RAA489110

Buck-Boost Configurable Battery Charger with SMBus Interface Supporting USB PD EPR

The RAA489110 is a digitally configurable buck-boost battery charger that supports Narrow Voltage Direct Charging (NVDC) and Hybrid Power Buck-Boost (HPBB/Bypass) charging, and it switches between these modes using firmware control. Bypass mode is also supported using the firmware of the controller, allowing the adapter to provide power directly to the system. The RAA489110 provides charging functionality, system bus regulation, and protection features using only N-MOSFETs for tablet, Ultrabook, and notebook platforms. The advanced Renesas R3™ technology provides an efficient Charging mode. The RAA489110 takes input power from a wide range of DC power sources (such as conventional AC/DC charger adapters, USB Type-C Power ports, and travel adapters) and safely charges battery packs with up to 4-series cell Li-ion batteries.

The system power is provided from the adapter, battery, or a combination of both. The reconfigurable internal registers of the charger allow the use of a smaller inductor for the HPBB mode to achieve higher efficiencies across multiple power levels. The RAA489110 can operate either with only a battery, only an adapter, or both connected. For Intel IMVP-compliant systems, the RAA489110 includes System Power monitor (PSYS) functionality that provides an analog signal representing total platform power. The PSYS output can connect to many different IMVP core regulators to provide an IMVP compliant power domain function. The RAA489110 supports reverse buck, boost, or buck-boost operation to the adapter port (OTG mode) from 2- to 4-cell batteries, allowing configurations to support USB-C Power Delivery (PD) output for Programmable Power Supply (PPS) ports. The RAA489110 serial communication uses SMBus/I^2C, allowing the programming of many key parameters to deliver a customized solution.

Applications

- 2- to 4-cell tablets, notebooks, power banks, DSLR, and any USB-C interface portable device requiring batteries

Features

- Buck-boost NVDC or hybrid power (turbo boost) charger for 2-, 3-, or 4-cell Li-ion batteries using all N-MOSFET transistors
- Input voltage range: 3.9V to 30V (no dead zone)
- System/battery output voltage: 3.9V to 18.304V
- Bypass mode supported to connect system to adapter
- Autonomous charging option (automatic end of charging)
- Adapter current and battery current monitor (AMON/BMON)
- PROCHOT# open-drain output, IMVP compliant
- System power monitor PSYS output, IMVP8/9 compliant
- Internal 8-bit ADC for monitoring key parameters
- USB-C PD Fast Role Swap support and PPS support
- Independent compensation pins for forward and reverse operation (OTG) modes
- Supports supplemental power (Intel V_{MIN} active protection)
- Battery Ship mode: IC ultra-low power state
- Supports programmable temperature profiles and JEITA compliance using an NTC
- 4x4 32 Ld TQFN package, pin-to-pin compatible with ISL9241 family of parts

