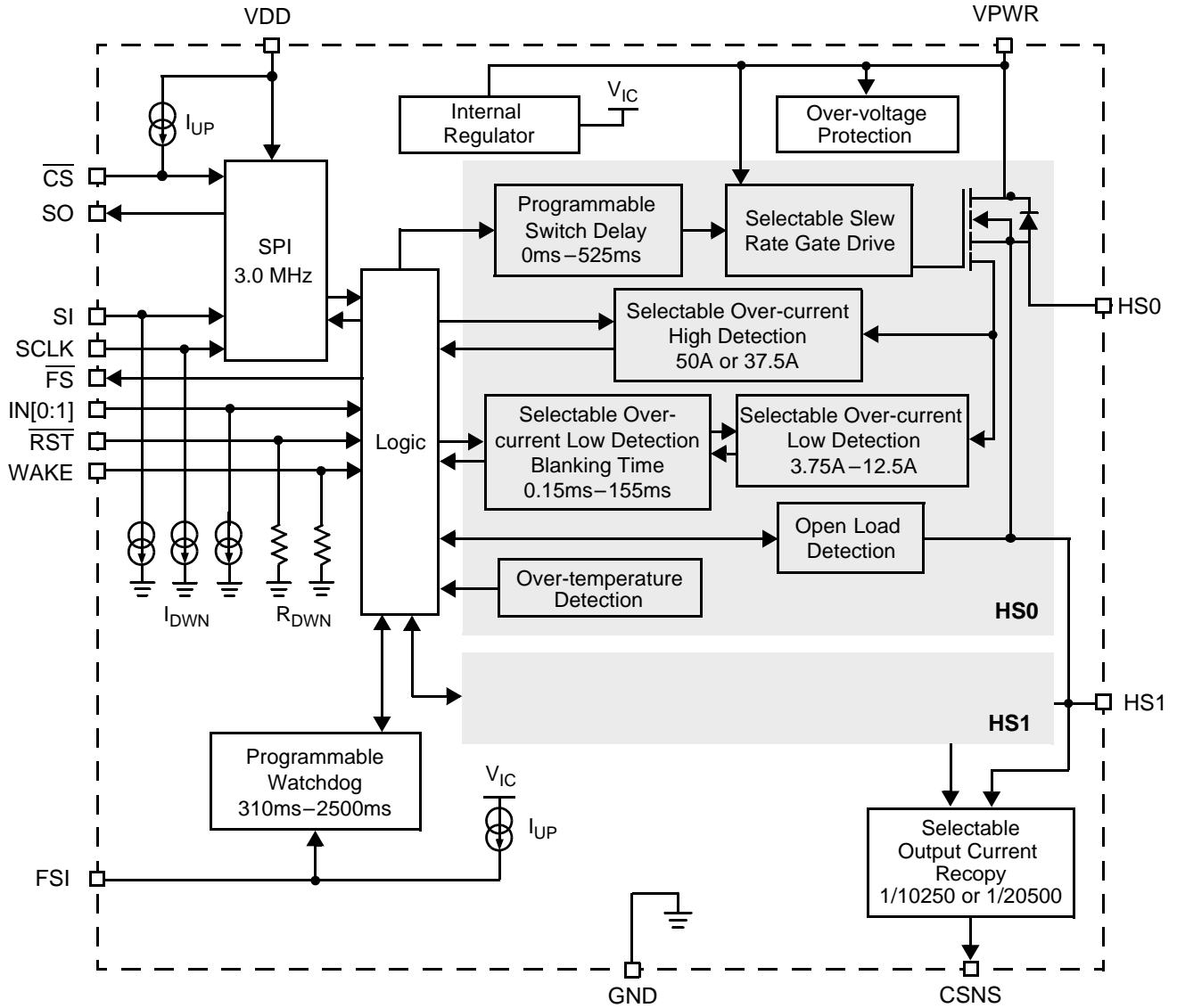


Figure 2. 33988 Simplified Internal Block Diagram

## PIN CONNECTIONS

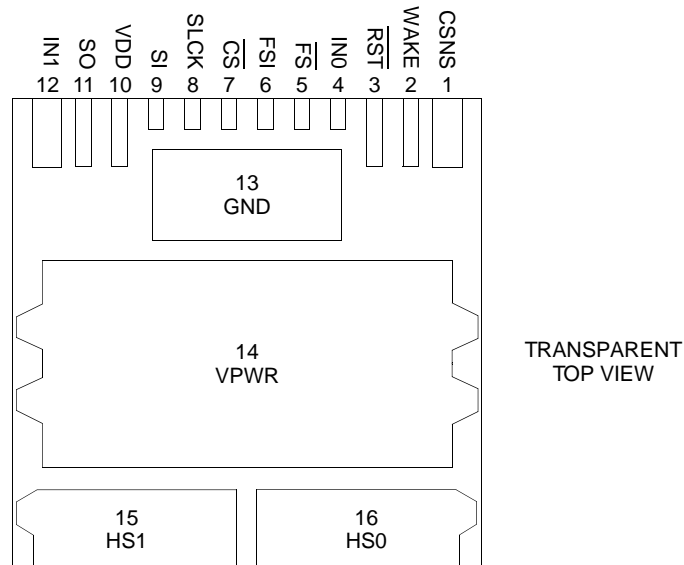


Figure 3. 33988 Pin Connections (Transparent Top View)

Table 1. Pin Definitions

Functional descriptions of many of these pins can be found in the Functional Pin Description section beginning on [page 16](#).

Pin	Pin Name	Pin Function	Formal Name	Definition
1	CSNS	Output	Output Current Monitoring	This pin is used to output a current proportional to the designated HS0-1 output.
2	WAKE	Input	Wake	This pin is used to input a Logic [1] signal so as to enable the watchdog timer function.
3	$\overline{\text{RST}}$	Input	Reset (Active Low)	This input pin is used to initialize the device configuration and fault registers, as well as place the device in a low-current Sleep mode.
4	IN0	Input	Direct Input 0	This input pin is used to directly control the output HS0.
5	$\overline{\text{FS}}$	Output	Fault Status (Active Low)	This is an open drain configured output requiring an external pull-up resistor to $V_{DD}$ for fault reporting.
6	FSI	Input	Fail-Safe Input	The value of the resistance connected between this pin and ground determines the state of the outputs after a watchdog timeout occurs.
7	$\overline{\text{CS}}$	Input	Chip Select (Active Low)	This input pin is connected to a chip select output of a master microcontroller (MCU).
8	SCLK	Input	Serial Clock	This input pin is connected to the MCU providing the required bit shift clock for SPI communication.
9	SI	Input	Serial Input	This is a command data input pin connected to the SPI Serial Data Output of the MCU or to the SO pin of the previous device of a daisy chain of devices.
10	VDD	Input	Digital Drain Voltage (Power)	This is an external voltage input pin used to supply power to the SPI circuit.

**Table 1. Pin Definitions (continued)**

Functional descriptions of many of these pins can be found in the Functional Pin Description section beginning on [page 16](#).

Pin	Pin Name	Pin Function	Formal Name	Definition
11	SO	Output	Serial Output	This output pin is connected to the SPI Serial Data Input pin of the MCU or to the SI pin of the next device of a daisy chain of devices.
12	IN1	Input	Direct Input 1	This input pin is used to directly control the output HS1.
13	GND	Ground	Ground	This pin is the ground for the logic and analog circuitry of the device.
14	VPWR	Input	Positive Power Supply	This pin connects to the positive power supply and is the source input of operational power for the device.
15	HS1	Output	High Side Output 1	Protected 8.0mΩ high side power output to the load.
16	HS0	Output	High Side Output 0	Protected 8.0mΩ high side power output to the load.

## ELECTRICAL CHARACTERISTICS

## MAXIMUM RATINGS

Table 2. Maximum Ratings

All voltages are with respect to ground unless otherwise noted.

Rating	Symbol	Value	Unit
<b>ELECTRICAL RATINGS</b>			
Operating Voltage Range Steady-State	$V_{PWR}$	-16 to 41	V
VDD Supply Voltage	$V_{DD}$	-0.3 to 5.5	V
Input/Output Voltage <sup>(1)</sup>	$V_{IN[0:1]}, \overline{RST}, FSI$ $CSNS, SI, SCLK,$ $\overline{CS}, \overline{FS}$	-0.3 to 7.0	V
SO Output Voltage <sup>(1)</sup>	$V_{SO}$	-0.3 to $V_{DD} + 0.3$	V
WAKE Input Clamp Current	$I_{CL(WAKE)}$	2.5	mA
CSNS Input Clamp Current	$I_{CL(CSNS)}$	10	mA
Output Voltage Positive Negative	$V_{HS}$	41 -15	V
Output Current <sup>(2)</sup>	$I_{HS[0:1]}$	30	A
Output Clamp Energy <sup>(3)</sup>	$E_{CL[0:1]}$	0.37	J
ESD Voltage <sup>(4)</sup> Human Body Model (HBM) Charge Device Model (CDM) Corner Pins (1, 12, 15, 16) All Other Pins (2, 11, 13, 14)	$V_{ESD1}$ $V_{ESD3}$	±2000 ±750 ±500	V

## Notes

- Exceeding this voltage limit may cause permanent damage to the device.
- Continuous high side output current rating so long as maximum junction temperature is not exceeded. Calculation of maximum output current using package thermal resistance is required.
- Active clamp energy using single-pulse method ( $L = 16\text{mH}$ ,  $R_L = 0$ ,  $V_{PWR} = 12\text{V}$ ,  $T_J = 150^\circ\text{C}$ ).
- ESD1 testing is performed in accordance with the Human Body Model (HBM) ( $C_{ZAP} = 100\text{pF}$ ,  $R_{ZAP} = 1500\Omega$ ); ESD3 testing is performed in accordance with the Charge Device Model (CDM), Robotic ( $C_{zap} = 4.0\text{pF}$ ).

**Table 2. Maximum Ratings**

All voltages are with respect to ground unless otherwise noted.

Rating	Symbol	Value	Unit
<b>THERMAL RATINGS</b>			
Operating Temperature			°C
Ambient	$T_A$	-40 to 125	
Junction	$T_J$	-40 to 150	
Storage Temperature	$T_{STG}$	-55 to 150	°C
Thermal Resistance <sup>(5)</sup>			°C/W
Junction-to-Case	$R_{\theta JC}$	<1.0	
Junction-to-Ambient	$R_{\theta JA}$	30	
Peak Package Reflow Temperature During Reflow <sup>(6), (7)</sup>	$T_{PPRT}$	Note 7	°C

Notes

- Device mounted on a 2s2p test board according to JEDEC JESD51-2.
- Pin soldering temperature limit is for 40 seconds maximum duration. Not designed for immersion soldering. Exceeding these limits may cause malfunction or permanent damage to the device.
- Freescale's Package Reflow capability meets Pb-free requirements for JEDEC standard J-STD-020. For Peak Package Reflow Temperature and Moisture Sensitivity Levels (MSL), Go to [www.freescale.com](http://www.freescale.com), search by part number [e.g. remove prefixes/suffixes and enter the core ID to view all orderable parts. (i.e. MC33xxx enter 33xxx), and review parametrics.

**STATIC ELECTRICAL CHARACTERISTICS**

**Table 3. Static Electrical Characteristics**

Characteristics noted under conditions  $4.5V \leq V_{DD} \leq 5.5V$ ,  $6.0V \leq V_{PWR} \leq 27V$ ,  $-40^{\circ}C \leq T_A \leq 125^{\circ}C$ , unless otherwise noted. Typical values noted reflect the approximate parameter mean at  $T_A = 25^{\circ}C$  under nominal conditions, unless otherwise noted.