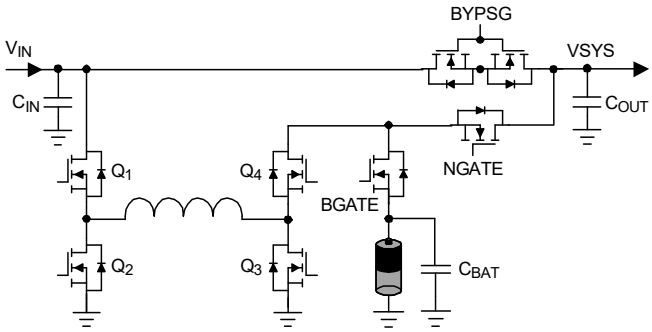


Figure 1. Typical Application

Contents

1. Overview

1.1 Simplified Application Circuits

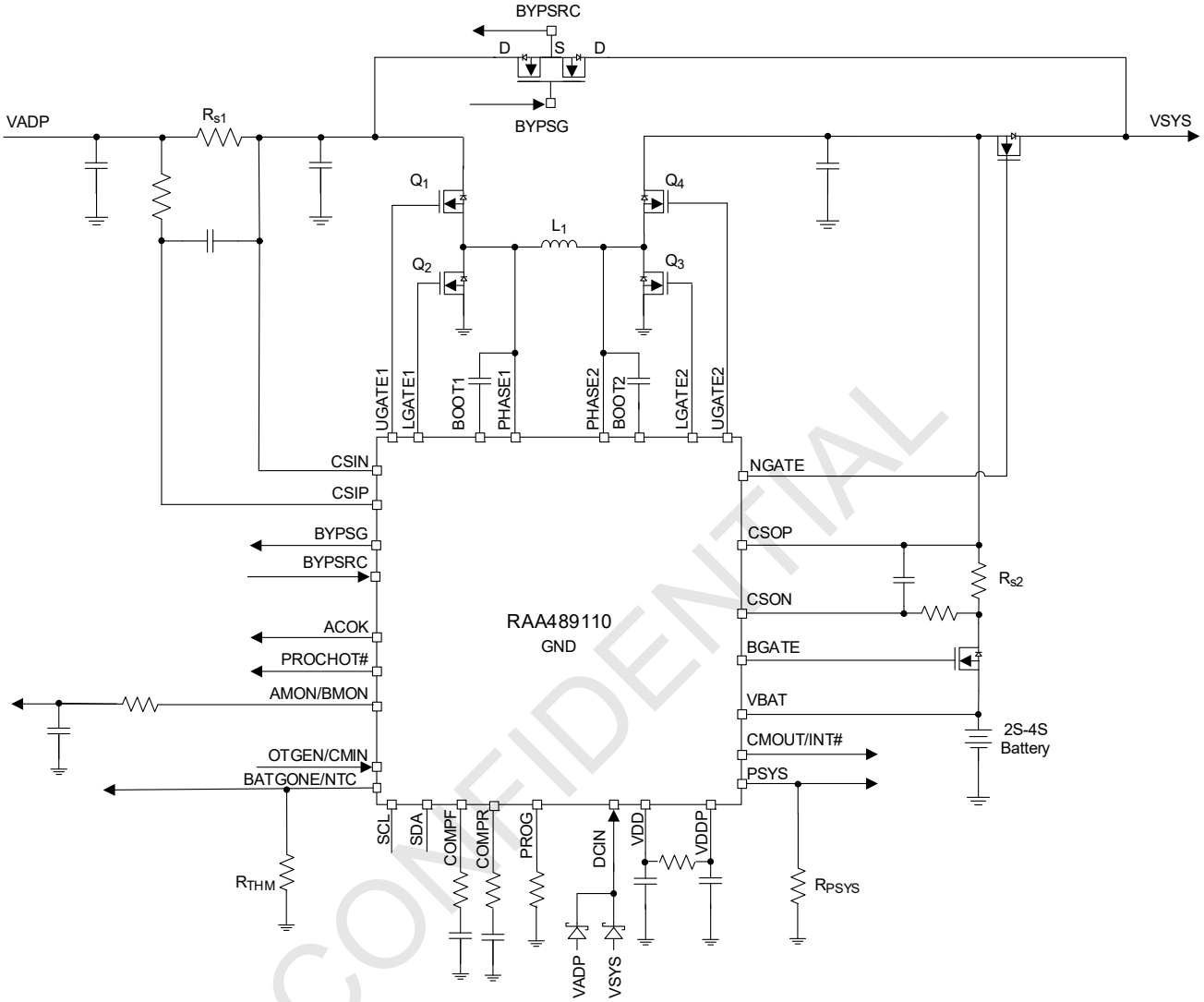


Figure 2. NVDC Plus HPBB Simplified Application Diagram

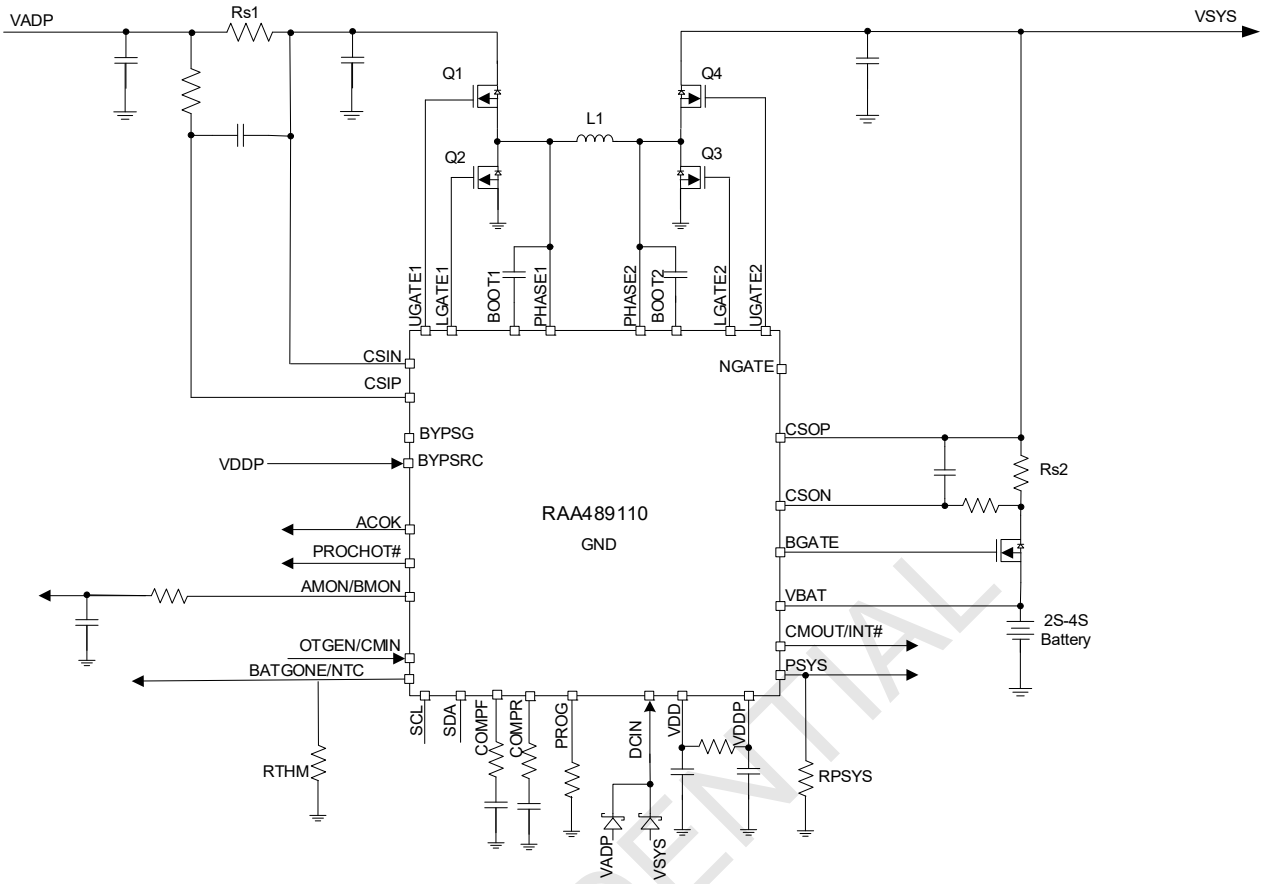


Figure 3. NVDC Only Simplified Application Diagram

1.2 Block Diagram

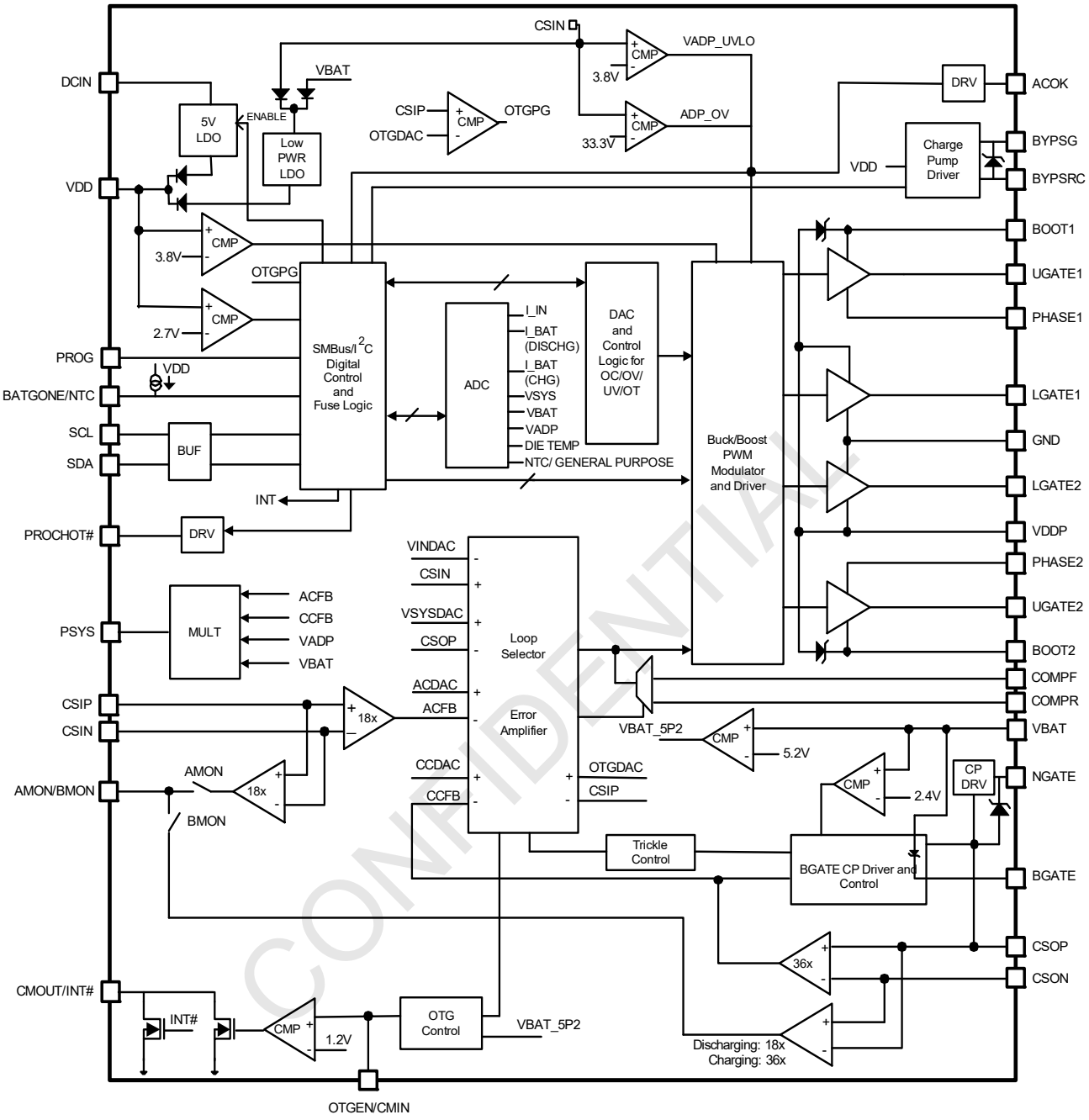
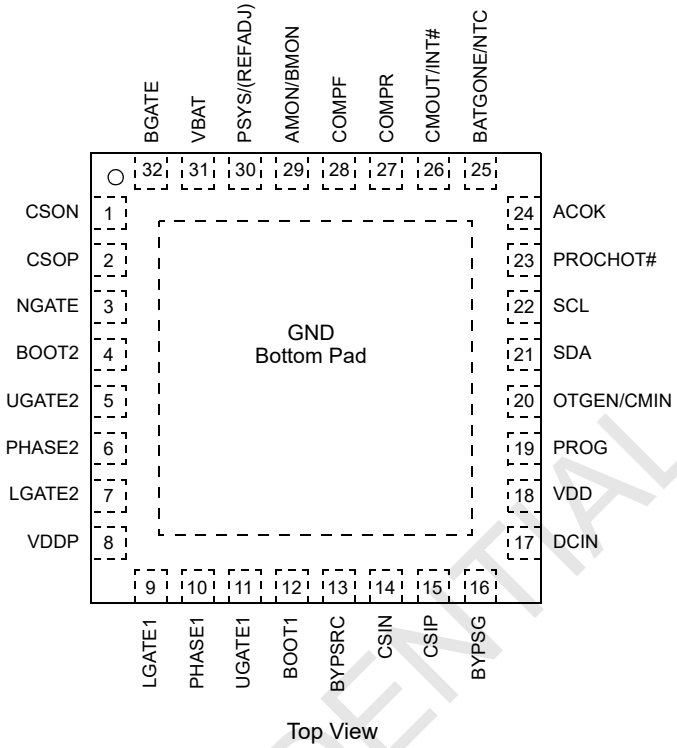


Figure 4. Block Diagram

2. Pin Information

2.1 Pin Assignments



Top View

2.2 Pin Descriptions

Pin Number	Pin Name	Description
Bottom Pad	GND	Signal common to the IC. Unless otherwise stated, signals are referenced to the GND pin. Use the bottom pad as the thermal pad for heat dissipation.
1	CSON	Battery current sense (–) input. Connect to the battery current resistor negative input. Place a ceramic capacitor between CSOP and CSON to provide Differential mode filtering.
2	CSOP	Battery current sense (+) input. Connect to the battery current resistor positive input. Place a ceramic capacitor between CSOP and CSON to provide Differential mode filtering. Reference input for NGATE. Sense node for VSYS voltage. Use a Kelvin line between the VSYS sense point and the CSOP pin.
3	NGATE	Gate drive output of the N-channel MOSFET between CSOP and VSYS. When NGATE is turned on, it is pumped 5V above CSOP. If the NGATE FET is not populated, leave this pin floating.
4	BOOT2	High-side MOSFET Q_4 gate driver supply. Connect a 0.47µF MLCC capacitor across the BOOT2 and PHASE2 pins. This boot capacitor is charged through an internal boot diode connected from the VDDP to BOOT2 pins when the PHASE2 pin drops below VDDP minus the voltage drop across the internal boot diode. The bootstrap capacitor must have an effective capacitance higher than 0.25µF at 5V and x50 effective high-side MOSFET gate capacitance.
5	UGATE2	High-side MOSFET Q_4 gate drive.
6	PHASE2	Current return path for the high-side MOSFET Q_4 gate drive. Connect this pin to the node consisting of the high-side MOSFET Q_4 source, the low-side MOSFET Q_3 drain, and one terminal of the inductor.
7	LGATE2	Low-side MOSFET Q_3 gate drive.

Pin Number	Pin Name	Description
8	VDDP	Power supply for the gate drivers. Connect to the VDD pin through a resistor and a 4.7µF (10V) MLCC capacitor to GND. The capacitor must have an effective capacitance higher than 0.4µF at 5V and x1.6 effective capacitance at the Boot pin at 5V.
9	LGATE1	Low-side MOSFET Q_2 gate drive.
10	PHASE1	Current return path for the high-side MOSFET Q1 gate drive. Connect this pin to the node consisting of the high-side MOSFET Q1 source, the low-side MOSFET Q2 drain, and one terminal of the inductor.
11	UGATE1	High-side MOSFET Q1 gate drive.
12	BOOT1	High-side MOSFET Q1 gate driver supply. Connect a 0.47µF MLCC capacitor across the BOOT1 and PHASE1 pins. The boot capacitor is charged through an internal boot diode connected from the VDDP to BOOT1 pins when the PHASE1 pin drops below VDDP minus the voltage drop across the internal boot diode. The bootstrap capacitor must have an effective capacitance higher than 0.25µF at 5V and x50 effective high-side MOSFET gate capacitance.
13	BYPSRC	N-channel MOSFET source input reference for bypass FETs. If not populating bypass FETs, this pin must be tied to VDDP.
14	CSIN	Connect to the input current sense resistor negative input. Input for sensing input voltage and phase comparator. Also used for sensing Q_1 drain for the modulator and VIN in forward-modes and VOUT for the modulator in reverse-modes. Use a Kelvin line between the voltage sense point and the CSIN pin.
15	CSIP	Connect to the input current sense resistor positive input through a resistor. Place a ceramic capacitor between CSIP and CSIN to provide differential-mode filtering.
16	BYPSG	Gate drive output of the N-channel MOSFET bypass FETs, pumped 5V above BYPSRC. If bypass FETs are not populated, this pin can be left floating.
17	DCIN	Input of an internal LDO providing power to the IC. Connect with a diode or from the adapter and system outputs. Bypass this pin with an MLCC capacitor and a resistor for filtering. Connect a 10Ω DCIN resistor between the DCIN pin and the VADP/VSYS diodes, and connect a 4.7µF (50V) DCIN capacitor to GND. The capacitor must have an effective capacitance higher than 0.4µF at 30V.
18	VDD	Output of the internal LDO; provides the bias power for the internal analog and digital circuit. Connect a 4.7µF (10V) MLCC capacitor to GND. The capacitor must have an effective capacitance higher than 0.4µF at 5V and x1.6 effective capacitance at the Boot pin at 5V. If V_{DD} is pulled below 2.5V, the RAA489110 resets all the SMBus register values to the default.
19	PROG	A resistor from the PROG pin to GND sets the following configurations: ▪ Default number of battery cells in series ▪ Default switching frequency ▪ Default adapter current limit value ▪ PSYS or REFADJ functionality See Table 18 for programming options.
20	OTGEN/ CMIN	Input pin. OTG function enable pin, stand-alone comparator input pin, or FRS/supplemental mode control input pin. When the OTG function is enabled and the general purpose comparator is disabled, pulling this pin high can activate the OTG function. When the general purpose comparator is enabled, this pin is the general purpose comparator input. This pin can also be used as the control input pin for fast role swap (FRS) or supplemental mode.
21	SDA	SMBus data I/O. Connect to the data line from the host controller or smart battery. Connect a 10k pull-up resistor according to the SMBus specification.
22	SCL	SMBus clock I/O. Connect to the clock line from the host controller or smart battery. Connect a 10k pull-up resistor according to the SMBus specification.
23	PROCHOT#	Open-drain output. Pulled low when ACHOT, DCHOT, or Low_VSYS are detected. IMVP compliant. Use SMBus commands to pull low with OTGHOT, BATGONE, ACOK, and the general purpose comparator (see Table 7).

Pin Number	Pin Name	Description
24	ACOK	Open-drain output. Adapter presence indicator output to indicate the adapter is ready according to a fixed undervoltage threshold or a programmable register threshold.
25	BATGONE/ NTC	Input pin to the IC. Logic high on this pin indicates the battery has been removed. Logic low on this pin indicates the battery is present. BATGONE pin logic high (pull up to VDD) forces the BGATE FET to turn off in any circumstances. A current source on this pin pulls it high if open, but if a battery is present with an NTC to GND (10kΩ at +25°C thermistor), the NTC resistor pulls down on the pin, indicating a battery is present. Next, the pull-up current source generates a voltage on the NTC that is measured by the part to determine temperature. If NTC and BATGONE are disabled, this pin can be used as a general ADC input. For any pin that is hot-plugged, such as BATGONE/NTC, a 10kΩ resistor is required to reduce any negative voltage on the pin.
26	CMOUT/ INT#	Open-drain output. The interrupt function is an active-low output and the stand-alone comparator selectable output. When configured, it is the general purpose comparator output. When configured to disable the CMOUT function, it is used as an interrupt for other functions and goes low when an interrupt function is detected. The interrupt status register must be read to clear the latch.
27	COMPR	Error amplifier output for Reverse/OTG mode. Connect a compensation network externally from COMPR to GND.
28	COMPF	Error amplifier output for forward/charging mode. Connect a compensation network externally from COMPF to GND.
29	AMON/ BMON	Adapter current, OTG output current, battery charging current, or battery discharging current monitor output. V_{AMON} = 18x (V_{CSIP} - V_{CSIN}) for adapter current monitor $V_{OTGCMON}$ = 18x (V_{CSIN} - V_{CSIP}) for OTG output current monitor $V_{BMON\_DISCHARGING}$ = 18x (V_{CSON} - V_{CSOP}) for battery discharging current monitor $V_{BMON\_CHARGING}$ = 36x (V_{CSOP} - V_{CSON}) for battery charging current monitor Add an RC filter from the AMON/BMON pin to ground. Filter value 4.5kΩ resistor and a 220nF capacitor.
30	PSYS/ (REFADJ)	Current source output that indicates the whole platform power consumption. (REFADJ - Separate pin functionality determined by the PROG pin. This pin is used as the feedback pin for current input to modify OTG output voltage by pushing/pulling current to support QC3.0 and other protocol controllers).
31	VBAT	Battery voltage sensing. Used for trickle charging detection, ideal diode mode control, and charge pump reference for BGATE. Connect an optional ceramic capacitor from VBAT to GND.
32	BGATE	Battery gate drive output to the N-channel MOSFET connecting the system and the battery. When BGATE turns on, it is pumped 5V above the VBAT input pin voltage.