Characteristic	Symbol	Min	Typ	Max	Unit
<b>POWER INPUT</b>					
Battery Supply Voltage Range Full Operational	$V_{PWR}$	6.0	–	27	V
VPWR Operating Supply Current Output ON, $I_{HS0}$ and $I_{HS1} = 0$ A	$I_{PWR(ON)}$	–	–	20	mA
VPWR Supply Current Output OFF, Open Load Detection Disabled, WAKE > $0.7 \times V_{DD}$ , $RST = V_{LOGIC HIGH}$	$I_{PWR(SBY)}$	–	–	5.0	mA
Sleep State Supply Current ( $V_{PWR} < 14V$ , $\overline{RST} < 0.5V$ , WAKE < 0.5V) $T_J = 25^{\circ}C$ $T_J = 85^{\circ}C$	$I_{PWR(SLEEP)}$	–	–	10 50	$\mu A$
VDD Supply Voltage	$V_{DD(ON)}$	4.5	5.0	5.5	V
VDD Supply Current No SPI Communication 3.0MHz SPI Communication	$I_{DD(ON)}$	–	–	1.0 5.0	mA
VDD Sleep State Current	$I_{DD(SLEEP)}$	–	–	5.0	$\mu A$
Over-voltage Shutdown Threshold	$V_{PWR(OV)}$	28	32	36	V
Over-voltage Shutdown Hysteresis	$V_{PWR(OVHYS)}$	0.2	0.8	1.5	V
Under-voltage Output Shutdown Threshold <sup>(8)</sup>	$V_{PWR(UV)}$	5.0	5.5	6.0	V
Under-voltage Hysteresis <sup>(9)</sup>	$V_{PWR(UVHYS)}$	–	0.25	–	V
Under-voltage Power-ON Reset	$V_{PWR(UVPOR)}$	–	–	5.0	V

Notes

8. This applies to all internal device logic supplied by  $V_{PWR}$  and assumes the external  $V_{DD}$  supply is within specification.
9. This applies when the under-voltage fault is not latched ( $IN[0:1] = 0$ ).

**Table 3. Static Electrical Characteristics (continued)**

Characteristics noted under conditions  $4.5V \leq V_{DD} \leq 5.5V$ ,  $6.0V \leq V_{PWR} \leq 27V$ ,  $-40^{\circ}C \leq T_A \leq 125^{\circ}C$ , unless otherwise noted. Typical values noted reflect the approximate parameter mean at  $T_A = 25^{\circ}C$  under nominal conditions, unless otherwise noted.

Characteristic	Symbol	Min	Typ	Max	Unit
<b>POWER OUTPUT</b>					
Output Drain-to-Source ON Resistance ( $I_{HS[0:1]} = 7.5A$ , $T_J = 25^{\circ}C$ ) $V_{PWR} = 6.0V$ $V_{PWR} = 10V$ $V_{PWR} = 13V$	$R_{DS(ON)}$	–	–	12.0 8.0 8.0	m $\Omega$
Output Drain-to-Source ON Resistance ( $I_{HS[0:1]} = 7.5A$ , $T_J = 150^{\circ}C$ ) $V_{PWR} = 6.0V$ $V_{PWR} = 10V$ $V_{PWR} = 13V$	$R_{DS(ON)}$	–	–	20.4 13.6 13.6	m $\Omega$
Output Source-to-Drain ON Resistance $I_{HS[0:1]} = 7.5A$ , $T_J = 25^{\circ}C$ <sup>(10)</sup> $V_{PWR} = -12V$	$R_{DS(ON)}$	–	–	16.0	m $\Omega$
Output Over-current High Detection Levels ( $9.0V \leq V_{PWR} \leq 16V$ ) SOCH = 0 SOCH = 1	$I_{OCH0}$ $I_{OCH1}$	40 30	50 37.5	60 45	A
Over-current Low Detection Levels (SOCL[2:0]) 000 001 010 011 100 101 110 111	$I_{OCL0}$ $I_{OCL1}$ $I_{OCL2}$ $I_{OCL3}$ $I_{OCL4}$ $I_{OCL5}$ $I_{OCL6}$ $I_{OCL7}$	10.5 9.0 8.0 7.0 6.0 5.0 4.0 3.0	12.5 11.25 10.0 8.75 7.5 6.25 5.0 3.75	14.5 13.5 12.0 10.5 9.0 7.5 6.0 4.5	A
Current Sense Ratio ( $9.0V \leq V_{PWR} \leq 16V$ , $CSNS \leq 4.5V$ ) DICR D2 = 0 DICR D2 = 1	$C_{SR0}$ $C_{SR1}$	– –	1/10250 1/20500	– –	–
Current Sense Ratio ( $C_{SR0}$ ) Accuracy Output Current 2.5A 5.0A 6.25A 7.5A 10.0A 12.5A	$C_{SR0\_ACC}$	–20 –14 –13 –12 –13 –13	– – – – – –	20 14 13 12 13 13	%

Notes

10. Source-Drain ON Resistance (Reverse Drain-to-Source ON Resistance) with negative polarity  $V_{PWR}$ .



**Table 3. Static Electrical Characteristics (continued)**

Characteristics noted under conditions  $4.5V \leq V_{DD} \leq 5.5V$ ,  $6.0V \leq V_{PWR} \leq 27V$ ,  $-40^{\circ}C \leq T_A \leq 125^{\circ}C$ , unless otherwise noted. Typical values noted reflect the approximate parameter mean at  $T_A = 25^{\circ}C$  under nominal conditions, unless otherwise noted.

Characteristic	Symbol	Min	Typ	Max	Unit
<b>POWER OUTPUT (CONTINUED)</b>					
Current Sense Ratio ( $C_{SR1}$ ) Accuracy Output Current	$C_{SR1\_ACC}$				%
2.5A		-25	–	25	
5.0A		-19	–	19	
6.25A		-18	–	18	
7.5A		-17	–	17	
10.0A		-18	–	18	
12.5A		-18	–	18	
Current Sense Clamp Voltage CSNS Open; $I_{HS[0:1]} = 15A$	$V_{CL(CSNS)}$	4.5	6.0	7.0	V
Open Load Detection Current <sup>(11)</sup>	$I_{OLDC}$	30	–	100	$\mu A$
Output Fault Detection Threshold Output Programmed OFF	$V_{OLD(THRES)}$	2.0	3.0	4.0	V
Output Negative Clamp Voltage $0.5A \leq I_{HS[0:1]} \leq 2.0A$ , Output OFF	$V_{CL}$	-20	–	-15	V
Over-temperature Shutdown <sup>(12)</sup>	$T_{SD}$	160	175	190	$^{\circ}C$
Over-temperature Shutdown Hysteresis <sup>(12)</sup>	$T_{SD(HYS)}$	5.0	–	20	$^{\circ}C$

Notes

- Output OFF Open Load Detection Current is the current required to flow through the load for the purpose of detecting the existence of an open load condition when the specific output is commanded OFF.
- Guaranteed by process monitoring. Not production tested.

**Table 3. Static Electrical Characteristics (continued)**

Characteristics noted under conditions  $4.5V \leq V_{DD} \leq 5.5V$ ,  $6.0V \leq V_{PWR} \leq 27V$ ,  $-40^{\circ}C \leq T_A \leq 125^{\circ}C$ , unless otherwise noted. Typical values noted reflect the approximate parameter mean at  $T_A = 25^{\circ}C$  under nominal conditions, unless otherwise noted.

Characteristic	Symbol	Min	Typ	Max	Unit
<b>CONTROL INTERFACE</b>					
Input Logic High-voltage <sup>(13)</sup>	$V_{IH}$	$0.7V_{DD}$	–	–	V
Input Logic Low-voltage <sup>(13)</sup>	$V_{IL}$	–	–	$0.2V_{DD}$	V
Input Logic Voltage Hysteresis <sup>(14)</sup>	$V_{IN[0:1](HYS)}$	100	600	1200	mV
Input Logic Pull-down Current (SCLK, IN, SI)	$I_{DWN}$	5.0	–	20	$\mu A$
$\overline{RST}$ Input Voltage Range	$V_{\overline{RST}}$	4.5	5.0	5.5	V
SO, $\overline{FS}$ Tri-state Capacitance <sup>(15)</sup>	$C_{SO}$	–	–	20	pF
Input Logic Pull-down Resistor ( $\overline{RST}$ ) and WAKE	$R_{DWN}$	100	200	400	k $\Omega$
Input Capacitance <sup>(15)</sup>	$C_{IN}$	–	4.0	12	pF
WAKE Input Clamp Voltage <sup>(16)</sup> $I_{CL(WAKE)} < 2.5 \text{ mA}$	$V_{CL(WAKE)}$	7.0	–	14	V
WAKE Input Forward Voltage $I_{CL(WAKE)} = -2.5 \text{ mA}$	$V_{F(WAKE)}$	-2.0	–	-0.3	V
SO High-state Output Voltage $I_{OH} = 1.0 \text{ mA}$	$V_{SOH}$	$0.8V_{DD}$	–	–	V
$\overline{FS}$ , SO Low-state Output Voltage $I_{OL} = -1.6 \text{ mA}$	$V_{SOL}$	–	0.2	0.4	V
SO Tri-state Leakage Current $\overline{CS} > 0.7 \times V_{DD}$	$I_{SO(LEAK)}$	-5.0	0	5.0	$\mu A$
Input Logic Pull-up Current <sup>(17)</sup> $\overline{CS}, V_{IN[0:1]} > 0.7 \times V_{DD}$	$I_{UP}$	5.0	–	20	$\mu A$
FSI Input Pin External Pull-down Resistance	RFS				k $\Omega$
FSI Disabled, HS[0:1] Indeterminate	$RFS_{DIS}$	–	0	1.0	
FSI Enabled, HS[0:1] OFF	$RFS_{OFFOFF}$	6.0	6.5	7.0	
FSI Enabled, HS0 ON, HS1 OFF	$RFS_{ONOFF}$	15	17	19	
FSI Enabled, HS[0:1] ON	$RFS_{ONON}$	40	Infinite	–	

Notes

- Upper and lower logic threshold voltage range applies to SI,  $\overline{CS}$ , SCLK,  $\overline{RST}$ , IN[0:1], and WAKE input signals. The WAKE and  $\overline{RST}$  signals may be supplied by a derived voltage reference to  $V_{PWR}$ .
- No hysteresis on FSI and wake pins. Parameter is guaranteed by processing monitoring but is not production tested.
- Input capacitance of SI,  $\overline{CS}$ , SCLK,  $\overline{RST}$ , and WAKE. This parameter is guaranteed by process monitoring but is not production tested.
- The current must be limited by a series resistance when using voltages  $> 7.0V$ .
- Pull-up current is with  $\overline{CS}$  OPEN.  $\overline{CS}$  has an active internal pull-up to  $V_{DD}$ .

## DYNAMIC ELECTRICAL CHARACTERISTICS

Table 4. Dynamic Electrical Characteristics

Characteristics noted under conditions  $4.5V \leq V_{DD} \leq 5.5V$ ,  $6.0V \leq V_{PWR} \leq 27V$ ,  $-40^{\circ}C \leq T_A \leq 125^{\circ}C$ , unless otherwise noted. Typical values noted reflect the approximate parameter mean at  $T_A = 25^{\circ}C$  under nominal conditions, unless otherwise noted.

Characteristic	Symbol	Min	Typ	Max	Unit
<b>POWER OUTPUT TIMING</b>					
Output Rising Slow Slew Rate A (DICR D3 = 0) <sup>(18)</sup> 9.0V < V <sub>PWR</sub> < 16V	SR <sub>RA_SLOW</sub>	0.3	1.0	2.0	V/ $\mu$ s
Output Rising Slow Slew Rate B (DICR D3 = 0) <sup>(19)</sup> 9.0V < V <sub>PWR</sub> < 16V	SR <sub>RB_SLOW</sub>	0.12	0.4	1.2	V/ $\mu$ s
Output Rising Fast Slew Rate A (DICR D3 = 1) <sup>(18)</sup> 9.0V < V <sub>PWR</sub> < 16V	SR <sub>RA_FAST</sub>	0.6	1.6	6.4	V/ $\mu$ s
Output Rising Fast Slew Rate B (DICR D3 = 1) <sup>(19)</sup> 9.0V < V <sub>PWR</sub> < 16V	SR <sub>RB_FAST</sub>	0.12	0.4	4.8	V/ $\mu$ s
Output Falling Slow Slew Rate A (DICR D3 = 0) <sup>(18)</sup> 9.0V < V <sub>PWR</sub> < 16V	SR <sub>FA_SLOW</sub>	0.3	1.0	2.0	V/ $\mu$ s
Output Falling Slow Slew Rate B (DICR D3 = 0) <sup>(19)</sup> 9.0V < V <sub>PWR</sub> < 16V	SR <sub>FB_SLOW</sub>	0.12	0.4	1.2	V/ $\mu$ s
Output Falling Fast Slew Rate A (DICR D3 = 1) <sup>(18)</sup> 9.0V < V <sub>PWR</sub> < 16V	SR <sub>FA_FAST</sub>	1.2	3.2	6.4	V/ $\mu$ s
Output Falling Fast Slew Rate B (DICR D3 = 1) <sup>(19)</sup> 9.0V < V <sub>PWR</sub> < 16V	SR <sub>FB_FAST</sub>	0.4	1.4	4.8	V/ $\mu$ s
Output Turn-ON Delay Time in Fast/Slow Slew Rate <sup>(20)</sup> DICR = 0, DICR = 1	t <sub>DLY(ON)</sub>	1.0	8.0	30	$\mu$ s
Output Turn-OFF Delay Time in Slow Slew Rate Mode <sup>(21)</sup> DICR = 0	t <sub>DLY_SLOW(OFF)</sub>	5	57	125	$\mu$ s
Output Turn-OFF Delay Time in Fast Slew Rate Mode <sup>(21)</sup> DICR = 1	t <sub>DLY_FAST(OFF)</sub>	2.0	15	50	$\mu$ s
Direct Input Switching Frequency (DICR D3 = 0)	f <sub>PWM</sub>	–	300	–	Hz

## Notes

18. Rise and Fall Slew Rates A measured across a 5.0 $\Omega$  resistive load at high side output = 0.5V to V<sub>PWR</sub> -3.5V. These parameters are guaranteed by process monitoring.
19. Rise and Fall Slew Rates B measured across a 5.0 $\Omega$  resistive load at high side output = V<sub>PWR</sub> -3.5V to V<sub>PWR</sub> -0.5V. These parameters are guaranteed by process monitoring.
20. Turn-ON delay time measured from rising edge of IN[0:1] signal that would turn the output ON to V<sub>HS[0:1]</sub> = 0.5V with R<sub>L</sub> = 5.0 $\Omega$  resistive load.
21. Turn-OFF delay time measured from falling edge that would turn the output OFF to V<sub>HS[0:1]</sub> = V<sub>PWR</sub> -0.5V with R<sub>L</sub> = 5.0 $\Omega$  resistive load.

**Table 4. Dynamic Electrical Characteristics (continued)**

Characteristics noted under conditions  $4.5V \leq V_{DD} \leq 5.5V$ ,  $6.0V \leq V_{PWR} \leq 27V$ ,  $-40^{\circ}C \leq T_A \leq 125^{\circ}C$ , unless otherwise noted. Typical values noted reflect the approximate parameter mean at  $T_A = 25^{\circ}C$  under nominal conditions, unless otherwise noted.

Characteristic	Symbol	Min	Typ	Max	Unit
<b>POWER OUTPUT TIMING (CONTINUED)</b>					
Overcurrent Detection Blanking Time (OCLT[1:0])					ms
00	$t_{OCL0}$	108	155	202	
01	$t_{OCL1}$	7.0	10	13	
10	$t_{OCL2}$	0.8	1.2	1.6	
11	$t_{OCL3}$	0.08	0.15	0.25	
Overcurrent High Detection Blanking Time	$t_{OCH}$	1.0	10	20	$\mu s$
$\overline{CS}$ to CSNS Valid Time <sup>(22)</sup>	$t_{CNSVAL}$	–	–	10	$\mu s$
HS1 Switching Delay Time (OSD[2:0])					ms
000	$t_{OSD0}$	–	0	–	
001	$t_{OSD1}$	55	75	95	
010	$t_{OSD2}$	110	150	190	
011	$t_{OSD3}$	165	225	285	
100	$t_{OSD4}$	220	300	380	
101	$t_{OSD5}$	275	375	475	
110	$t_{OSD6}$	330	450	570	
111	$t_{OSD7}$	385	525	665	
HS0 Switching Delay Time (OSD[2:0])					ms
000	$t_{OSD0}$	–	0	–	
001	$t_{OSD1}$	–	0	–	
010	$t_{OSD2}$	110	150	190	
011	$t_{OSD3}$	110	150	190	
100	$t_{OSD4}$	220	300	380	
101	$t_{OSD5}$	220	300	380	
110	$t_{OSD6}$	330	450	570	
111	$t_{OSD7}$	330	450	570	
Watchdog Timeout (WD[1:0]) <sup>(23)</sup>					ms
00	$t_{WDTO0}$	434	620	806	
01	$t_{WDTO1}$	207	310	403	
10	$t_{WDTO2}$	1750	2500	3250	
11	$t_{WDTO3}$	875	1250	1625	

Notes

22. Time necessary for the CSNS to be within  $\pm 5\%$  of the targeted value.
23. Watchdog timeout delay measured from the rising edge of WAKE to  $\overline{RST}$  from a sleep state condition to output turn-ON with the output driven OFF and FSI floating. The values shown are for WDR setting of [00]. The accuracy of  $t_{WDTO}$  is consistent for all configured watchdog timeouts.

**Table 4. Dynamic Electrical Characteristics (continued)**

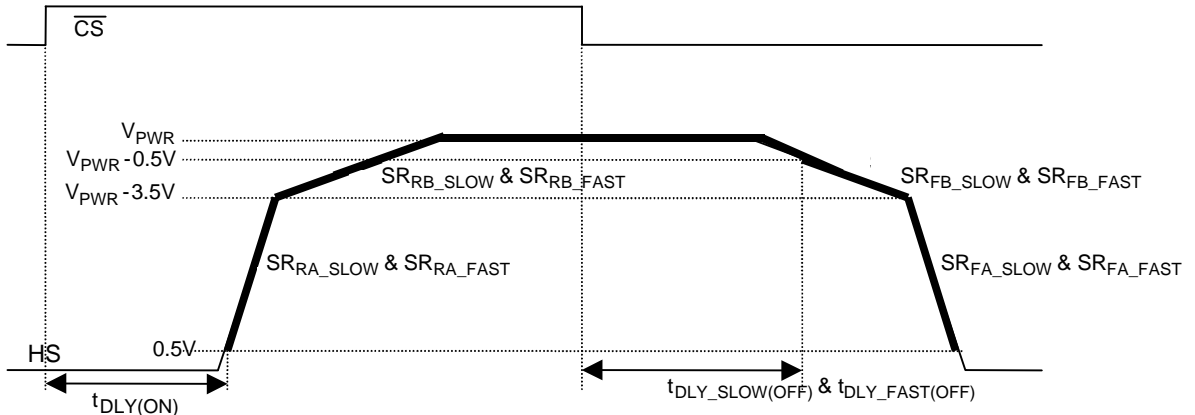
Characteristics noted under conditions  $4.5V \leq V_{DD} \leq 5.5V$ ,  $6.0V \leq V_{PWR} \leq 27V$ ,  $-40^{\circ}C \leq T_A \leq 125^{\circ}C$ , unless otherwise noted. Typical values noted reflect the approximate parameter mean at  $T_A = 25^{\circ}C$  under nominal conditions, unless otherwise noted.

Characteristic	Symbol	Min	Typ	Max	Unit
<b>SPI INTERFACE CHARACTERISTICS</b>					
Recommended Frequency of SPI Operation	$f_{SPI}$	–	–	3.0	MHz
Required Low State Duration for $\overline{RST}^{(24)}$	$t_{WRST}$	–	50	350	ns
Rising Edge of $\overline{CS}$ to Falling Edge of $\overline{CS}$ (Required Setup Time) <sup>(25)</sup>	$t_{CS}$	–	–	300	ns
Rising Edge of $\overline{RST}$ to Falling Edge of $\overline{CS}$ (Required Setup Time) <sup>(25)</sup>	$t_{ENBL}$	–	–	5.0	$\mu s$
Falling Edge of $\overline{CS}$ to Rising Edge of SCLK (Required Setup Time) <sup>(25)</sup>	$t_{LEAD}$	–	50	167	ns
Required High State Duration of SCLK (Required Setup Time) <sup>(25)</sup>	$t_{WSCLKh}$	–	–	167	ns
Required Low State Duration of SCLK (Required Setup Time) <sup>(25)</sup>	$t_{WSCLKl}$	–	–	167	ns
Falling Edge of SCLK to Rising Edge of $\overline{CS}$ (Required Setup Time) <sup>(25)</sup>	$t_{LAG}$	–	50	167	ns
SI to Falling Edge of SCLK (Required Setup Time) <sup>(26)</sup>	$t_{SI(SU)}$	–	25	83	ns
Falling Edge of SCLK to SI (Required Setup Time) <sup>(26)</sup>	$t_{SI(HOLD)}$	–	25	83	ns
SO Rise Time $C_L = 200pF$	$t_{RSO}$	–	25	50	ns
SO Fall Time $C_L = 200pF$	$t_{FSO}$	–	25	50	ns
SI, $\overline{CS}$ , SCLK, Incoming Signal Rise Time <sup>(26)</sup>	$t_{RSI}$	–	–	50	ns
SI, $\overline{CS}$ , SCLK, Incoming Signal Fall Time <sup>(26)</sup>	$t_{RSI}$	–	–	50	ns
Time from Falling Edge of $\overline{CS}$ to SO Low-impedance <sup>(27)</sup>	$t_{SO(EN)}$	–	–	145	ns
Time from Rising Edge of $\overline{CS}$ to SO High-impedance <sup>(28)</sup>	$t_{SO(DIS)}$	–	65	145	ns
Time from Rising Edge of SCLK to SO Data Valid <sup>(29)</sup> $0.2 \times V_{DD} \leq SO \leq 0.8 \times V_{DD}$ , $C_L = 200pF$	$t_{VALID}$	–	65	105	ns

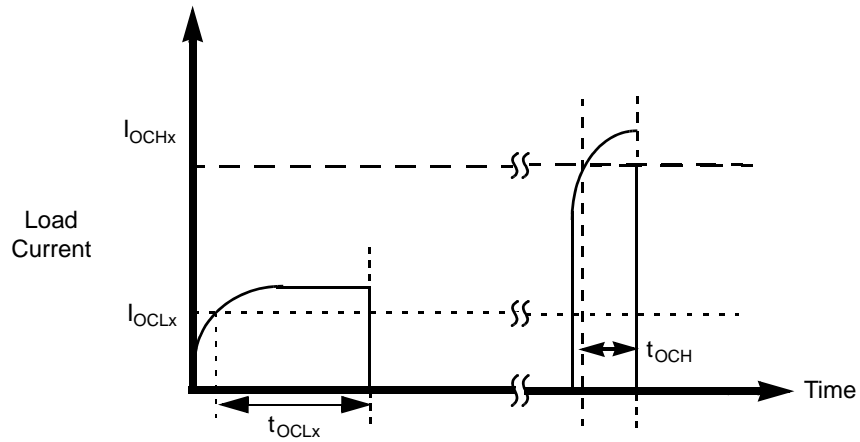
Notes

24.  $\overline{RST}$  low duration measured with outputs enabled and going to OFF or disabled condition.
25. Maximum setup time required for the 33988 is the minimum guaranteed time needed from the microcontroller.
26. Rise and Fall time of incoming SI,  $\overline{CS}$ , and SCLK signals suggested for design consideration to prevent the occurrence of double pulsing.
27. Time required for output status data to be available for use at SO. 1.0k $\Omega$  on pull-up on  $\overline{CS}$ .
28. Time required for output status data to be terminated at SO. 1.0k $\Omega$  on pull-up on  $\overline{CS}$ .
29. Time required to obtain valid data out from SO following the rise of SCLK.

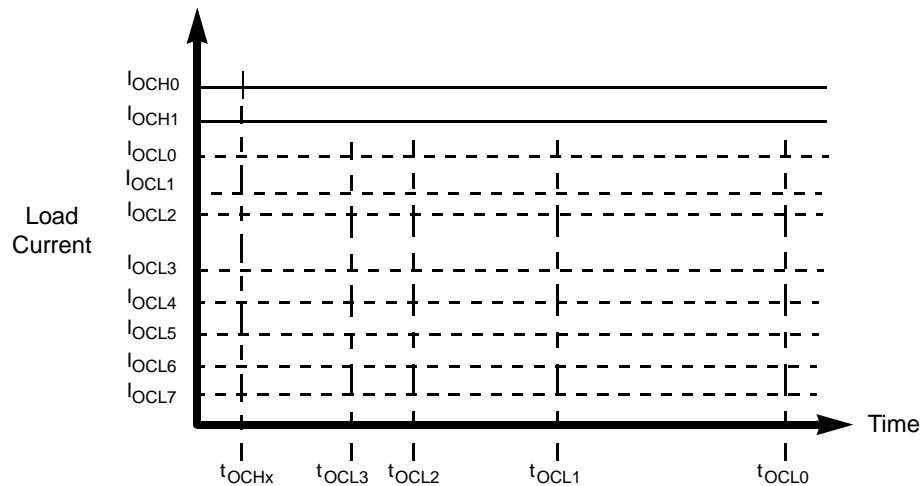
**TIMING DIAGRAMS**



**Figure 4. Output Slew Rate and Time Delays**



**Figure 5. Overcurrent Shutdown**



**Figure 6. Over-current Low and High Detection**

Figure 6 illustrates the over-current detection level ( $I_{OCLX}$ ,  $I_{OCHX}$ ) the device can reach for each over-current detection blanking time ( $t_{OCHX}$ ,  $t_{OCLX}$ ):

- During  $t_{OCHX}$ , the device can reach up to  $I_{OCH0}$  over-current level.
- During  $t_{OCL3}$  or  $t_{OCL2}$  or  $t_{OCL1}$  or  $t_{OCL0}$ , the device can be programmed to detect up to  $I_{OCL0}$ .