3. Specifications

3.1 Absolute Maximum Ratings

Caution: Do not operate at or near the maximum ratings listed for extended periods of time. Exposure to such conditions can adversely impact product reliability and result in failures not covered by warranty.

Parameter	Minimum	Maximum	Unit
VDD, VDDP	-0.3	+6.5	V
COMPF, COMPR, OTGEN/CMIN, BATGONE, PROG			
ACOK, AMON/BMON, PSYS			
SCL, SDA, PROCHOT#, CMOUT/INT#			
(BYPSG - BYPSRC), (NGATE - CSOP), (BGATE - VBAT)			
(BOOT1 - PHASE1), (BOOT2 - PHASE2)			
BOOT1	-0.3	VDDP + 36	V
BOOT2	-0.3	VDDP + 27	V
CSIP, CSIN, DCIN, BYPSRC	-0.3	+36	V
DCIN - VDD	-0.3	+31	
BOOT1 - VDDP	-1.5	+36	V
BOOT2 - VDDP	-0.9	+27	V
(BOOT1 - UGATE1), (BOOT2 - UGATE2)	-0.3, -2 (<20ns)	+6.5	V
LGATE1, LGATE2			
(VDDP - LGATE1), (VDDP - LGATE2)			
(UGATE1 - PHASE1), (UGATE2 - PHASE2)			
PHASE1	-0.3, -4 (<20ns)	+36, +39(<20ns)	V
PHASE2	-0.3, -2 (<20ns)	+24	V
VBAT, CSOP, CSON	-0.3	+24	V
(CSIP - CSIN), (CSOP - CSON)	-0.3	+0.3	V
Human Body Model (Tested per JS-001-2017)	-	1.5	kV
Charged Device Model (Tested per JS-002-2018)	-	750	V
Latch-Up (Tested per JESD78E; Class 2, Level A)	-	100	mA

3.2 Thermal Information

Parameter	Package	Symbol	Conditions	Typical Value	Unit
Thermal Resistance	32 Ld TQFN Package	θ_{JA}[1]	Junction to air	38	°C/W
		θ_{JC}[2]	Junction to case	2.5	°C/W

1. θ_{JA} is measured in free air with the component mounted on a high-effective thermal conductivity test board with direct attach features. See TB379.
2. For θ_{JC}, the case temperature location is the center of the exposed metal pad on the package underside.

Parameter	Minimum	Maximum	Unit
Junction Temperature Range (T_J)	-40	+125	°C
Storage Temperature Range (T_S)	-65	+150	°C
Pb-Free Reflow Profile	see TB493		

3.3 Recommended Operating Conditions

Parameter	Minimum	Maximum	Unit
Ambient Temperature			
RAA489110ARGNP	-10	+100	°C
RAA489110A3GNP	-40	+100	°C
Junction Temperature			
RAA489110ARGNP	-10	+125	°C
RAA489110A3GNP	-40	+125	°C
Adapter Voltage	+5	+30	V

3.4 Electrical Specifications

Operating conditions: CSIP = CSIN = 5V and 28V, V_{SYS} = V_{BAT} = CSOP = CSON = 8V, unless otherwise noted. **Boldface limits apply across the junction temperature range, -10°C to +125°C unless otherwise specified.**

Parameter	Symbol	Test Conditions	Min[1]	Typ	Max[1]	Unit
UVLO/ACOK						
V_{ADP} (CSIN) ACOK Threshold[2]	VADP_ACOK_r	CSIN = ADP	**3.5**	3.7	**3.9**	V
V_{ADP} (CSIN) ACOK Hysteresis[2]	VADP_ACOK_h	-	-	600	-	mV
V_{BAT} 5P2V Rising	VBAT_5P2_r	-	**4.95**	5.20	**5.65**	V
V_{BAT} 5P2V Hysteresis	VBAT_5P2_h	-	-	450	-	mV
V_{DD} 2P7 POR Falling Threshold	VDD_2P7_f	SMBus and BGATE/BMON Active	**2.5**	2.7	**2.9**	V
V_{DD} 2P7 POR Hysteresis[2]	VDD_2P7_h	-	-	150	-	mV
V_{DD} 3P8 POR Rising	VDD_3P8_r	Modulator and Gate Driver Active	**3.6**	3.8	**4**	V
V_{DD} 3P8 POR Hysteresis	VDD_3P8_h	-	-	150	-	mV
ACOK Input Leakage Current	-	-	-	-	**1**	µA
ACOK, Output Sink Current	-	V_{ACOK} = 0.4V	**4**	-	-	mA
Linear Regulator						
V_{DD} Output Voltage	V_{DD}	6V < V_{DCIN} < 30V, no load	**4.5**	5	**5.5**	V
V_{DD} Dropout Voltage	VDD_dp	30mA, V_{DCIN} = 4V	-	85	-	mV
V_{DD} Overcurrent Threshold	VDD_OC	RAA489110ARGNP	**90**	115	**165**	mA
		RAA489110A3GNP	**90**	115	**165**	mA

Operating conditions: CSIP = CSIN = 5V and 28V, V_{SYS} = V_{BAT} = CSOP = CSON = 8V, unless otherwise noted. **Boldface limits apply across the junction temperature range, -10°C to +125°C unless otherwise specified. (Cont.)**

Parameter	Symbol	Test Conditions	Min[1]	Typ	Max[1]	Unit
Battery Current	I_{BAT1}	Battery only, BGATE off, NGATE off, GPCOMP off, PSYS OFF, BMON OFF, V_{BAT} = 8.4V, DCIN current comes from battery, $I_{BAT} = I_{VBAT} + I_{CSOP} + I_{CSON} + I_{DCIN}$	**5**	20	**30**	µA
	I_{BAT2}	Battery only, BGATE normal, NGATE on, GPCOMP on, PSYS OFF, BMON OFF, V_{BAT} = 16.8V, DCIN current comes from battery, $I_{BAT} = I_{VBAT} + I_{CSOP} + I_{CSON} + I_{DCIN}$	**15**	30	**55**	µA
	I_{BAT3}	Battery only, BGATE normal, NGATE on, GPCOMP on, PSYS ON, BMON ON, ADC on V_{BAT} = 16.8V, DCIN current comes from battery, $I_{BAT} = I_{VBAT} + I_{CSOP} + I_{CSON} + I_{DCIN}$	**700**	1100	**1200**	µA
	I_{Q1}	VSYS state, no switching V_{BAT} = 12.6V, V_{ADP} = 28V $I_Q = I_{VBAT} + I_{CSOP} + I_{CSON} + I_{DCIN} + I_{PH1} + I_{PH2} + I_{CSIP} + I_{CSIN} + I_{BYPSRC}$	-	2.25	**2.35**	mA
	I_{Q2}	OTG State, no switching V_{BAT} = 8.4V, V_{OTG} = 5V $I_Q = I_{VBAT} + I_{CSOP} + I_{CSON} + I_{DCIN} + I_{PH1} + I_{PH2} + I_{CSIP} + I_{CSIN} + I_{BYPSRC}$	-	1.9	**2.1**	mA
Adapter Current Regulation, R_{s1} = 20mΩ						
Adapter Current Accuracy	-	$V_{CSIP} - V_{CSIN}$ = 100mV (5A)	**-2**	-	**2**	%
		$V_{CSIP} - V_{CSIN}$ = 80mV (4A)	**-2.25**	-	**2.25**	%
		$V_{CSIP} - V_{CSIN}$ = 60mV (3A)	**-2.5**	-	**2.5**	%
		$V_{CSIP} - V_{CSIN}$ = 40mV (2A)	**-2.5**	-	**2.5**	%
		$V_{CSIP} - V_{CSIN}$ = 20mV (1A)	**-4**	-	**4**	%
		$V_{CSIP} - V_{CSIN}$ = 10mV (0.5A)	**-10**	-	**10**	%
		$V_{CSIP} - V_{CSIN}$ = 5mV (0.25A)	**-16**	-	**16**	%
Adapter Current PROCHOT# Threshold R_{s1} = 20mΩ	$I_{ADP\_HOT\_TH10}$	ACProchot = 0x1580H (5504mA)	-1.5	-	1.5	%
		ACProchot = 0x0FA0H (4000mA)	-2	-	2	%
		ACProchot = 0x0A80H (2688mA)	-3	-	3	%
		ACProchot = 0x07E0H (2016mA)	-4	-	4	%
		ACProchot = 0x0400H (1024mA)	-6	-	6	%
System Voltage Regulation						
Maximum System Voltage Accuracy	-	MaxSystemVoltage for 2-cell, 3-cell, and 4-cell (8.4V, 12.6V, 16.8V) (RAA489110ARGNP) and 2-cell and 3-cell (8.4V, 12.6V) (RAA489110A3GNP)	**-0.5**	-	**0.5**	%
		MaxSystemVoltage for 4-cell (16.8V) (RAA489110A3GNP)	**-0.6**	-	**0.6**	%

Operating conditions: CSIP = CSIN = 5V and 28V, V_{SYS} = V_{BAT} = CSOP = CSON = 8V, unless otherwise noted. **Boldface limits apply across the junction temperature range, -10°C to +125°C unless otherwise specified. (Cont.)**