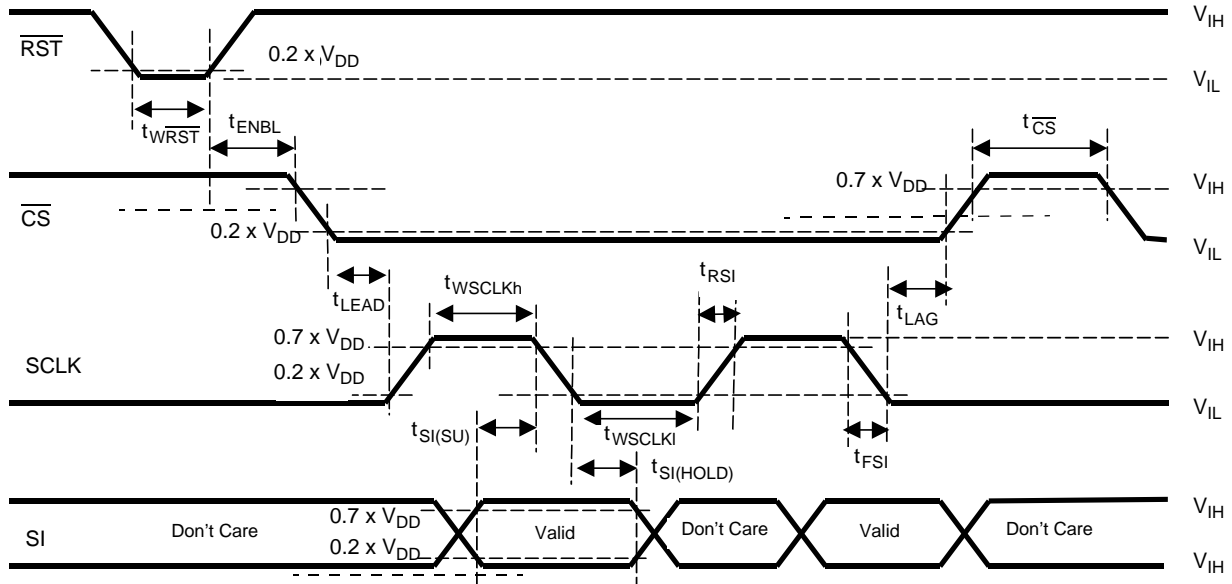


Figure 7. Input Timing Switching Characteristics

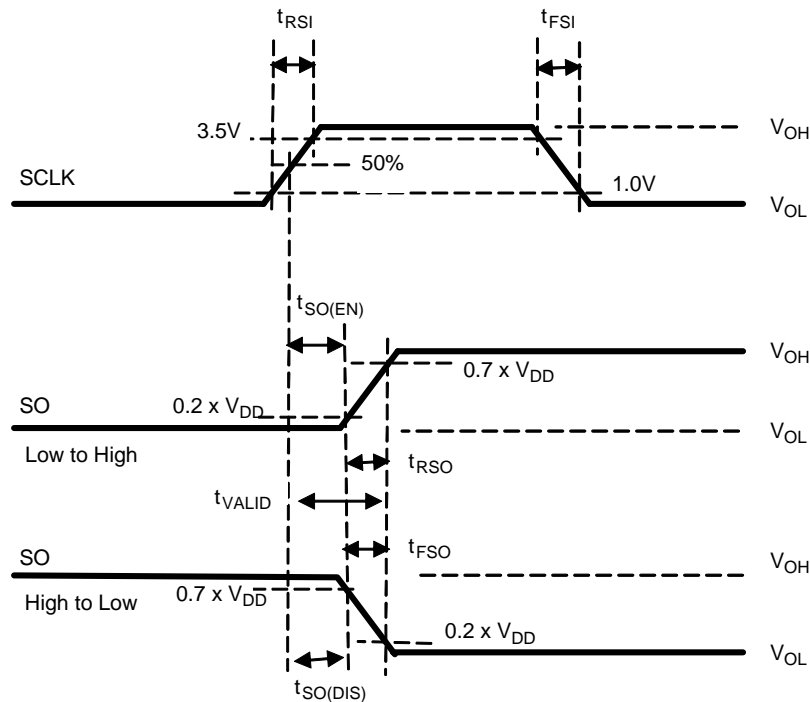


Figure 8. SCLK Waveform and Valid SO Data Delay Time

## FUNCTIONAL DESCRIPTION

### INTRODUCTION

The 33988 is a dual self-protected 8.0mΩ silicon switch used to replace electromechanical relays, fuses, and discrete devices in power management applications. The 33988 is designed for harsh environments, and includes self-recovery features. The device is suitable for loads with high inrush current, as well as motors and all types of resistive and inductive loads.

Programming, control, and diagnostics are implemented via the Serial Peripheral Interface (SPI). A dedicated parallel input is available for alternate and Pulse Width Modulation (PWM) control of each output. SPI-programmable fault trip thresholds allow the device to be adjusted for optimal performance in the application.

The 33988 is packaged in a power-enhanced 12 x 12 nonlead PQFN package with exposed tabs.

### FUNCTIONAL PIN DESCRIPTION

#### OUTPUT CURRENT MONITORING (CSNS)

This pin is used to output a current proportional to the designated HS0-1 output. That current is fed into a ground-referenced resistor and its voltage is monitored by an MCU's A/D. The channel to be monitored is selected via the SPI. This pin can be tri-stated through the SPI.

#### WAKE (WAKE)

This pin is used to input a Logic [1] signal so as to enable the watchdog timer function. An internal clamp protects this pin from high damaging voltages when the output is current limited with an external resistor. This input has a passive internal pull-down.

#### RESET ( $\overline{\text{RST}}$ )

This input pin is used to initialize the device configuration and fault registers, as well as place the device in a low-current Sleep mode. The pin also starts the watchdog timer when transitioning from Logic LOW to Logic HIGH. This pin should not be allowed to be Logic HIGH until  $V_{DD}$  is in regulation. This pin has a passive internal pull-down.

#### DIRECT IN 0 & 1 (INx)

This input pin is used to directly control the output HS0 and 1. This input has an active internal pull-down current source and requires CMOS logic levels. This input may be configured via the SPI.

#### FAULT STATUS ( $\overline{\text{FS}}$ )

This is an open drain configured output requiring an external pull-up resistor to  $V_{DD}$  for fault reporting. When a device fault condition is detected, this pin is active LOW. Specific device diagnostic faults are reported via the SPI SO pin.

#### FAIL-SAFE INPUT (FSI)

The value of the resistance connected between this pin and ground determines the state of the outputs after a

watchdog timeout occurs. Depending on the resistance value, either all outputs are OFF, ON, or the output HS0 only is ON. When the FSI pin is connected to GND, the watchdog circuit and fail-safe operation are disabled. This pin incorporates an active internal pull-up current source.

#### CHIP SELECT ( $\overline{\text{CS}}$ )

This input pin is connected to a chip select output of a master microcontroller (MCU). The MCU determines which device is addressed (selected) to receive data by pulling the  $\overline{\text{CS}}$  pin of the selected device Logic LOW, enabling SPI communication with the device. Other *unselected* devices on the serial link having their  $\overline{\text{CS}}$  pins pulled-up Logic HIGH disregard the SPI communication data sent. This pin incorporates an active internal pull-up current source.

#### SERIAL CLOCK (SCLK)

This input pin is connected to the MCU providing the required bit shift clock for SPI communication. It transitions one time per bit transferred at an operating frequency,  $f_{SPI}$ , defined by the communication interface. The 50 percent duty cycle CMOS-level serial clock signal is idle between command transfers. The signal is used to shift data into and out of the device. This input has an active internal pull-down current source.

#### SERIAL INPUT (SI)

This is a command data input pin connected to the SPI Serial Data Output of the MCU or to the SO pin of the previous device of a daisy chain of devices. The input requires CMOS logic-level signals and incorporates an active internal pull-down current source. Device control is facilitated by the input's receiving the MSB first of a serial 8-bit control command. The MCU ensures data is available upon the falling edge of SCLK. The logic state of SI present upon the rising edge of SCLK loads that bit command into the internal command shift register.



**DIGITAL DRAIN VOLTAGE (VDD)**

This is an external voltage input pin used to supply power to the SPI circuit. In the event  $V_{DD}$  is lost, an internal supply provides power to a portion of the logic, ensuring limited functionality of the device. All device configuration registers are reset.

**SERIAL OUTPUT (SO)**

This output pin is connected to the SPI Serial Data Input pin of the MCU or to the SI pin of the next device of a daisy chain of devices. This output will remain tri-stated (high-impedance OFF condition) so long as the  $\overline{CS}$  pin of the device is Logic HIGH. SO is only active when the  $\overline{CS}$  pin of the device

is asserted Logic LOW. The generated SO output signals are CMOS logic levels. SO output data is available on the falling edge of SCLK and transitions immediately on the rising edge of SCLK.

**POSITIVE POWER SUPPLY (VPWR)**

This pin connects to the positive power supply and is the source input of operational power for the device. The VPWR pin is a backside surface mount tab of the package.

**HIGH-SIDE OUTPUT 0 & 1 (HSx)**

This pin protects 8.0m $\Omega$  high-side power output to the load.

## FUNCTIONAL INTERNAL BLOCK DESCRIPTION

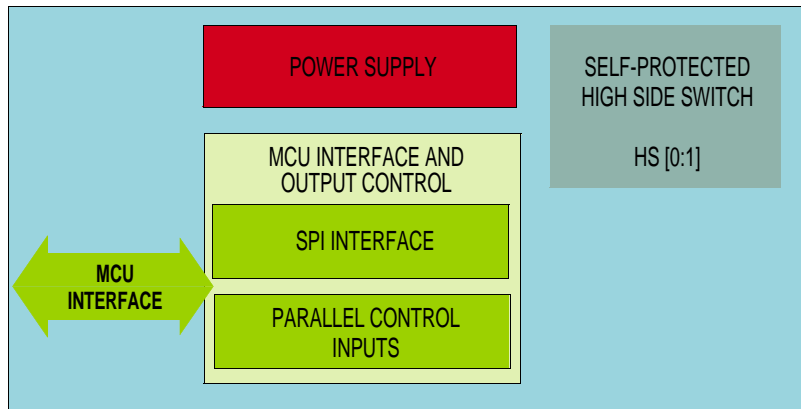


Figure 9. Functional Internal Block Diagram

### POWER SUPPLY

The 33988 is designed to operate from 4.0V to 28V on the VPWR pin. Characteristics are provided from 6.0V to 20V for the device. The VPWR pin supplies power to internal regulator, analog, and logic circuit blocks. The VDD supply is used for Serial Peripheral Interface (SPI) communication in order to configure and diagnose the device. This IC architecture provides a low quiescent current sleep mode. Applying  $V_{PWR}$  and  $V_{DD}$  to the device will place the device in the Normal mode. The device will transit to Fail-safe mode in case of failures on the SPI (watchdog timeout).

### HIGH-SIDE SWITCH: HS[0:1]

Those pins are the high side outputs controlling multiple automotive loads with high inrush current, as well as motors and all types of resistive and inductive loads. This N-channel MOSFET with  $8m\Omega$  RDS(ON), is self-protected and each N-channel presents extended diagnostics in order to detect

load disconnections and short-circuit fault conditions. The HS[0:1] outputs are actively clamped during a turn-off of inductive loads.

### MCU INTERFACE AND OUTPUT CONTROL

In Normal mode, the loads are controlled directly from the MCU through the SPI. With a dedicated SPI command, it is possible to independently turn on and off several loads that are PWM'd at the same frequency, and duty cycles with only one PWM signal. An analog feedback output provides a current proportional to each load current. The SPI is used to configure and to read the diagnostic status (faults) of the high side output. The reported fault conditions are: open load, short-circuit to ground (OCLO-resistive and OCHI-severe short-circuit), thermal shutdown, and under/over-voltage.

In Fail-safe mode, the loads are controlled with dedicated parallel input pins. The device is configured in default mode.

## FUNCTIONAL DEVICE OPERATION

### OPERATIONAL MODES

The 33988 has four operating modes: Sleep, Normal, Fault, and Fail-safe. [Table 5](#) summarizes details contained in succeeding paragraphs.

**Table 5. Fail-Safe Operation and Transitions to Other 33988 Modes**

Mode	$\overline{FS}$	WAKE	RST	WDTO	Comments
Sleep	x	0	0	x	Device is in Sleep mode. All outputs are OFF.
Normal	1	x	1	No	Normal mode. Watchdog is active if enabled.
Fault	0	1	x	No	The device is currently in Fault mode. The faulted output(s) is (are) OFF.
	0	x	1		
Fail-safe	1	0	1	Yes	Watchdog has timed out and the device is in Fail-safe mode. The outputs are as configured with the RFS resistor connected to FSI. $\overline{RST}$ and WAKE must be transitioned to Logic [0] simultaneously to bring the device out of the Fail-safe mode or momentarily tied the FSI pin to ground.
	1	1	1		
	1	1	0		

x = Don't care.

#### SLEEP MODE

The default mode of the 33988 is the Sleep mode. This is the state of the device after first applying battery voltage ( $V_{PWR}$ ), prior to any I/O transitions. This is also the state of the device when the WAKE and  $\overline{RST}$  are both Logic [0]. In the Sleep mode, the output and all unused internal circuitry, such as the internal 5.0 V regulator, are off to minimize current draw. In addition, all SPI-configurable features of the device are as if set to Logic [0]. The device will transition to the Normal or Fail-safe operating modes based on the WAKE and  $\overline{RST}$  inputs as defined in [Table 5](#).

#### NORMAL MODE

The 33988 is in Normal mode when:

- $V_{PWR}$  is within the normal voltage range.
- $\overline{RST}$  pin is Logic [1].
- No fault has occurred.

#### FAIL-SAFE AND WATCHDOG

If the FSI input is not grounded, the watchdog timeout detection is active when either the WAKE or  $\overline{RST}$  input pin

transitions from Logic [0] to Logic [1]. The WAKE input is capable of being pulled up to  $V_{PWR}$  with a series of limiting resistance that limits the internal clamp current according to the specification.

The watchdog timeout is a multiple of an internal oscillator and is specified in [Table 14](#). As long as the WD bit (D7) of an incoming SPI message is toggled within the minimum watchdog timeout period (WDTO), based on the programmed value of the WDR the device will operate normally. If an internal watchdog timeout occurs before the WD bit, the device will revert to a Fail-safe mode until the device is reinitialized.

During the Fail-safe mode, the outputs will be ON or OFF depending upon the resistor RFS connected to the FSI pin, regardless of the state of the various direct inputs and modes ([Table 6](#)). In this mode, the SPI register content is retained except for over-current high and low detection levels and timing, which are reset to their default value (SOCL, SOCH, and OCLT). Then the watchdog, over-voltage, over-temperature, and over-current circuitry (with default value) are fully operational.

**Table 6. Output State During Fail-safe Mode**

RFS (k $\Omega$ )	High Side State
0	Fail-safe mode Disabled
6.0	Both HS0 and HS1 OFF
17	HS0 ON, HS1 OFF
Open	Both HS0 and HS1 ON

The Fail-safe mode can be detected by monitoring the WDTO bit D2 of the WD register. This bit is Logic [1] when the device is in Fail-safe mode. The device can be brought out of the Fail-safe mode by transitioning the WAKE and  $\overline{RST}$  pins from Logic [1] to Logic [0] or forcing the FSI pin to Logic [0]. [Table 5](#) summarizes the various methods for resetting the device from the latched Fail-safe mode.

If the FSI pin is tied to GND, the Watchdog Fail-safe operation is disabled.

#### LOSS OF $V_{DD}$

If the external 5.0V supply is not within specification, or even disconnected, all register content is reset. The two outputs can still be driven by the direct inputs IN1:IN0. The 33988 uses the battery input to power the output MOSFET-related current sense circuitry and any other internal logic providing Fail-safe device operation with no  $V_{DD}$  supplied. In this state, the watchdog, over-voltage, over-temperature, and over-current circuitry are fully operational with default values.

## FAULT MODE

The 33988 indicates the following faults as they occur by driving the  $\overline{FS}$  pin to Logic [0]:

- Over-temperature fault
- Open load fault
- Over-current fault (high and low)
- Over-voltage and under-voltage fault

## PROTECTION AND DIAGNOSIS FEATURES

### OVER-TEMPERATURE FAULT (NON-LATCHING)

The 33988 incorporates over-temperature detection and shutdown circuitry in each output structure. Over-temperature detection is enabled when an output is in the ON state.

For the output, an over-temperature fault (OTF) condition results in the faulted output turning OFF until the temperature falls below the  $T_{SD(HYS)}$ . This cycle will continue indefinitely until action is taken by the MCU to shut OFF the output, or until the offending load is removed.

When experiencing this fault, the OTF fault bit will be set in the status register and cleared after either a valid SPI read or a power reset of the device.

### OVER-VOLTAGE FAULT (NON-LATCHING)

The 33988 shuts down the output during an over-voltage fault (OVF) condition on the  $V_{PWR}$  pin. The output remains in the OFF state until the over-voltage condition is removed. When experiencing this fault, the OVF fault bit is set in the bit OD1 and cleared after either a valid SPI read or a power reset of the device.

The over-voltage protection and diagnostic can be disabled through SPI (bit  $OV\_dis$ ).

### UNDER-VOLTAGE SHUTDOWN (LATCHING OR NON-LATCHING)

The output(s) will latch off at some battery voltage below 6.0 V. As long as the  $V_{DD}$  level stays within the normal specified range, the internal logic states within the device will be sustained.

In the case where the battery voltage drops below the under-voltage threshold ( $VPWRUV$ ) output will turn off,  $\overline{FS}$  will go to Logic [0], and the fault register UVF bit will be set to 1. Two cases need to be considered when the battery level recovers:

- If output(s) command is (are) low,  $\overline{FS}$  will go to Logic [1] but the UVF bit will remain set to 1 until the next read operation.
- If the output command is ON, then  $\overline{FS}$  will remain at Logic [0]. The output must be turned OFF and ON again to re-enable the state of output and release  $\overline{FS}$ . The UVF bit will remain set to 1 until the next read operation.

The under-voltage protection can be disabled through the SPI (bit  $UV\_dis = 1$ ). In this case, the  $\overline{FS}$  and UVF bit do not

The  $\overline{FS}$  pin will automatically return to Logic [1] when the fault condition is removed, except for over-current and in some cases under-voltage.

Fault information is retained in the fault register and is available (and reset) via the SO pin during the first valid SPI communication (refer to [Table 16](#)).

report any under-voltage fault condition and the output state will not be changed as long as the battery voltage does not drop any lower than 2.5V.

### OPEN LOAD FAULT (NON-LATCHING)

The 33988 incorporates open load detection circuitry on each output. Output open load fault (OLF) is detected and reported as a fault condition when that output is disabled (OFF). The open load fault is detected and latched into the status register after the internal gate voltage is pulled low enough to turn OFF the output. The OLF fault bit is set in the status register. If the open load fault is removed, the status register will be cleared after reading the register.

The open load protection can be disabled through SPI (bit  $OL\_dis$ ). It is recommended to disable the open load detection circuitry ( $OL\_dis$  bit sets to logic [1]) in case of permanent open load fault condition.

### OVER-CURRENT FAULT (LATCHING)

The device has eight programmable over-current low detection levels ( $I_{OCL}$ ) and two programmable over-current high detection levels ( $I_{OCH}$ ) for maximum device protection. The two selectable, simultaneously active over-current detection levels, defined by  $I_{OCH}$  and  $I_{OCL}$ , are illustrated in [Figure 6](#). The eight different over-current low detect levels ( $I_{OCL0}:I_{OCL7}$ ) are likewise illustrated in [Figure 6](#).

If the load current level ever reaches the selected over-current low detect level and the over-current condition exceeds the programmed over-current time period ( $t_{OCx}$ ), the device will latch the effected output OFF.

If at any time the current reaches the selected  $I_{OCH}$  level, then the device will immediately latch the fault and turn OFF the output, regardless of the selected  $t_{OCL}$  driver.

For both cases, the device output will stay off indefinitely until the device is commanded OFF and then ON again.

### REVERSE BATTERY

The output survives the application of reverse voltage as low as -16V. Under these conditions, the output's gates are enhanced to keep the junction temperature less than 150°C. The ON resistance of the output is fairly similar to that in the Normal mode. No additional passive components are required.

**GROUND DISCONNECT PROTECTION**

In the event the 33988 ground is disconnected from load ground, the device protects itself and safely turns OFF the output regardless the state of the output at the time of

disconnection. A 10K resistor needs to be added between the wake pin and the rest of the circuitry in order to ensure that the device turns off in case of ground disconnect and to prevent this pin to exceed its maximum ratings

**Table 7. Device Behavior in Case of Under-voltage**

High Side Switch (VPWR Battery Voltage)**	State	UV Enable IN = 0 (Falling VPWR)	UV Enable IN = 0 (Rising VPWR)	UV Enable IN*** = 1 (Falling VPWR)	UV Enable IN*** = 1 (Rising VPWR)	UV Disable IN = 0 (Falling or Rising VPWR)	UV Disable IN*** = 1 (Falling or Rising VPWR)
VPWR > VPWRUV	Output State	OFF	OFF	ON	OFF	OFF	ON
	$\overline{FS}$ State	1	1	1	0	1	1
	SPI Fault Register UVF Bit	0	1 until next read	0	1	0	0
VPWRUV > VPWR > UVPOR	Output State	OFF	OFF	OFF	OFF	OFF	ON
	$\overline{FS}$ State	0	0	0	0	1	1
	SPI Fault Register UVF Bit	1	1	1	1	0	0
UVPOR > VPWR > 2.5V*	Output State	OFF	OFF	OFF	OFF	OFF	ON
	$\overline{FS}$ State	1	1	1	1	1	1
	SPI Fault Register UVF Bit	1 until next read	1	1 until next read	1 until next read	0	0
2.5V > VPWR > 0V	Output State	OFF	OFF	OFF	OFF	OFF	OFF
	$\overline{FS}$ State	1	1	1	1	1	1
	SPI Fault Register UVF Bit	1 until next read	1 until next read	1 until next read	1 until next read	0	0
	Comments	UV fault is not latched	UV fault is not latched		UV fault is latched		

\* Typical value; not guaranteed

\*\* While VDD remains within specified range.

\*\*\* = IN is equivalent to IN direct input or IN\_spi SPI input.

## LOGIC COMMANDS AND REGISTERS

### SPI PROTOCOL DESCRIPTION

The SPI interface has a full duplex, three-wire synchronous data transfer with four I/O lines associated with it: Serial Clock (SCLK), Serial Input (SI), Serial Output (SO), and Chip Select ( $\overline{CS}$ ).

The SI/SO pins of the 33988 follow a first-in first-out (D7/D0) protocol with both input and output words transferring the most significant bit (MSB) first. All inputs are compatible with 5.0 V CMOS logic levels.

The SPI lines perform the following functions:

#### SERIAL CLOCK (SCLK)

Serial clocks (SCLK) the internal shift registers of the 33988 device. The serial input (SI) pin accepts data into the input shift register on the falling edge of the SCLK signal while the serial output (SO) pin shifts data information out of the SO line driver on the rising edge of the SCLK signal. It is important that the SCLK pin be in a logic low state whenever  $\overline{CS}$  makes any transition. For this reason, it is recommended that the SCLK pin be in a Logic [0] state whenever the device is not accessed ( $\overline{CS}$  Logic [1] state). SCLK has an active internal pull-down,  $I_{DWN}$ . When  $\overline{CS}$  is Logic [1], signals at the SCLK and SI pins are ignored and SO is tri-stated (high-impedance). See [Figure 10](#) and [Figure 11](#).

#### SERIAL INPUT (SI)

This is a serial interface (SI) command data input pin. SI instruction is read on the falling edge of SCLK. An 8-bit stream of serial data is required on the SI pin, starting with D7

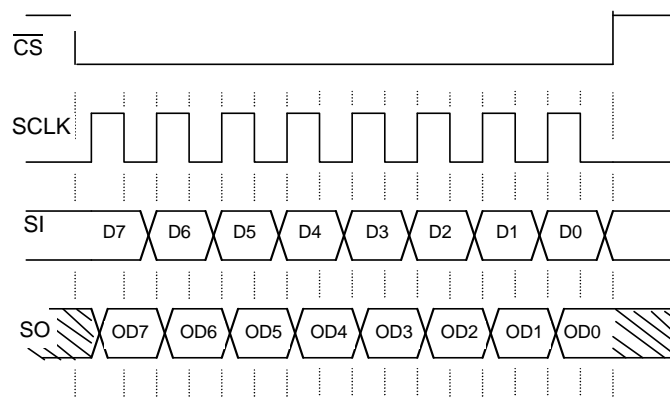
to D0. The internal registers of the 33988 are configured and controlled using a 4-bit addressing scheme, as shown in [Table 8](#). Register addressing and configuration are described in [Table 9](#). The SI input has an active internal pull-down,  $I_{DWN}$ .