Parameter	Symbol	Test Conditions	Min[1]	Typ	Max[1]	Unit
Minimum System Voltage Accuracy	-	-	**-3**	-	**3**	%
Input Voltage Regulation Accuracy	-	V_{CSIN} = 4.096V	**3.98**	-	**4.22**	V
Charge Current Regulation, R_{s2} = 10mΩ (Limits apply across temperature range of 0°C to +60°C)						
Charge Current Accuracy	-	V_{CSOP} - V_{CSON} = 60mV (6A)	**-2.5**	-	**2.5**	%
		V_{CSOP} - V_{CSON} = 50mV (5A)	**-2.7**	-	**2.7**	%
		V_{CSOP} - V_{CSON} = 40mV (4A)	**-3.0**	-	**3.0**	%
		V_{CSOP} - V_{CSON} = 30mV (3A)	**-3.5**	-	**3.5**	%
		V_{CSOP} - V_{CSON} = 20mV (2A)	**-4.0**	-	**4.0**	%
		V_{CSOP} - V_{CSON} = 10mV (1A)	**-6.0**	-	**6.0**	%
		V_{CSOP} - V_{CSON} = 5mV (0.5A)	**-12.0**	-	**12.0**	%
Trickle Charging Current Regulation, R_{s2} = 10mΩ (Limits apply across temperature range of 0°C to +60°C)						
Trickle Charge Current Accuracy	-	Control2 register Bits[15:13] = 001	**20**	64	**100**	mA
		Control2 register Bits[15:13] = 010	**55**	96	**135**	mA
		Control2 register Bits[15:13] = 011	**80**	128	**170**	mA
		Control2 register Bits[15:13] = 100	**112**	160	**208**	mA
		Control2 register Bits[15:13] = 101	**134**	192	**250**	mA
		Control2 register Bits[15:13] = 110	**157**	224	**291**	mA
		Control2 register Bits[15:13] = 111	**180**	256	**333**	mA
End of Charge Current Accuracy when Using Autonomous Charging	EOC	Control7 register Bits[9:8] = 00	**40**	105	**170**	mA
		Control7 register Bits[9:8] = 01	**5**	60	**120**	mA
		Control7 register Bits[9:8] = 10	**120**	190	**270**	mA
		Control7 register Bits[9:8] = 11	**75**	145	**230**	mA
Auto Recharge Threshold Relative to Maximum System Voltage	ART	2-cell battery	-	490	-	mV
		3-cell battery	-	680	-	mV
		4-cell battery	-	820	-	mV
Ideal Diode Mode						
Entering Ideal Diode Mode VSYS Voltage Threshold	-	BGATE off, VSYS falling V_{VBAT} - V_{VSYS}	**110**	180	**255**	mV
Exiting Ideal Diode Mode Battery Discharging Current Threshold	-	R_{s2} = 10mΩ	**25**	125	**230**	mA
Exiting Ideal Diode Mode Battery Charging Current Threshold	-	R_{s2} = 10mΩ	**80**	165	**255**	mA

Operating conditions: CSIP = CSIN = 5V and 28V, V_{SYS} = V_{BAT} = CSOP = CSON = 8V, unless otherwise noted. **Boldface limits apply across the junction temperature range, -10°C to +125°C unless otherwise specified. (Cont.)**

Parameter	Symbol	Test Conditions	Min[1]	Typ	Max[1]	Unit
AMON/BMON						
Input Current Sense Amplifier, R_{S1} = 20mΩ						
CSIP/CSIN Input Voltage Range	$V_{CSIP/N}$	-	**4**	-	**30**	V
AMON Gain	-	-	-	17.97	-	V/V
AMON Accuracy V_{AMON} = AMON gain x (CSIP - CSIN)	-	V_{CSIP} - V_{CSIN} = 100mV (5A), CSIP = 5V, 28V	**-2.5**	-	**2.5**	%
		V_{CSIP} - V_{CSIN} = 60mV (3A), CSIP = 5V, 28V	**-3.0**	-	**3.0**	%
		V_{CSIP} - V_{CSIN} = 20mV (1A), CSIP = 5V, 28V	**-5.5**	-	**5.5**	%
		V_{CSIP} - V_{CSIN} = 10mV (0.5A), CSIP = 5V, 28V	**-12.0**	-	**12.0**	%
		V_{CSIP} - V_{CSIN} = 2mV (0.1A), CSIP = 5V, 28V	**-30.0**	-	**30.0**	%
Reverse AMON Gain	-	-	-	17.9	-	V/V
AMON Accuracy V_{AMON} = AMON gain x (CSIN - CSIP)	-	V_{CSIN} - V_{CSIP} = 80mV (4A), CSIP = 5V, 28V	**-3.5**	-	**3.5**	%
		V_{CSIN} - V_{CSIP} = 60mV (3A), CSIP = 5V, 28V	**-4.5**	-	**4.5**	%
		V_{CSIN} - V_{CSIP} = 20mV (1A), CSIP = 5V, 28V	**-6.0**	-	**6.0**	%
		V_{CSIN} - V_{CSIP} = 10mV (0.5A), CSIP = 5V, 28V	**-12.0**	-	**12.0**	%
		V_{CSIN} - V_{CSIP} = 5.12mV (0.256A), CSIP = 5V, 28V	**-25.0**	-	**25.0**	%
AMON Minimum Output Voltage	-	V_{CSIP} - V_{CSIN} = 0V	-	-	**30**	mV
Discharge Current Sense Amplifier, R_{S2} = 10mΩ						
BMON Gain (Battery Discharging)	-	-	-	17.97	-	V/V
BMON Accuracy V_{BMON} = BMON Gain x (V_{CSON} - V_{CSOP})	-	V_{CSON} - V_{CSOP} = 100mV (10A), V_{CSON} = 8V	**-2**	-	**2**	%
		V_{CSON} - V_{CSOP} = 20mV (2A), V_{CSON} = 8V	**-6**	-	**6**	%
		V_{CSON} - V_{CSOP} = 10mV (1A), V_{CSON} = 8V	**-10**	-	**10**	%
		V_{CSON} - V_{CSOP} = 6mV (0.6A), V_{CSON} = 8V	**-20**	-	**20**	%

Operating conditions: CSIP = CSIN = 5V and 28V, V_{SYS} = V_{BAT} = CSOP = CSON = 8V, unless otherwise noted. **Boldface limits apply across the junction temperature range, -10°C to +125°C unless otherwise specified. (Cont.)**

Parameter	Symbol	Test Conditions	Min[1]	Typ	Max[1]	Unit
BMON Charging Accuracy, R_{s2} = 10mΩ (Limits apply across temperature range of 0°C to +60°C)						
BMON Gain (Battery Charging)	-	-	-	36.18	-	V/V
BMON Accuracy V_{BMON} = BMON Gain x (V_{CSON} - V_{CSOP})	-	V_{CSOP} - V_{CSON} = 60mV (6A), V_{CSON} = 8V	-3	-	3	%
		V_{CSOP} - V_{CSON} = 40mV (4A), V_{CSON} = 8V	-4	-	4	%
		V_{CSOP} - V_{CSON} = 10mV (1A), V_{CSON} = 8V	-10	-	10	%
		V_{CSOP} - V_{CSON} = 5mV (0.5A), V_{CSON} = 8V	-25	-	25	%
BMON Minimum Output Voltage	-	V_{CSOP} - V_{CSON} = 0V	-	-	30	mV
Discharging Current PROCHOT# Threshold	$I_{DIS\_HOT\_TH}$	R_{s2} = 10mΩ, DCProchot = 2.048A	1.77	2.03	2.39	A
Discharging Current PROCHOT# Threshold, Battery Only	$I_{DIS\_HOT\_TH}$	R_{s2} = 10mΩ, DCProchot = 12A	9.4	12.5	17	A
		R_{s2} = 10mΩ, DCProchot = 6A	4.5	6	8	A
AMON/BMON Source Resistance[2]	-	-	-	-	5	Ω
AMON/BMON Sink Resistance[2]	-	-	-	-	5	Ω
BATGONE and OTGEN						
OTGEN High-Level Input Voltage	-	-	**0.9**	-	-	V
OTGEN Low-Level Input Voltage	-	-	-	-	**0.4**	V
BATGONE High-Level Input Voltage	-	-	**V_{DD} - 0.6**	-	-	V
BATGONE Low-Level Input Voltage	-	-	-	-	**V_{DD} - 1.2**	V
Pull-Up Current	-	$V_{BATGONE}$ = 5V; V_{OTGEN} = 3.3V, 5V	-	1	-	µA
NTC Step1 Pull-Up Current	-	-	**62**	65	**68**	µA
NTC Step2 Pull-Up Current	-	-	**126**	130	**134**	µA
NTC Step3 Pull-Up Current	-	-	**250**	260	**270**	µA
PROCHOT#						
PROCHOT# Debounce Time[2]	-	Control2 register Bit [10:9] = 11	**0.85**	1	**1.15**	ms
		Control2 register Bit [10:9] = 10	**425**	500	**575**	µs
PROCHOT# Duration Time[2]	-	Control2 register Bit [8:6] = 000	**8.5**	10	**11.5**	ms
		Control2 register Bit [8:6] = 001	**17**	20	**23**	ms

Operating conditions: CSIP = CSIN = 5V and 28V, V_{SYS} = V_{BAT} = CSOP = CSON = 8V, unless otherwise noted. **Boldface limits apply across the junction temperature range, -10°C to +125°C unless otherwise specified. (Cont.)**

Parameter	Symbol	Test Conditions	Min[1]	Typ	Max[1]	Unit
Low VSYS PROCHOT# Trip Falling Threshold	$V_{LOW\_VSYS\_HOT}$	Control8 register Bits[12:10] = 000	**5.1**	5.3	**5.5**	V
		Control8 register Bits[12:10] = 001	**4.5**	4.7	**4.9**	V
		Control8 register Bits[12:10] = 010	**5.3**	5.7	**5.7**	V
		Control8 register Bits[12:10] = 011	**5.7**	5.9	**6.1**	V
		Control8 register Bits[12:10] = 100	**5.9**	6.1	**6.3**	V
		Control8 register Bits[12:10] = 101	**6.1**	6.3	**6.5**	V
		Control8 register Bits[12:10] = 110	**6.3**	6.5	**6.7**	V
		Control8 register Bits[12:10] = 111	**6.5**	6.7	**6.9**	V
PROCHOT# Input Leakage Current	-	-	-	-	**1**	µA
PROCHOT#, Output Sink Current	-	$V_{PROCHOT}$ = 0.4V	**4**	-	-	mA
PSYS[2]						
PSYS Output Current R_{s1} = 20mΩ R_{s2} = 10mΩ Control3 Bits[9:8] = 11 Control4 Bit[11] = 0 I_{PSYS} = Gain × Power + Offset	I_{PSYS}	V_{CSIP} = 12V, $V_{CSIP - CSIN}$ = 80mV, V_{BAT} = 12V, $V_{CSOP - CSON}$ = 0mV	**-5**	-	**5**	%
		V_{CSIP} = 28V, $V_{CSIP - CSIN}$ = 0mV, V_{BAT} = 8.4V, $V_{CSOP - CSON}$ = 50mV	**-5**	-	**5**	%
		V_{CSIP} = 28V, $V_{CSIP - CSIN}$ = 80mV, V_{BAT} = 12V, $V_{CSOP - CSON}$ = 20mV	**-5**	-	**5**	%
Maximum PSYS Output Voltage	V_{PSYS_MAX}	-	**3**	-	-	V
PSYS Gain R_{s1}:R_{s2} = 20mΩ:10mΩ or 10mΩ:10mΩ Control4 Bit[11] = 0 or 1	V_{PSYS_G}	Control3 Bits[9:8] = 11 (default), offset - 0.0µA	-	0.65	-	µA/W
		Control3 Bits[9:8] = 10, offset - 0.0µA	-	0.43	-	µA/W
		Control3 Bits[9:8] = 01, offset - 0.0µA	-	1.33	-	µA/W
		Control3 Bits[9:8] = 00, offset - 0.0µA	-	0.99	-	µA/W

Operating conditions: CSIP = CSIN = 5V and 28V, V_{SYS} = V_{BAT} = CSOP = CSON = 8V, unless otherwise noted. **Boldface limits apply across the junction temperature range, -10°C to +125°C unless otherwise specified. (Cont.)**