#### SERIAL OUTPUT (SO)

The SO data pin is a tri-stateable output from the shift register. The SO pin remains in a high-impedance state until the  $\overline{CS}$  pin is put into a Logic [0] state. The SO data is capable of reporting the status of the output, the device configuration, and the state of the key inputs. The SO pin changes states on the rising edge of SCLK and reads out on the falling edge of SCLK. Fault and Input Status descriptions are provided in [Table 5](#).

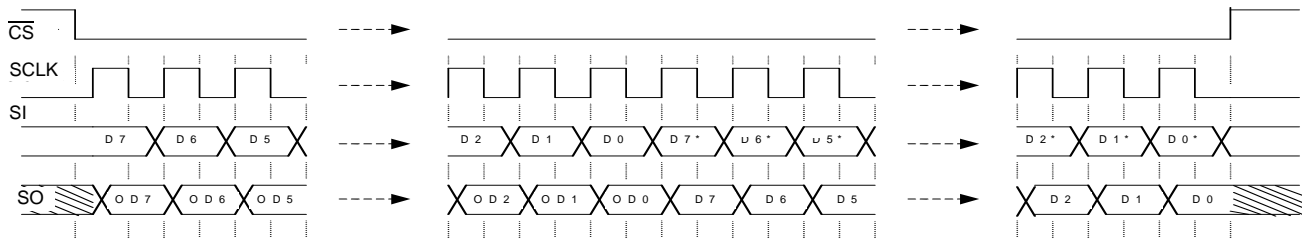
#### CHIP SELECT ( $\overline{CS}$ )

The  $\overline{CS}$  pin enables communication with the master microcontroller (MCU). When this pin is in a Logic [0] state, the device is capable of transferring information to, and receiving information from, the MCU. The 33988 device latches in data from the Input shift registers to the addressed registers on the rising edge of  $\overline{CS}$ . The device transfers status information from the power output to the shift register on the falling edge of  $\overline{CS}$ . The SO output driver is enabled when  $\overline{CS}$  is Logic [0].  $\overline{CS}$  should transition from a Logic [1] to a Logic [0] state only when SCLK is a Logic [0].  $\overline{CS}$  has an active internal pull-up,  $I_{UP}$ .



- Notes
1.  $\overline{RST}$  is a Logic [1] state during the above operation.
  2. D7:D0 relate to the most recent ordered entry of data into the device.
  3. OD7:OD0 relate to the first 8 bits of ordered fault and status data out of the device.

Figure 10. Single 8-Bit Word SPI Communication



- Notes
1.  $\overline{RST}$  is a Logic [1] state during the above operation.
  2. D7:D0 relate to the most recent ordered entry of data into the device.
  3. D7\*:D0\* relate to the previous 8 bits (last command word) of data that was previously shifted into the device.
  4. OD7:OD0 relate to the first 8 bits of ordered fault and status data out of the device.

Figure 11. Multiple 8-Bit Word SPI Communication

### SERIAL INPUT COMMUNICATION

SPI communication is accomplished using 8-bit messages. A message is transmitted by the MCU starting with the MSB, D7, and ending with the LSB, D0 (Table 8). Each incoming command message on the SI pin can be interpreted using the following bit assignments: the MSB (D7) is the watchdog bit and in some cases a register address bit common to both outputs or specific to an output; the next three bits, D6:D4, are used to select the command register; and the remaining four bits, D3:D0, are used to configure and control the outputs and their protection features.

Multiple messages can be transmitted in succession to accommodate those applications where daisy chaining is desirable, or to confirm transmitted data, as long as the messages are all multiples of eight bits. Any attempt made to latch in a message that is not eight bits will be ignored.

The 33988 has defined registers, which are used to configure the device and to control the state of the output. Table 9, summarizes the SI registers. The registers are addressed via D6:D4 of the incoming SPI word (Table 8).

Table 8. SI Message Bit Assignment

Bit Sig	SI Msg Bit	Message Bit Description
MSB	D7	Register address bit for output selection. Also used for Watchdog: toggled to satisfy watchdog requirements.
	D6:D4	Register address bits.
	D3:D1	Used to configure the inputs, outputs, and the device protection features and SO status content.
LSB	D0	Used to configure the inputs, outputs, and the device protection features and SO status content.

Table 9. Serial Input Address and Configuration Bit Map

SI Register	Serial Input Data							
	D7	D6	D5	D4	D3	D2	D1	D0
STATR	s	0	0	0	0	SOA2	SOA1	SOA0
OCR	x	0	0	1	CSNS1 EN	IN1_SPI	CSNS0 EN	IN0_SPI
SOCHLR	s	0	1	0	SOCHs	SOCL2s	SOCL1s	SOCL0s
CDTOLR	s	0	1	1	OL_DIS s	CD_DIS s	OCLT1s	OCLT0s
DICR	s	1	0	0	FAST SR s	CSNS high s	IN DIS s	A/Os
OSDR	0	1	0	1	0	OSD2	OSD1	OSD0
WDR	1	1	0	1	0	0	WD1	WD0
NAR	0	1	1	0	0	0	0	0
UOVR	1	1	1	0	0	0	UV_dis	OV_dis
TEST	x	1	1	1	Freescale Internal Use (Test)			

x = Don't care.

s (SOA3 bit) = Selection of output: Logic [0] = HS0, Logic [1] = HS1.

## DEVICE REGISTER ADDRESSING

The following section describes the possible register addresses and their impact on device operation.

### Address x000—Status Register (STATR)

The STATR register is used to read the device status and the various configuration register contents without disrupting the device operation or the register contents. The register bits D2:D0, determine the content of the first eight bits of SO data. When register content is specific to one of the two outputs, bit D7 is used to select the desired output (SOA3). In addition to the device status, this feature provides the ability to read the content of the OCR, SOCHLR, CDTOLR, DICR, OSDR, WDR, NAR, and UOVR registers. (Refer to the section entitled [Serial Output Communication \(Device Status Return Data\)](#).)

### Address x001—Output Control Register (OCR)

The OCR register allows the MCU to control the outputs through the SPI. Incoming message bit D0 reflects the desired states of the high side output HS0 (IN0\_SPI): a Logic [1] enables the output switch and a Logic [0] turns it OFF. A Logic [1] on message bit D1 enables the Current Sense (CSNS) pin. Similarly, incoming message bit D2 reflects the desired states of the high side output HS1 (IN1\_SPI): Logic [1] enables the output switch and a Logic [0] turns it OFF. A Logic [1] on message bit D3 enables the CSNS pin. In the event that the current sense is enabled for both outputs, the current will be summed. Bit D7 is used to feed the watchdog if enabled.

### Address x010— Select Over-current High and Low Register (SOCHLR)

The SOCHLR register allows the MCU to configure the output over-current low and high detection levels, respectively. Each output is independently selected for configuration based on the state of the D7 bit; a write to this register when D7 is Logic [0] will configure the current detection levels for the HS0. Similarly, if D7 is Logic [1] when this register is written, HS1 is configured. Each output can be configured to different levels. In addition to protecting the device, this slow blow fuse emulation feature can be used to optimize the load requirements matching system characteristics. Bits D2:D0 set the over-current low detection level to one of eight possible levels, as shown in [Table 10](#). Bit D3 sets the over-current high detection level to one of two levels, which is described in [Table 11](#).

**Table 10. Over-current Low Detection Levels**

SOCL2 (D2)	SOCL1 (D1)	SOCL0 (D0)	Over-current Low Detection (Amperes)
0	0	0	12.5
0	0	1	11.25
0	1	0	10.0
0	1	1	8.75
1	0	0	7.5
1	0	1	6.25
1	1	0	5.0
1	1	1	3.75

**Table 11. Over-current High Detection Levels**

SOCH (D3)	Over-current High Detection (Amperes)
0	50
1	37.5

### Address x011—Current Detection Time and Open Load Register (CDTOLR)

The CDTOLR register is used by the MCU to determine the amount of time the device will allow an over-current low condition before output latches OFF occurs. Each output is independently selected for configuration based on the state of the D7 bit. A write to this register when bit 7 is Logic [0] will configure the timeout for the HS0. Similarly, if D7 is Logic [1] when this register is written, then HS1 is configured. Bits D1:D0 allow the MCU to select one of four fault blanking times defined in [Table 12](#). Note that these timeouts apply only to the over-current low detection levels. If the selected over-current high level is reached, the device will latch off within 20µs.

**Table 12. Over-current Low Detection Blanking Time**

OCLT[1:0]	Timing
00	155ms
01	10ms
10	1.2ms
11	150µs

A Logic [1] on bit D2 disables the over-current low (CD\_dis) detection timeout feature. A Logic [1] on bit D3 disables the open load (OL) detection feature.



### Address x100—Direct Input Control Register (DICR)

The DICR register is used by the MCU to enable, disable, or configure the direct IN pin control of each output. Each output is independently selected for configuration based on the state of bit D7. A write to this register when bit D7 is Logic [0] will configure the direct input control for the HS0. Similarly, if D7 is Logic [1] when this register is written, then HS1 is configured.

A Logic [0] on bit D1 will enable the output for direct control by the IN pin. A Logic [1] on bit D1 will disable the output from direct control. While addressing this register, if the input was enabled for direct control, a Logic [1] for the D0 bit will result in a Boolean AND of the IN pin with its corresponding D0 message bit when addressing the OCR register. Similarly, a Logic [0] on the D0 pin results in a Boolean OR of the IN pin with the corresponding message bits when addressing the OCR register.

The DICR register is useful if there is a need to independently turn on and off several loads that are PWM'd at the same frequency and duty cycle with only one PWM signal. This type of operation can be accomplished by connecting the pertinent direct IN pins of several devices to a PWM output port from the MCU and configuring each of the outputs to be controlled via their respective direct IN pin. The DICR is then used to Boolean AND the direct IN(s) of each of the outputs with the dedicated SPI bit that also controls the output. Each configured SPI bit can now be used to enable and disable the common PWM signal from controlling its assigned output.

A Logic [1] on bit D2 is used to select the high ratio ( $C_{SR1}$ , 1/20500) on the CSNS pin for the selected output. The default value [0] is used to select the low ratio ( $C_{SR0}$ , 1/10250). A Logic [1] on bit D3 is used to select the high speed slew rate for the selected output. The default value [0] corresponds to the low speed slew rate.

### Address 0101—Output Switching Delay Register (OSDR)

The OSDR register configures the device with a programmable time delay that is active during Output ON transitions initiated via SPI (not via direct input).

A write to this register configures both outputs for different delay. Whenever the input is commanded to transition from Logic [0] to Logic [1], both outputs will be held OFF for the time delay configured in the OSDR. The programming of the contents of this register have no effect on device Fail-safe mode operation. The default value of the OSDR register is 000, equating to no delay. This feature allows the user a way to minimize inrush currents, or surges, thereby allowing loads to be switched ON with a single command. There are eight selectable output switching delay times that range from 0ms to 525ms. Refer to [Table 13](#).

**Table 13. Switching Delay**

OSD[2:0] (D2:D0)	Turn ON Delay (ms) HS0	Turn ON Delay (ms) HS1
000	0	0
001	0	75
010	150	150
011	150	225
100	300	300
101	300	375
110	450	450
111	450	525

### Address 1101—Watchdog Register (WDR)

The WDR register is used by the MCU to configure the watchdog timeout. Watchdog timeout is configured using bits D1:D0. When D1:D0 bits are programmed for the desired watchdog timeout period, the WD bit (D7) should be toggled as well, ensuring the new timeout period is programmed at the beginning of a new count sequence. Refer to [Table 14](#).

**Table 14. Watchdog Timeout**

WD[1:0] (D1:D0)	Timing (ms)
00	620
01	310
10	2500
11	1250

### Address 0110—No Action Register (NAR)

The NAR register can be used to no-operation fill SPI data packets in a daisy chain SPI configuration. This allows devices to not be affected by commands being clocked over a daisy-chained SPI configuration, and by toggling the WD bit (D7), the watchdog circuitry will continue to be reset while no programming or data readback functions are being requested from the device.

### Address 1110—Under-voltage/Over-voltage Register (UOVR)

The UOVR register can be used to disable or enable over-voltage and/or under-voltage protection. By default (Logic [0]), both protections are active. When disabled, an under-voltage or over-voltage condition fault will not be reported in the output fault register.

### Address x111—TEST

The TEST register is reserved for test and is not accessible with the SPI during normal operation.

## SERIAL OUTPUT COMMUNICATION (DEVICE STATUS RETURN DATA)

When the  $\overline{CS}$  pin is pulled low, the output status register is loaded. Meanwhile, the data is clocked out MSB- (OD7-) first as the new message data is clocked into the SI pin. The first eight bits of data clocking out of the SO, and following a  $\overline{CS}$  transition, are dependant upon the previously written SPI word.

Any bits clocked out of the SO pin after the first eight will be representative of the initial message bits clocked into the SI pin since the  $\overline{CS}$  pin first transitioned to a Logic [0]. This feature is useful for daisy chaining devices as well as message verification.

A valid message length is determined following a  $\overline{CS}$  transition of Logic [0] to Logic [1]. If there is a valid message length, the data is latched into the appropriate registers. A valid message length is a multiple of eight bits. At this time, the SO pin is tri-stated and the fault status register is now able to accept new fault status information.

The output status register correctly reflects the status of the STATR-selected register data at the time that the  $\overline{CS}$  is pulled to a Logic [0] during SPI communication and/or for the period of time since the last valid SPI communication, with the following exceptions:

- The previous SPI communication was determined to be invalid. In this case, the status will be reported as though the invalid SPI communication never occurred.
- Battery transients below 6.0V resulting in an under-voltage shutdown of the outputs may result in incorrect data loaded into the status register. The SO data transmitted to the MCU during the first SPI communication following an under-voltage  $V_{PWR}$  condition should be ignored.
- The  $\overline{RST}$  pin transition from a Logic [0] to Logic [1] while the WAKE pin is at Logic [0] may result in incorrect data loaded into the status register. The SO data transmitted

to the MCU during the first SPI communication following this condition should be ignored.

## SERIAL OUTPUT BIT ASSIGNMENT

The 8 bits of serial output data depend on the previous serial input message, as explained in the following paragraphs. [Table 15](#) summarizes the SO register content.

Bit OD7 reflects the state of the watchdog bit (D7) addressed during the prior communication. The value of the previous D7 will determine which output the status information applies to for the Fault (FLTR), SOCHLR, CDTOLR, and DICR registers. SO data will represent information ranging from fault status to register contents, user selected by writing to the STATR bits D2:D0. Note that the SO data will continue to reflect the information for each output (depending on the previous D7 state) that was selected during the most recent STATR write until changed with an updated STATR write.

### Previous Address SOA[2:0]=000

If the previous three MSBs are 000, bits OD6:OD0 will reflect the current state of the Fault register (FLTR) corresponding to the output previously selected with the bit OD7 ([Table 16](#)).

### Previous Address SOA[2:0]=001

Data in bits OD1:OD0 contain  $\overline{CSNS0\ EN}$  and  $\overline{IN0\_SPI}$  programmed bits, respectively. Data in bits OD3:OD2 contain  $\overline{CSNS0\ EN}$  and  $\overline{IN0\_SPI}$  programmed bits, respectively.

### Previous Address SOA[2:0]=010

The data in bit OD3 contain the programmed over-current high detection level (refer to [Table 11](#)), and the data in bits OD2:OD0 contain the programmed over-current low detection levels (refer to [Table 12](#)).

**Table 15. Serial Output Bit Map Description**

Previous STATR D7, D2, D1, D0				Serial Output Returned Data							
SOA3	SOA2	SOA1	SOA0	OD7	OD6	OD5	OD4	OD3	OD2	OD1	OD0
s	0	0	0	s	OTFs	OCHF <sub>s</sub>	OCLF <sub>s</sub>	OLF <sub>s</sub>	UVF	OVF	FAULT
x	0	0	1	x	0	0	1	CSNS1 $\overline{EN}$	IN1_SPI	CSNS0 $\overline{EN}$	IN0_SPI
s	0	1	0	s	0	1	0	SOCH <sub>s</sub>	SOCL2 <sub>s</sub>	SOCL1 <sub>s</sub>	SOCL0 <sub>s</sub>
s	0	1	1	s	0	1	1	OL_DIS <sub>s</sub>	CD_DIS <sub>s</sub>	OCLT1 <sub>s</sub>	OCLT0 <sub>s</sub>
s	1	0	0	s	1	0	0	FAST SR <sub>s</sub>	CSNS high <sub>s</sub>	IN DIS <sub>s</sub>	A/O <sub>s</sub>
0	1	0	1	0	1	0	1	FSM_HS0	OSD2	OSD1	OSD0
1	1	0	1	1	1	0	1	FSM_HS1	WDTO	WD1	WD0
0	1	1	0	0	1	1	0	IN1 Pin	IN0 Pin	FSI Pin	WAKE Pin
1	1	1	0	1	1	1	0	–	–	UV_dis	OV_dis
x	1	1	1	–	–	–	–	–	–	–	–

s = Selection of output: Logic [0] = HS0, Logic [1] = HS1.

x = Don't care.

**Table 16. Fault Register**

OD7	OD6	OD5	OD4	OD3	OD2	OD1	OD0
s	OTF	OCHF <sub>s</sub>	OCLF <sub>s</sub>	OLF <sub>s</sub>	UVF	OVF	FAULT

OD7 (s) = Selection of output: Logic [0] = HS0, Logic [1] = HS1.

OD6 (OTF) = Over-temperature Flag.

OD5 (OCHF<sub>s</sub>) = Over-current High Flag. (This fault is latched.)

OD4 (OCLF<sub>s</sub>) = Over-current Low Flag. (This fault is latched.)

OD3 (OLF<sub>s</sub>) = Open Load Flag.

OD2 (UVF) = Under-voltage Flag. (This fault is latched or not latched.)

OD1 (OVF) = Over-voltage Flag.

OD0 (FAULT) = This flag reports a fault and is reset by a read operation.

FAULT report of any fault on HS0 or HS1

**Note** The  $\overline{FS}$  pin reports a fault. For latched faults, this pin is reset by a new Switch ON command (via SPI or direct input IN).

**Previous Address SOA[2:0]=011**

Data returned in bits OD1 and OD0 are current values for the over-current fault blanking time, illustrated in [Table 12](#). Bit OD2 reports if the over-current detection timeout feature is active. OD3 reports if the open load circuitry is active.

**Previous Address SOA[2:0]=100**

The returned data contain the programmed values in the DICR.

**Previous Address SOA[2:0]=101**

- SOA3 = 0. The returned data contain the programmed values in the OSDR. Bit OD3 (FSM\_HS0) reflects the state of the output HS0 in the Fail-safe mode after a watchdog timeout occurs.
- SOA3 = 1. The returned data contain the programmed values in the WDR. Bit OD2 (WDTO) reflects the status of the watchdog circuitry. If WDTO bit is Logic [1], the watchdog has timed out and the device is in Fail-safe mode. If WDTO is Logic [0], the device is in Normal mode (assuming the device is powered and not in Sleep mode), with the watchdog either enabled or disabled. Bit OD3 (FSM\_HS1) reflects the state of the output HS1 in the Fail-safe mode after a watchdog timeout occurs.

**Previous Address SOA[2:0]=110**

- SOA3 = 0. OD3:OD0 return the state of the IN1, IN0, FSI, and WAKE pins, respectively ([Table 17](#)).

**Table 17. Pin Register**

OD3	OD2	OD1	OD0
IN1 Pin	IN0 Pin	FSI Pin	WAKE Pin

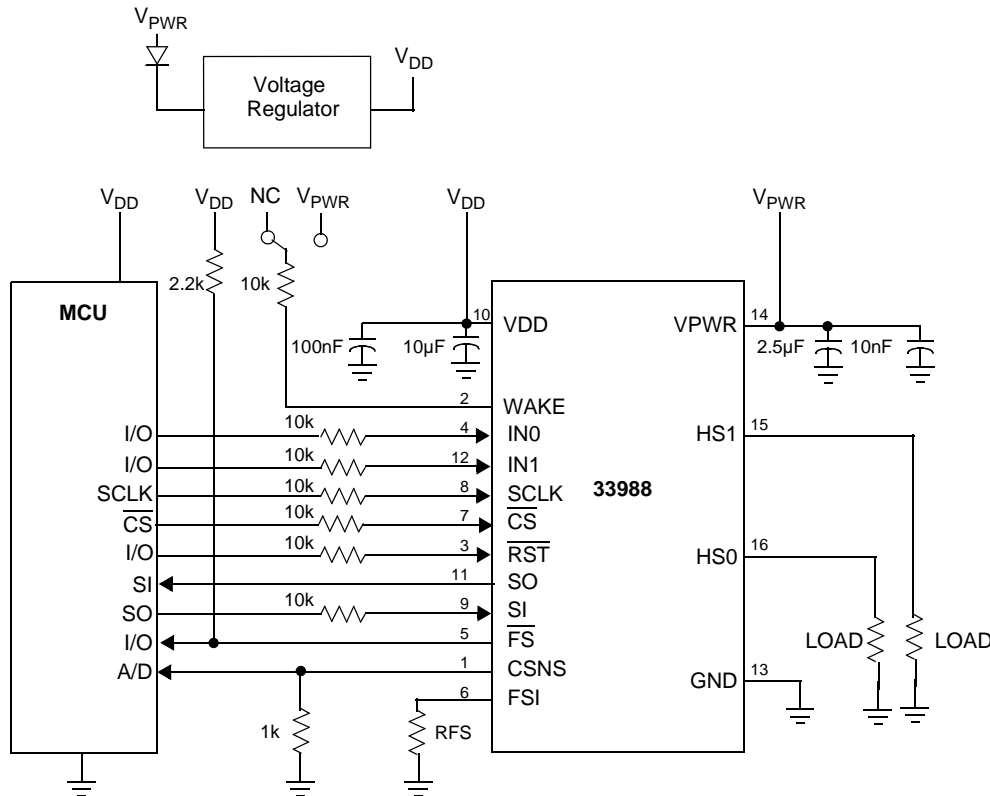
- SOA3 = 1. The returned data contain the programmed values in the UOVR. Bit OD1 reflects the state of the under-voltage protection and bit OD0 reflects the state of the over-voltage protection. Refer to [Table 15](#).

**Previous Address SOA[2:0]=111**

Null Data. No previous register Read Back command received, so bits OD2:OD0 are null, or 000.

## TYPICAL APPLICATIONS

The 33988 can be configured in several applications. The figure below shows the 33988 in a typical main switch application.



**Figure 12. Typical Applications**

The loads must be chosen in order to guarantee the device normal operating condition as junction temperature from -40 to 150°C. In case of permanent short-circuit conditions, the duration and number of activation cycles must be limited with a dedicated MCU fault management using the fault reporting through SPI.

[Figure 13](#) describes the maximum turn-off current versus load inductance for single-pulse method, based on lab characterization results. When driving DC motor or Solenoid loads demanding multiple switching, an external recirculation device must be used to maintain the device in its Safe Operating Area.

Two application notes are available in order to:

- propose safe configurations of the eXtreme Switch devices in case of application faults and protect all circuitry with minimum external components (AN 3274),
- provide guidelines for Printed Circuit Board (PCB) design and assembly (AN 2469).

Development effort will be required by the end users to optimize the board design and PCB layout in order to reach electromagnetic compatibility standards (emission and immunity).