Parameter	Symbol	Test Conditions	Min[1]	Typ	Max[1]	Unit
OTG						
OTG Voltage	-	OTG voltage register, DAC = Default = 0x08B0h	**4.93**	5	**5.15**	V
OTG Current	-	R_{s1} = 20mΩ OTG current register = 512mA OTG voltage register = 5.004V, 12.006V	**450**	512	**585**	mA
		R_{s1} = 20mΩ OTG current register = 1024mA OTG voltage register = 5.004V, 12.006V	**960**	1024	**1100**	mA
		R_{s1} = 20mΩ OTG current register = 1504mA OTG voltage register = 5.004V, 12.006V	**1455**	1504	**1575**	mA
		R_{s1} = 20mΩ OTG current register = 3008mA OTG voltage register = 5.004V, 12.006V	**2955**	3008	**3095**	mA
		R_{s1} = 20mΩ OTG current register = 4096mA OTG voltage register = 5.004V, 12.006V	**3975**	4096	**4240**	mA
Analog Support of OTG Output[2]	-	When configured OTG_EN = 1	-	-	150	µs
General Purpose Comparator						
General Purpose Comparator Rising Threshold	-	Reference = 1.2V	**1.15**	1.2	**1.25**	V
		Reference = 2V (not available in Battery mode)	**1.95**	2	**2.05**	V
General Purpose Comparator Hysteresis	-	Reference = 1.2V	**25**	40	**50**	mV
		Reference = 2V (not available in Battery mode)	**25**	40	**50**	mV
CMOUT/INT# Input Leakage Current	-	-	-	-	**1**	µA
CMOUT/INT#, Output Sink Current	-	V_{CMOUT} = 0.4V	**4**	-	-	mA

Operating conditions: CSIP = CSIN = 5V and 28V, V_{SYS} = V_{BAT} = CSOP = CSON = 8V, unless otherwise noted. **Boldface limits apply across the junction temperature range, -10°C to +125°C unless otherwise specified. (Cont.)**

Parameter	Symbol	Test Conditions	Min[1]	Typ	Max[1]	Unit
Protection						
BYPASS/PTM Absolute Overvoltage Rising Threshold	-	-	**23**	23.4	**24**	V
BYPASS/PTM Absolute Overvoltage Hysteresis	-	-	-	375	-	mV
VSYS Absolute Overvoltage Rising Threshold	-	-	**23**	23.4	**24**	V
VSYS Absolute Overvoltage Hysteresis	-	-	-	690	-	mV
VSYS Overvoltage Rising Threshold	-	MaxSystemVoltage register value = 8.4V	**8.9**	9.15	**9.35**	V
VSYS Overvoltage Hysteresis	-		**250**	375	**550**	mV
VSYS OK Threshold	-	-	**0.45**	0.6	**0.75**	V
VSYS OK Source Current	-	-	-	10	-	mA
Adapter Way Overcurrent Rising Threshold	-	R_{s1} = 20mΩ	**10**	11.5	**13**	A
Battery Discharge Way Overcurrent Rising Threshold	-	R_{s2} = 10mΩ	**16**	18	**20**	A
Over-Temperature Threshold[2]	-	-	**140**	150	**160**	°C
Adapter Overvoltage Rising Threshold	-	CSIN = ADP	**32.5**	33.3	**33.95**	V
Adapter Overvoltage Hysteresis	-	-	**460**	525	**680**	mV
OTG Undervoltage Falling Threshold	-	OTG voltage setting = 5.004V Register 0x49 = 0x08B0h	**2.85**	3.3	**3.75**	V
OTG Overvoltage Rising Threshold	-	OTG voltage setting = 5.004V Register 0x49 = 0x08B0h	**6.2**	6.8	**7.4**	V
Oscillator						
Oscillator Frequency, Digital Core Only	-	-	**0.85**	1	**1.15**	MHz
Digital Debounce Time Accuracy[2]	-	-	**-15**	-	**15**	%
Miscellaneous						
Switching Frequency Accuracy	-	V_{COMP} > 1.7V and not in period stretching	**-15**	-	**15**	%
Battery Learn Mode Auto-Exit Threshold	-	MinSystemVoltage = 5.376V Control1 register Bit[13] = 1	**5.05**	5.35	**5.7**	V
Battery Learn Mode Auto-Exit Hysteresis [2])	-		**180**	330	**480**	mV

Operating conditions: CSIP = CSIN = 5V and 28V, V_{SYS} = V_{BAT} = CSOP = CSON = 8V, unless otherwise noted. **Boldface limits apply across the junction temperature range, -10°C to +125°C unless otherwise specified. (Cont.)**

Parameter	Symbol	Test Conditions	Min[1]	Typ	Max[1]	Unit
Gate Driver[2]						
UGATE1 Pull-Up Resistance	$UG1_{RPU}$	100mA source current	-	800	**1200**	mΩ
UGATE1 Source Current	$UG1_{SRC}$	V_{UGATE1} - V_{PHASE1} = 2.5V	**1.3**	2	-	A
UGATE1 Pull-Down Resistance	$UG1_{RPD}$	100mA sink current	-	350	**475**	mΩ
UGATE1 Sink Current	$UG1_{SNK}$	V_{UGATE1} - V_{PHASE1} = 2.5V	**1.9**	2.8	-	A
LGATE1 Pull-Up Resistance	$LG1_{RPU}$	100mA source current	-	800	**1200**	mΩ
LGATE1 Source Current	$LG1_{SRC}$	V_{LGATE1} - GND = 2.5V	**1.3**	2	-	A
LGATE1 Pull-Down Resistance	$LG1_{RPD}$	100mA sink current	-	300	**450**	mΩ
LGATE1 Sink Current	$LG1_{SNK}$	V_{LGATE1} - GND = 2.5V	**2.3**	3.5	-	A
LGATE2 Pull-Up Resistance	$LG2_{RPU}$	100mA source current	-	800	**1200**	mΩ
LGATE2 Source Current	$LG2_{SRC}$	V_{LGATE2} - GND = 2.5V	**1.3**	2	-	A
LGATE2 Pull-Down Resistance	$LG2_{RPD}$	100mA sink current	-	300	**450**	mΩ
LGATE2 Sink Current	$LG2_{SNK}$	V_{LGATE2} - GND = 2.5V	**2.3**	3.5	-	A
UGATE2 Pull-Up Resistance	$UG2_{RPU}$	100mA source current	-	800	**1200**	mΩ
UGATE2 Source Current	$UG2_{SRC}$	V_{UGATE2} - V_{PHASE2} = 2.5V	**1.3**	2	-	A
UGATE2 Pull-Down Resistance	$UG2_{RPD}$	100mA sink current	-	300	**450**	mΩ
UGATE2 Sink Current	$UG2_{SNK}$	V_{UGATE2} - V_{PHASE2} = 2.5V	**2.3**	3.5	-	A
UGATE1 to LGATE1 Dead Time	$t_{UG1LG1DEAD}$	-	**10**	20	**40**	ns
LGATE1 to UGATE1 Dead Time	$t_{LG1UG1DEAD}$	-	**10**	20	**40**	ns
LGATE2 to UGATE2 Dead Time	$t_{LG2UG2DEAD}$	-	**10**	20	**40**	ns
UGATE2 to LGATE2 Dead Time	$t_{UG2LG2DEAD}$	-	**10**	20	**40**	ns
Charge Pump Gate Drivers						
BYPSG Gate Drive Current	-	BYPSG Off BYPSG = V_{BYPSRC} + 2V	**490**	500	**513**	µA
NGATE Gate Drive Current	-	NGATE Off NGATE = V_{CSOP} + 2V	**605**	625	**645**	µA
BGATE Gate Drive Current	-	BGATE Off BGATE = V_{VBAT} + 2V	**165**	200	**250**	µA
BYPSG Gate Drive Current	-	BYPSG On V_{BYPSG} = V_{BYPSRC} + 2V, V_{BYPSRC} > 3.9V	**15**	40	**70**	µA
NGATE Gate Drive Current	-	NGATE On V_{NGATE} = V_{CSOP} + 2V, V_{CSOP} > 3.9V	**15**	40	**70**	µA

Operating conditions: CSIP = CSIN = 5V and 28V, V_{SYS} = V_{BAT} = CSOP = CSON = 8V, unless otherwise noted. **Boldface limits apply across the junction temperature range, -10°C to +125°C unless otherwise specified. (Cont.)**

Parameter	Symbol	Test Conditions	Min[1]	Typ	Max[1]	Unit
BGATE Gate Drive Current	-	BGATE On V_{BGATE} = V_{VBAT} + 2V, V_{VBAT} > 2.7V	**15**	40	**70**	µA
SMBus						
SDA/SCL Input Low Voltage	-	-	-	-	**0.7**	V
SDA/SCL Input High Voltage	-	-	**1.5**	-	-	V
SDA/SCL Input Bias Current	-	-	-	-	**1**	µA
SDA, Output Sink Current	-	V_{SDA} = 0.4V, on	**4**	-	-	mA

1. Parameters with MIN and/or MAX limits are 100% tested at +25°C, unless otherwise specified. Temperature limits established by characterization and are not production tested.
2. Limits established by characterization and are not production tested.

3.5 SMBus Timing Specification

Parameters[1]	Symbol	Test Conditions	Min[2]	Typ	Max[2]	Unit
SMBus Frequency	f_{SMB}	(Supports Standard-Mode and Fast-mode)	**10**	-	**400**	kHz
Bus Free Time	t_{BUF}	-	**4.7**	-	-	µs
Start Condition Hold Time from SCL	$t_{HD:STA}$	-	**4**	-	-	µs
Start Condition Set-Up Time from SCL	$t_{SU:STA}$	-	**4.7**	-	-	µs
Stop Condition Set-Up Time from SCL	$t_{SU:STO}$	-	**4**	-	-	µs
SDA Hold Time from SCL	$t_{HD:DAT}$	-	**300**	-	-	ns
SDA Set-Up Time from SCL	$t_{SU:DAT}$	-	**250**	-	-	ns
SCL Low Period	t_{LOW}	For SMBus Standard-mode	**4.7**	-	-	µs
SCL High Period	t_{HIGH}	For SMBus Standard-mode	**4**	-	-	µs
SMBus Inactivity Timeout	-	Maximum charging period without a SMBus Write to MaxSystemVoltage or ChargeCurrent register when enabled	**-**	175	-	s

1. Parameters with MIN and/or MAX limits are 100% tested at +25°C, unless otherwise specified. Temperature limits established by characterization and are not production tested.
2. Limits established by characterization and are not production tested.

4. Typical Performance

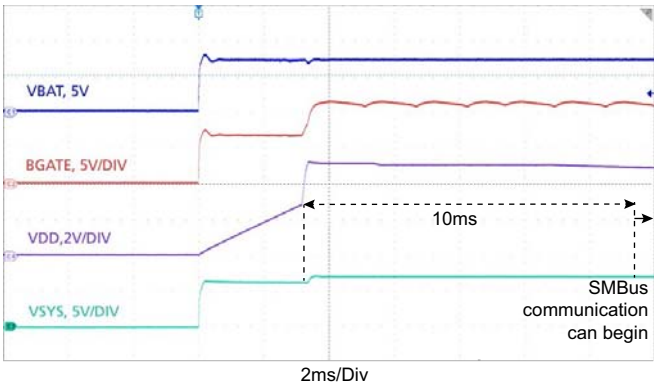


Figure 5. Start-Up Time with Battery for Communication

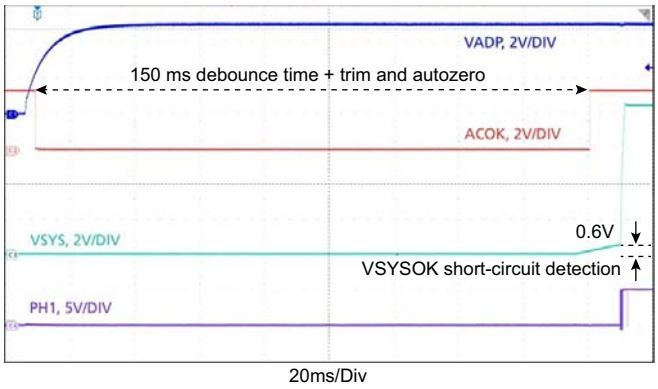


Figure 6. Start Up with 5V Adapter and ACOK Timing

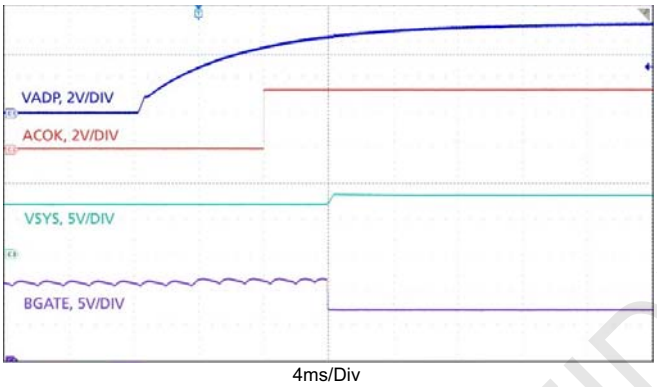


Figure 7. Adapter Insertion with Battery Connected. VADP: 0V → 5V, MaxSystemVoltage = 8.384V, VBAT = 7V, ChargeCurrent = 0A

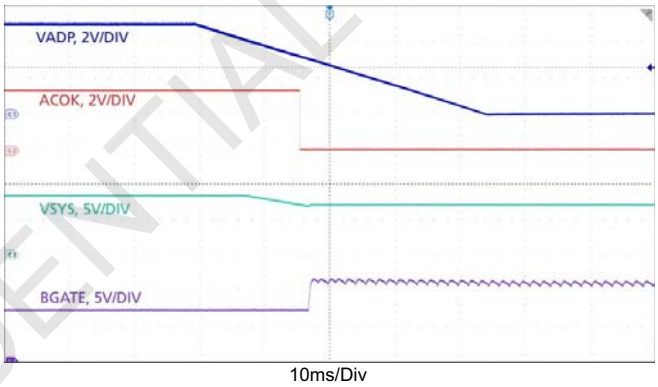


Figure 8. Adapter Removal with Battery Connected. VADP: 5V → 0V, MaxSystemVoltage = 8.384V, VBAT = 7V, ChargeCurrent = 0A, SystemLoad = 20mA

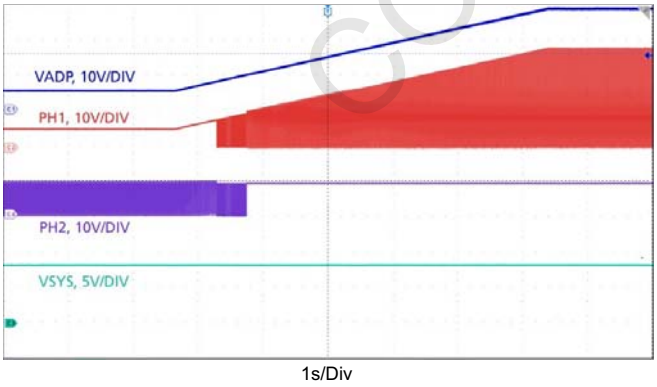


Figure 9. Adapter Voltage Ramp Up, Boost → Buck_Boost → Buck Operation Mode Transitions. VADP: 5V → 28V, SystemLoad = 200mA

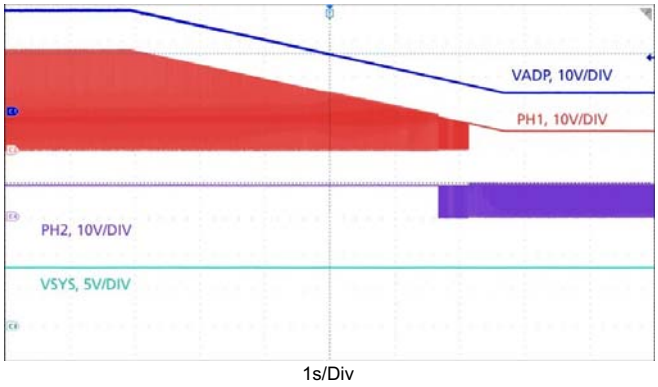


Figure 10. Adapter Voltage Ramp Down, Buck → Buck_Boost → Boost Operation Mode Transitions. VADP: 28V → 5V, SystemLoad = 200mA

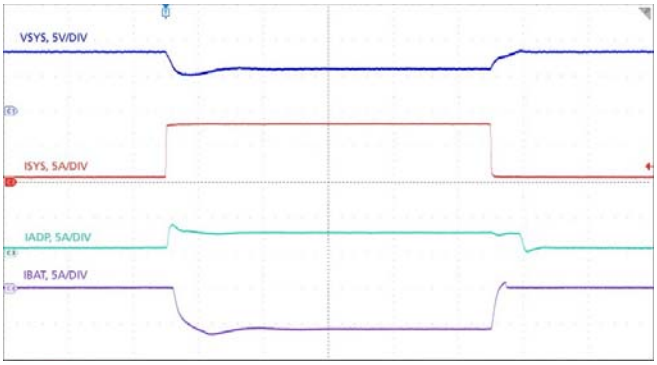


Figure 11. Boost Mode Transitions: Output Voltage Loop to/from Adapter Current Loop. VADP = 5V, VBAT = 7V, MaxSystemVoltage = 8.384V, AdapterCurrentLimit = 3A, ChargeCurrent = 0, SystemLoad: 0.5A → 8A → 0.5A

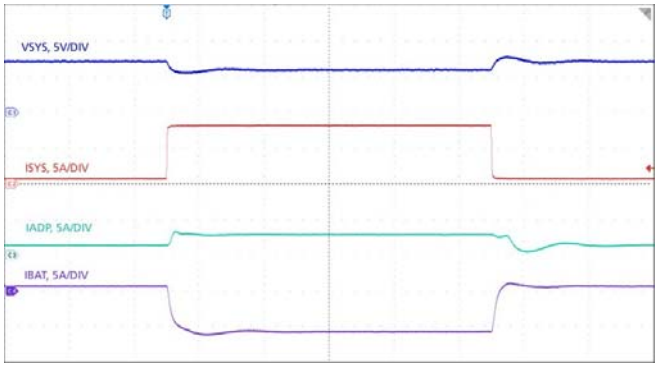


Figure 12. Boost Mode Transitions: Charge Current Loop to/from Adapter Current Loop. VADP = 5V, VBAT = 7V, MaxSystemVoltage = 8.384V, AdapterCurrentLimit = 3A, ChargeCurrent = 0.5A, SystemLoad: 0.5A → 8A → 0.5A

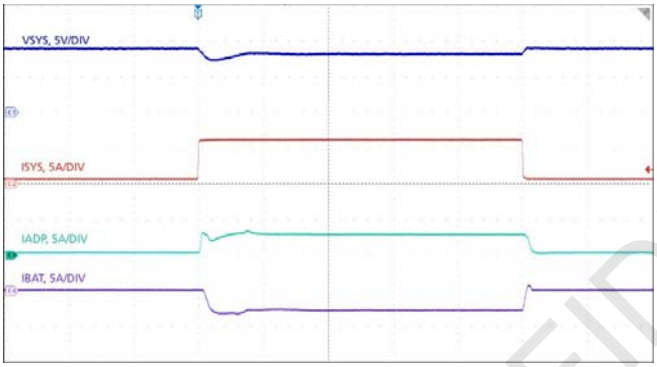


Figure 13. Buck_Boost Mode Transitions: Output Voltage Loop to/from Adapter Current Loop. VADP = 9V, VBAT = 8.4V, MaxSystemVoltage = 8.8V, AdapterCurrentLimit = 3A, ChargeCurrent = 0, SystemLoad: 0.5A → 6A → 0.5A, Buck_Boost_CCM_stretch_period = 2x

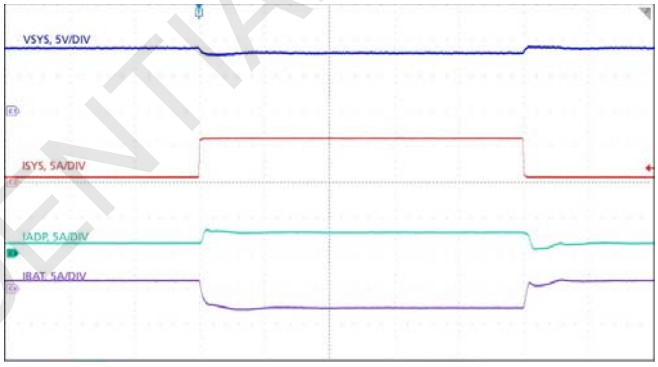


Figure 14. Buck_Boost Mode Transitions: Charge Current Loop to/from Adapter Current Loop. VADP = 9V, VBAT = 8.4V, MaxSystemVoltage = 8.8V, AdapterCurrentLimit = 3A, ChargeCurrent = 1A, SystemLoad: 0.5A → 6A → 0.5A, Buck_Boost_CCM_stretch_period = 2x

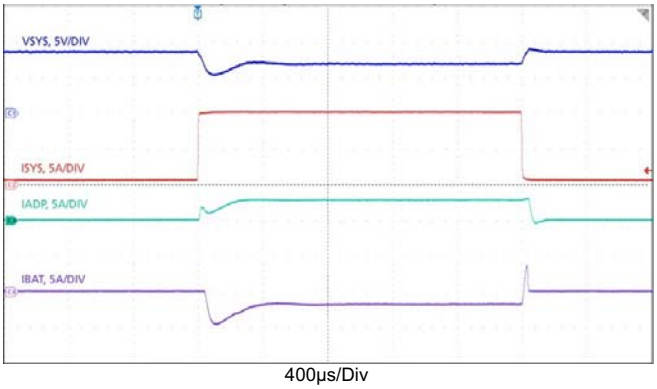


Figure 15. Buck Mode Transitions: Output Voltage Loop to/from Adapter Current Loop. VADP = 20V, VBAT = 7V, MaxSystemVoltage = 8.384V, AdapterCurrentLimit = 3A, ChargeCurrent = 0, SystemLoad: 0.5A → 10A → 0.5A

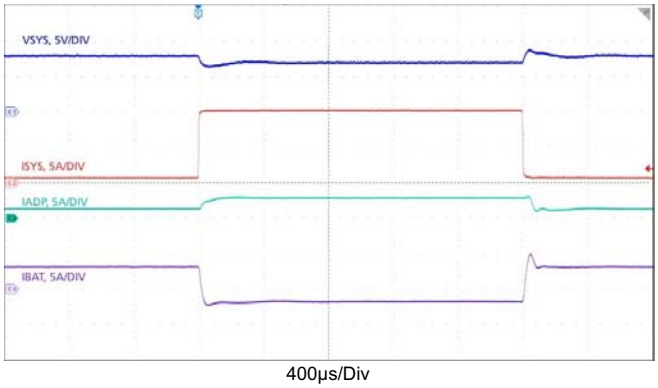


Figure 16. Buck Mode Transitions: Charge Current Loop to/from Adapter Current Loop. VADP = 20V, VBAT = 7V, MaxSystemVoltage = 8.384V, AdapterCurrentLimit = 3A, ChargeCurrent = 3A, SystemLoad: 0.5A → 10A → 0.5A

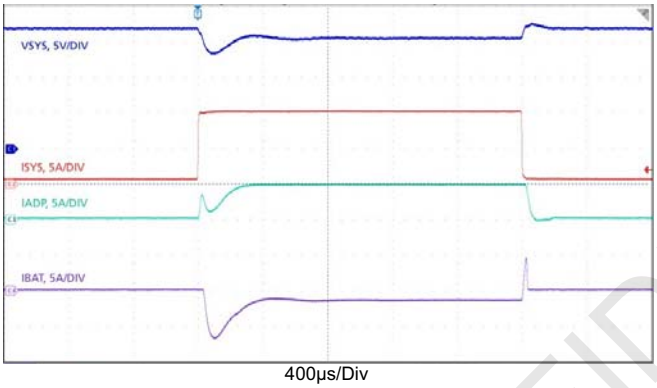


Figure 17. Buck Mode Transitions: Output Voltage Loop to/from Adapter Current Loop. VADP = 28V, VBAT = 15.5V, MaxSystemVoltage = 16.768V, AdapterCurrentLimit = 5A, ChargeCurrent = 0, SystemLoad: 0.5A → 10A → 0.5A