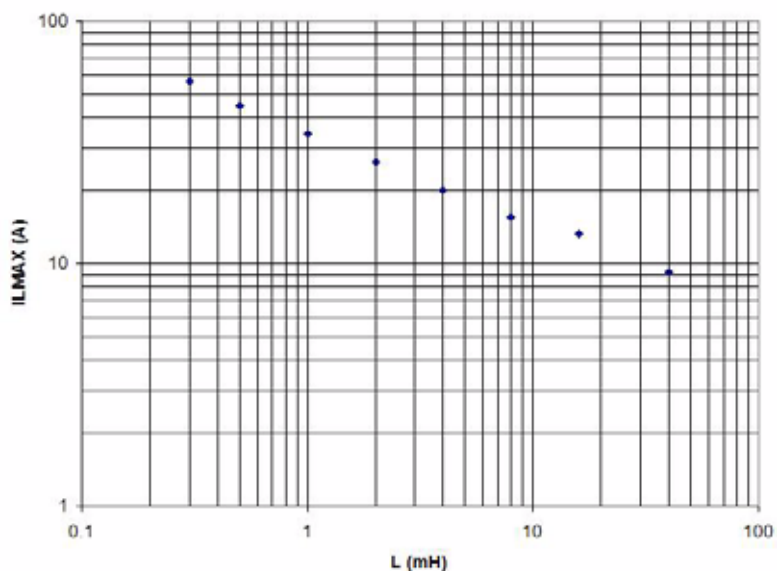


Figure 13. Maximum Turn-off Current Versus Inductive Load (Single Pulse for  $R_L = 0$  and  $V_{PWR} = 12$  V at  $T_J = 150^\circ\text{C}$  Initial)

## PACKAGING

### [SOLDERING INFORMATION](#)

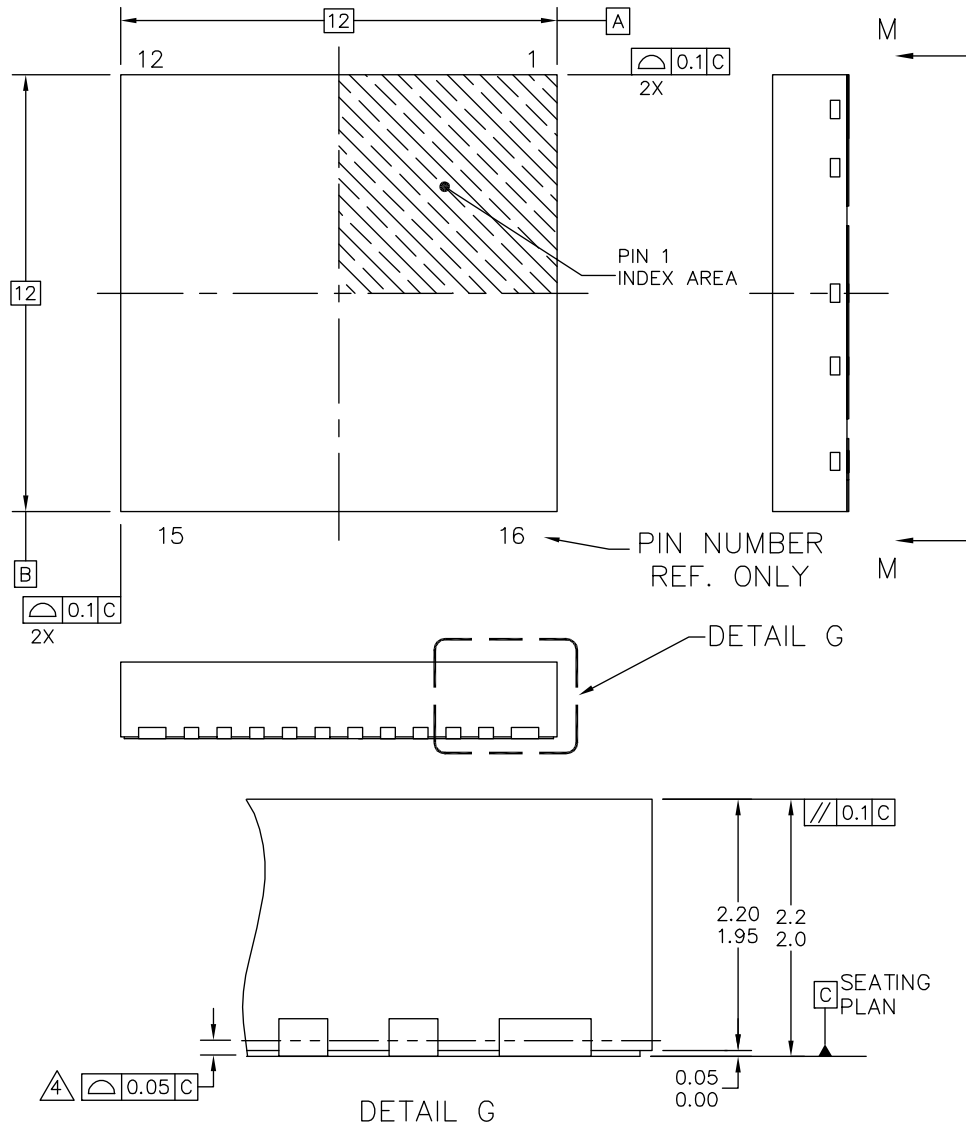
#### **SOLDERING INFORMATION**

The 33988 is packaged in a surface mount power package (PQFN), intended to be soldered directly on the printed circuit board.

The [AN2467](#) provides guidelines for Printed Circuit Board design and assembly.

**PACKAGE DIMENSIONS**

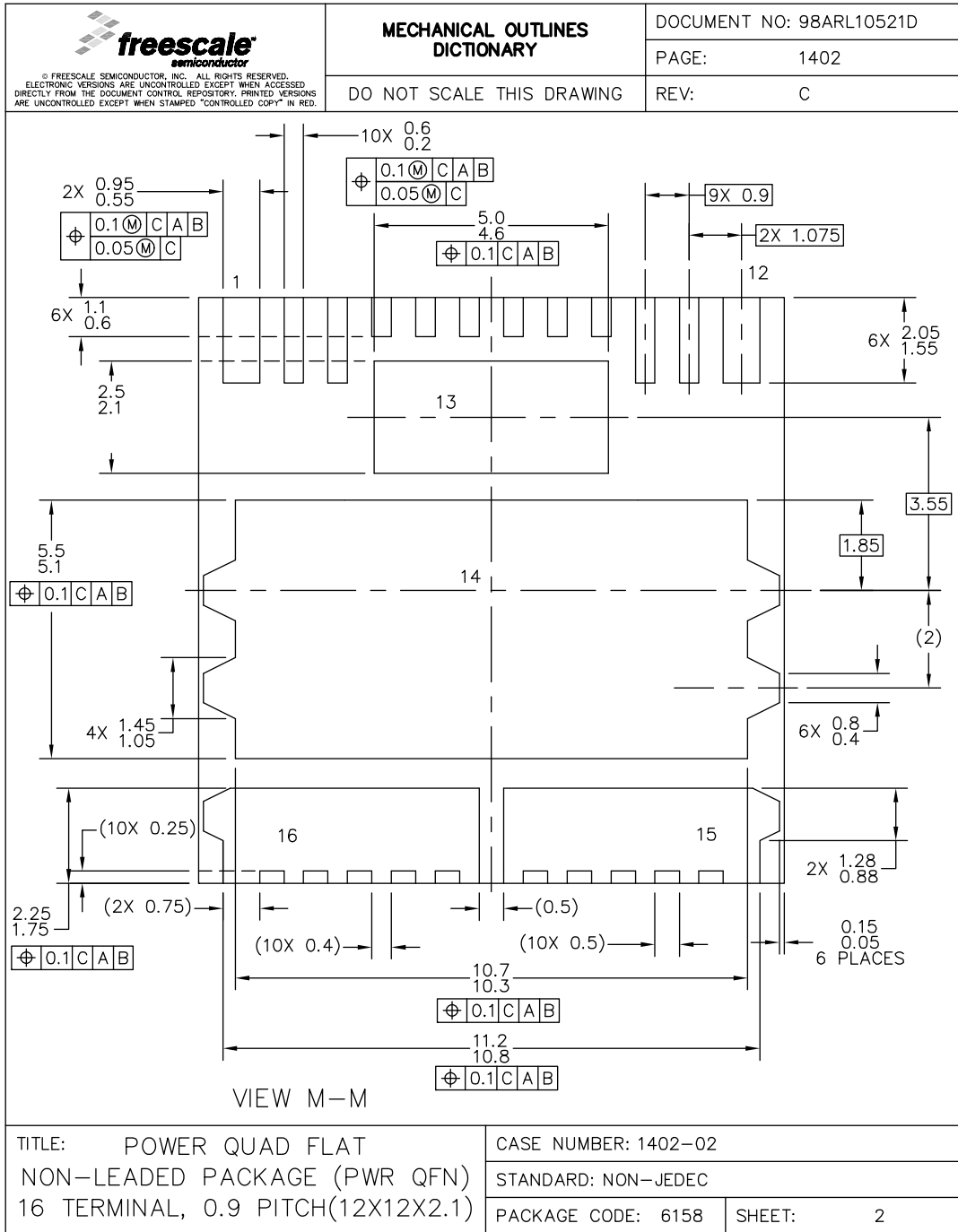
For the most current revision of the package, visit [www.freescale.com](http://www.freescale.com) and perform a keyword search on 98ARL10521D.  
Dimensions shown are provided for reference ONLY.



© FREESCALE SEMICONDUCTOR, INC. ALL RIGHTS RESERVED.	<b>MECHANICAL OUTLINE</b>	PRINT VERSION NOT TO SCALE
TITLE: POWER QUAD FLAT NON-LEADED PACKAGE (PWR QFN) 16 TERMINAL, 0.9 PITCH(12X12X2.1)	DOCUMENT NO: 98ARL10521D	REV: C
	CASE NUMBER: 1402-02	27 APR 2005
	STANDARD: NON-JEDEC	

**FK SUFFIX**  
16-PIN PQFN  
98ARL10521D  
ISSUE C

PACKAGE DIMENSIONS (CONTINUED)



**FK SUFFIX**  
16-PIN PQFN  
98ARL10521D  
ISSUE C



## REVISION HISTORY

REVISION	DATE	DESCRIPTION OF CHANGES
1.0	1/2007	<ul style="list-style-type: none"> <li>Initial release</li> </ul>
2.0	5/2007	<ul style="list-style-type: none"> <li>Changed typ and max number on <a href="#">Output Turn-ON Delay Time in Fast/Slow Slew Rate</a><sup>(20)</sup></li> <li>Changed min on <a href="#">Output Turn-OFF Delay Time in Fast Slew Rate Mode</a><sup>(21)</sup></li> <li>Changed labels on <a href="#">HS1 Switching Delay Time (OSD[2:0])</a> and <a href="#">HS0 Switching Delay Time (OSD[2:0])</a></li> <li>Corrected labels on <a href="#">Figure 12. Typical Applications</a></li> </ul>
3.0	8/2007	<ul style="list-style-type: none"> <li>Updated Freescale format and style</li> <li>Updated <a href="#">Junction-to-Ambient</a></li> <li>Added <a href="#">Functional Internal Block Description</a></li> <li>Updated <a href="#">Device Behavior in Case of Under-voltage</a></li> </ul>
4.0	11/2009	<ul style="list-style-type: none"> <li>Added one paragraph and figure to <a href="#">Typical Applications</a></li> </ul>
5.0	7/2010	<ul style="list-style-type: none"> <li>Corrected typo in Tables 15 and 16 (Faults to Fault) and added "FAULT report of any fault on HS0 or HS1" to Table 16.</li> </ul>
6.0	9/2010	<ul style="list-style-type: none"> <li>Corrected Logic on bit 2, <a href="#">Address x100—Direct Input Control Register (DICR) on page 25</a>.</li> </ul>
7.0	5/2012	<ul style="list-style-type: none"> <li>Changed orderable part number from MC33988CPNA to MC33988CHFK</li> <li>Updated <sup>(6)</sup></li> <li>Updated <a href="#">soldering information</a></li> <li>Updated Freescale form and style</li> </ul>
8.0	6/2012	<ul style="list-style-type: none"> <li>Updated values in <a href="#">Table 13</a>.</li> </ul>

**How to Reach Us:**

**Home Page:**  
freescale.com

**Web Support:**  
freescale.com/support

Information in this document is provided solely to enable system and software implementers to use Freescale products. There are no express or implied copyright licenses granted hereunder to design or fabricate any integrated circuits on the information in this document.

Freescale reserves the right to make changes without further notice to any products herein. Freescale makes no warranty, representation, or guarantee regarding the suitability of its products for any particular purpose, nor does Freescale assume any liability arising out of the application or use of any product or circuit, and specifically disclaims any and all liability, including without limitation consequential or incidental damages. "Typical" parameters that may be provided in Freescale data sheets and/or specifications can and do vary in different applications, and actual performance may vary over time. All operating parameters, including "typicals," must be validated for each customer application by customer's technical experts. Freescale does not convey any license under its patent rights nor the rights of others. Freescale sells products pursuant to standard terms and conditions of sale, which can be found at the following address: <http://www.reg.net/v2/webservices/Freescale/Docs/TermsandConditions.htm>

Freescale, the Freescale logo, AltiVec, C-5, CodeTest, CodeWarrior, ColdFire, C-Ware, Energy Efficient Solutions logo, mobileGT, PowerQUICC, QorIQ, Qorivva, StarCore, and Symphony are trademarks of Freescale Semiconductor, Inc., Reg. U.S. Pat. & Tm. Off. Airfast, BeeKit, BeeStack, ColdFire+, CoreNet, Flexis, MagniV, MXC, Platform in a Package, Processor expert, QorIQ Qonverge, QUICC Engine, Ready Play, SMARTMOS, TurboLink, Vybrid, and Xtrinsic are trademarks of Freescale Semiconductor, Inc. All other product or service names are the property of their respective owners.

© 2012 Freescale Semiconductor, Inc.