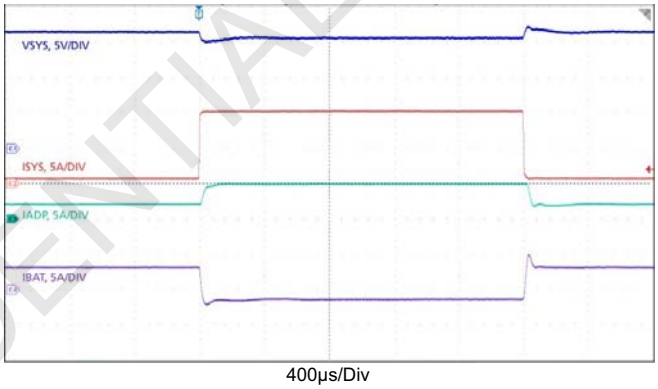


Figure 18. Buck Mode Transitions: Charge Current Loop to/from Adapter Current Loop. VADP = 28V, VBAT = 15.5V, MaxSystemVoltage = 16.768V, AdapterCurrentLimit = 5A, ChargeCurrent = 3A, SystemLoad: 0.5A → 10A → 0.5A

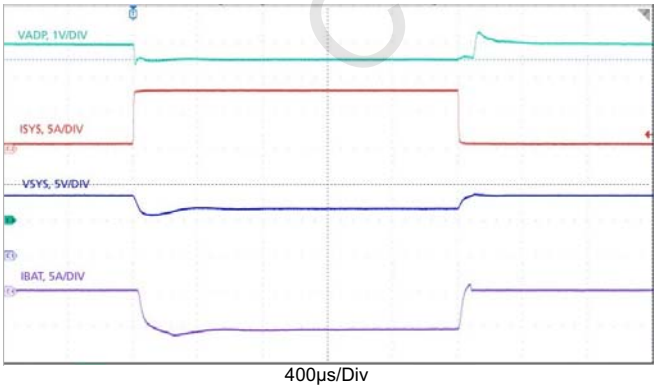


Figure 19. Boost Mode Transitions: Output Voltage Loop to/from Input Voltage Loop. VADP = 5V, VBAT = 7.5V, MaxSystemVoltage = 8.384V, AdapterCurrentLimit Disabled, ChargeCurrent = 0, SystemLoad: 0.5A → 8A → 0.5A, InputVoltageLimit = 4.48V

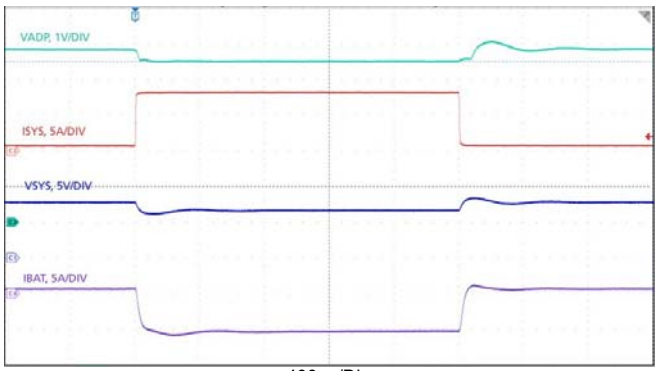


Figure 20. Boost Mode Transitions: Charge Current Loop to/from Input Voltage Loop. VADP = 5V, VBAT = 7.5V, MaxSystemVoltage = 8.384V, AdapterCurrentLimit Disabled, ChargeCurrent = 0.5A, SystemLoad: 0.5A → 8A → 0.5A, InputVoltageLimit = 4.48V

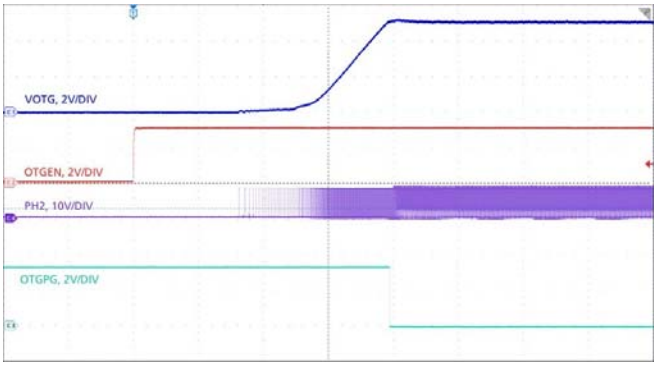


Figure 21. OTG Mode Enable Using OTGEN Pin. VBAT = 8V, VOTG = 5V, General-Purpose Comparator Disabled, OTGEN Control Bit Enabled

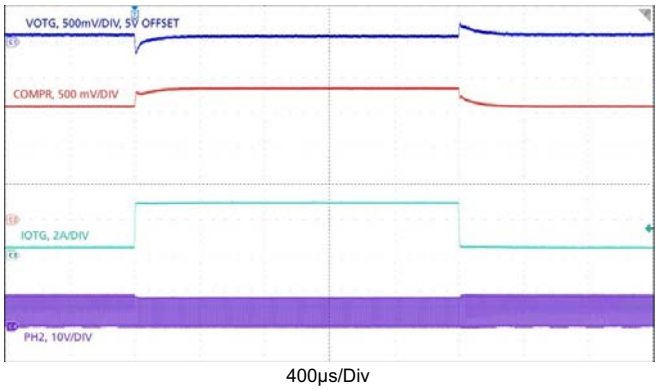


Figure 22. OTG Mode Transients. VBAT = 8V, VOTG = 5V, OTG Current = 4A, SystemLoad: 0.5A → 3A → 0.5A

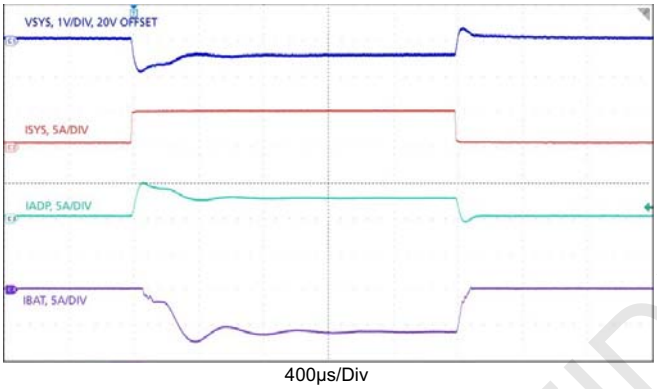


Figure 23. Bypass (HPBB) Mode, Reverse Turbo Boost Enabled. Output Voltage Loop to/from Adapter Current Limit Loop Transitions, VADP = 20V, VBAT = 8V, MaxSystemVotlage = 8.384V, AdapterCurrentLimit = 3A, ChargeCurent = 0, SystemLoad: 0.5A → 5A → 0.5A

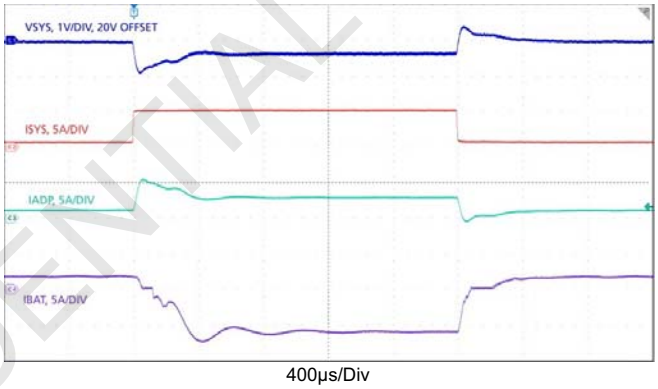


Figure 24. Bypass (HPBB) Mode, Reverse Turbo Boost Enabled. Charge Current Loop to/from Adapter Current Limit Loop Transitions, VADP = 20V, VBAT = 8V, MaxSystemVotlage = 8.384V, AdapterCurrentLimit = 3A, ChargeCurent = 2A, SystemLoad: 0.5A → 5A → 0.5A

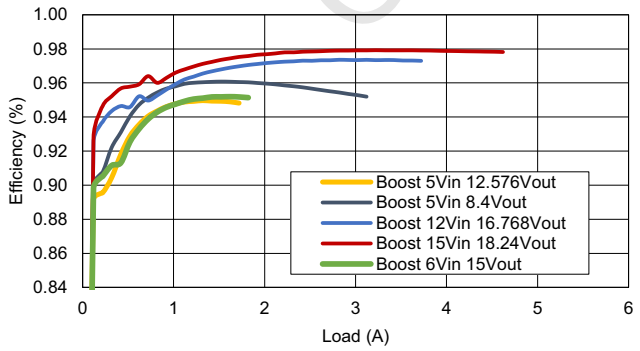


Figure 25. Boost Mode Efficiency

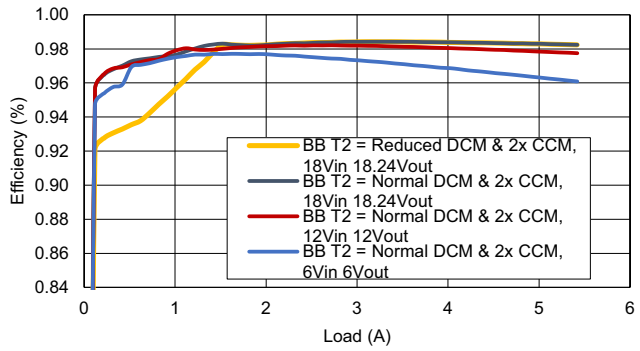


Figure 26. Buck-Boost Mode Efficiency

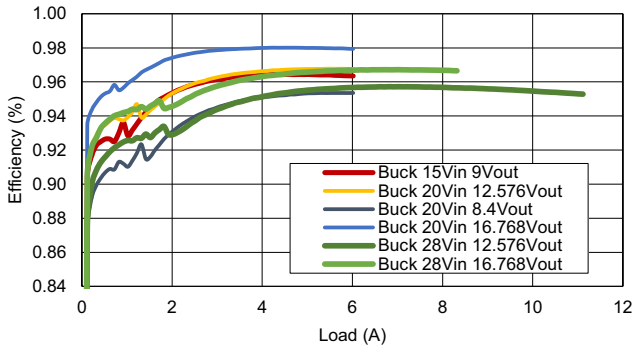


Figure 27. Buck Mode Efficiency

5. General SMBus Architecture

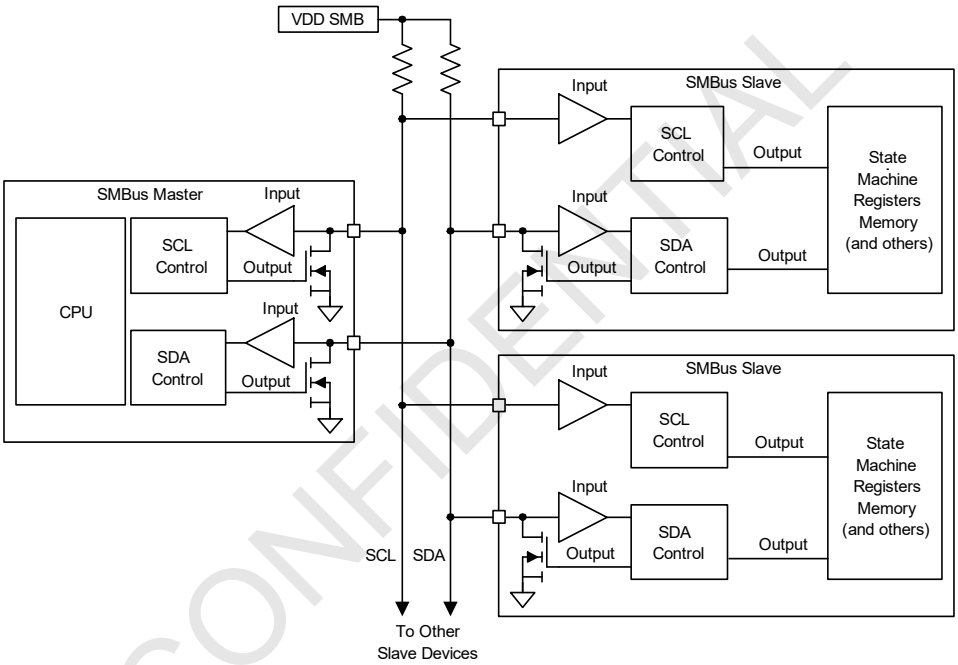


Figure 28. General SMBus Architecture

5.1 Data Validity

The data on the SDA line must be stable during the HIGH period of the SCL, unless generating a START or STOP condition. The HIGH or LOW state of the data line can change only when the clock signal on the SCL line is LOW. See Figure 29.

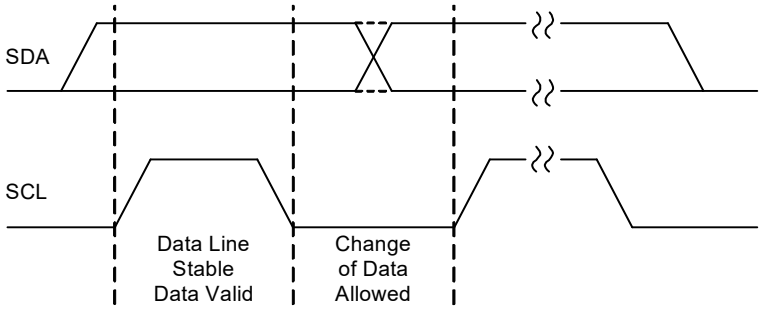


Figure 29. Data Validity

5.2 START and STOP Conditions

Figure 30 shows that the START condition is a HIGH to LOW transition of the SDA line while SCL is HIGH.

The STOP condition is a LOW to HIGH transition on the SDA line while SCL is HIGH.

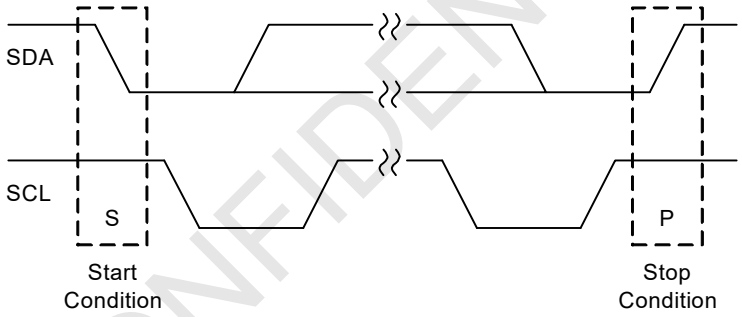


Figure 30. Start and Stop Waveforms

5.3 Acknowledge

Each address and data transmission uses nine clock pulses. The ninth pulse is the Acknowledge bit (ACK). After the start condition, the master sends seven slave address bits and a R/$\overline{W}$ bit during the next eight clock pulses. During the ninth clock pulse, the device that recognizes its own address holds the data line low to acknowledge (see Figure 31). Both the master and the slave use the ACK bit to acknowledge receipt of register addresses and data.

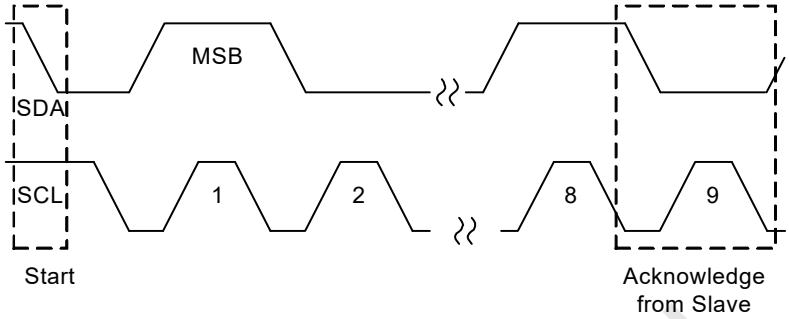


Figure 31. Acknowledge on the SMBus

5.4 SMBus Transactions

All transactions start with a control byte sent from the SMBus master device. The control byte begins with a Start condition followed by seven bits of slave address (0001001) and the R/$\overline{W}$ bit. The R/$\overline{W}$ bit is 0 for a WRITE or 1 for a READ. If any slave device on the SMBus bus recognizes its address, it acknowledges by pulling the Serial Data (SDA) line low for the last clock cycle in the control byte. If no slave exists at that address or it is not ready to communicate, the data line is 1 indicating a not acknowledge condition.

After the control byte is sent and the RAA489110 acknowledges it, the second byte sent by the master must be a register address byte such as 0x14 for the ChargeCurrent register. The register address byte tells the RAA489110 which register the master writes or reads. See Table 1 for details about the registers. When the RAA489110 receives a register address byte, it responds with an acknowledge.

5.5 Byte Format

Every byte put on the SDA line must be eight bits long and must be followed by an ACK bit. Data is transferred with the Most Significant Bit (MSB) first and the Least Significant Bit (LSB) last. The LO Byte data is transferred before the HI Byte data. For example when writing 0x41A0, 0xA0 is written first, and 0x41 is written second.

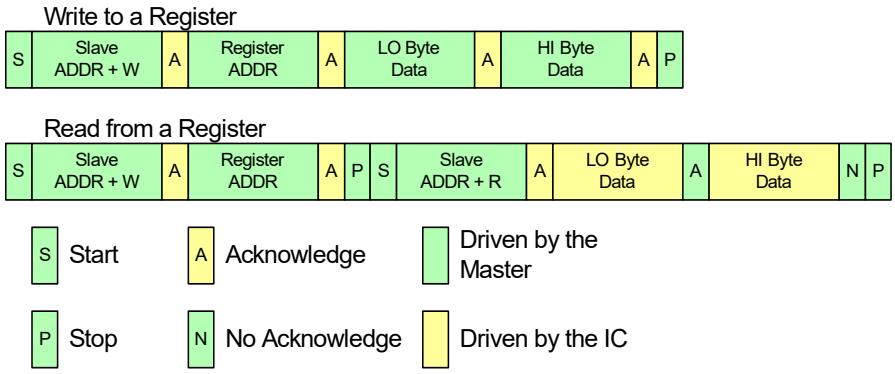


Figure 32. SMBus Read and Write Protocol

5.6 SMBus and I²C Compatibility

The RAA489110 SMBus minimum input logic high voltage is 1.5V, so it is compatible with an I²C with a pull-up power supply higher than 1.5V.

The RAA489110 SMBus registers are 16 bits, so it is compatible with a 16-bit I²C or an 8-bit I²C with auto-increment capability.

5.7 SMBus Commands

The RAA489110 receives control inputs from the SMBus interface after a power-on reset (POR). The serial interface complies with the System Management Bus Specification, which can be downloaded from www.smbus.org. The RAA489110 uses the SMBus Read-word and Write-word protocols (see Figure 32) to communicate with the host system and a smart battery. The RAA489110 is an SMBus slave device and does not initiate communication on the bus. It responds to the 7-bit address 0b0001001x (RAA489110) as follows:

The Read and Write address for the RAA489110 is:

- Read address = 0b00010011 (0x13h)
- Write address = 0b00010010 (0x12h)

The data (SDA) and clock (SCL) pins have Schmitt-trigger inputs that can accommodate slow edges. Choose pull-up resistors for SDA and SCL to achieve rise times according to the SMBus specifications.

Register DAC values in this datasheet are based on current-sensing resistors R_{s1} = 20mΩ and R_{s2} = 10mΩ unless otherwise specified.

Other addresses are available on request and require unique part numbers (alternative write addresses are 0x92h, 0x94h, and 0x96h).

6. Registers

6.1 Register Summary

Table 1. Detailed Summary of Registers[1]

Register Names	Register Address	Read/ Write	# of Bits	Description	Default
ChargeCurrentLimit (Table 2)	0x14	R/W	11	[12:2] 11-bit (0x0000h = disables both fast charging and trickle charging)	0x0000h (0A)
MaxSystemVoltage (Table 2)	0x15	R/W	12	[14:3] 12-bit, (0x0000h = disables switching)	Set by PROG 8.384V for 2-cell 0x20C0h 12.576V for 3-cell 0x3120h 16.768V for 4-cell 0x4180h
Control7 (Table 8)	0x38	R/W	16	Configures various charger options	0x0000h
Control0 (Table 3)	0x39	R/W	16	Configures various charger options	0x0000h
Information1 (Table 14)	0x3A	R	16	Indicates various charger status	0x0000h
AdapterCurrentLimit2 (Table 2)	0x3B	R/W	11	[12:2] 11 bit register to set higher level of adapter current when 2-level adapter current limiting is enabled	0x05DCh (1500mA)
Control1 (Table 4)	0x3C	R/W	16	Configures various charger options	0x0280h (Includes value set by PROG pin)
Control2 (Table 5)	0x3D	R/W	16	Configures various charger options	0x6000h
MinSystemVoltage (Table 2)	0x3E	R/W	8	[13:6] 8-bit (0x0000h = disables all battery charging)	0x0000h (0V)
AdapterCurrentLimit1 (Table 2)	0x3F	R/W	11	[12:2] 11-bit register to set the Adapter current limit	Set by PROG pin
ACOK Reference (Table 2)	0x40	R/W	8	[13:6] x 8-Bit, (0x0000h = disables functionality)	Disabled (0x0000h)
Control6 (Table 13)	0x43	R/W	14	Interrupt trigger level direction 0 = Event went High to Low 1 = Event went Low to High	0x3FFFh
Control8 (Table 9)	0x44	R/W	16	Configures various charger options for Vmin Active protection/ supplemental mode	0x0780h
Control9 (Table 10)	0x45	R/W	16	Configures various charger options	0x0000h
Control10 (Table 11)	0x46	R/W	16	Configures various charger options for Programmable temperature profile	0x0000h
ACProchot# (Table 2)	0x47	R/W	8	[12:5] Adapter current PROCHOT# threshold	0x0C00h (3.072A)
DCProchot# (Table 2)	0x48	R/W	8	[13:6] Battery discharging current PROCHOT# threshold	0x1000h (4.096A)
OTG Voltage (Table 2)	0x49	R/W	12	[14:3] 12-bit OTG mode voltage reference	0x08B0h (5.004V)
OTG Current (Table 2)	0x4A	R/W	8	[12:5] 8-bit, OTG mode maximum current limit	0x0200h (0.512A)

Table 1. Detailed Summary of Registers[1] (Cont.)

Register Names	Register Address	Read/ Write	# of Bits	Description	Default
V_{IN} Voltage (Table 2)	0x4B	R/W	6	[13:6] 8-bit, V_{IN} loop voltage reference	0x0800h (4.096V)
Control3 (Table 6)	0x4C	R/W	16	Configures various charger options	0x0300h
Information2 (Table 15)	0x4D	R	16	Indicates various charger status	0x0000h
Control4 (Table 7)	0x4E	R/W	16	Configures various charger options	0x0000h
Control5 (Table 13)	0x4F	R/W	14	Interrupt mask control enable 0 = Not enabled/masked 1 = Enabled/unmasked	0x0000h
NTC ADC Results	0x80	R	10	ADC result for NTC/GP measurements LSB = 8mV	Table 17
VBAT ADC Results	0x81	R	8	ADC result for VBAT measurements, LSB = 64mV	Table 17
TJ ADC Results	0x82	R	8	ADC result for internal T_J measurements, LSB = 8mV	Table 17
IADP ADC Results	0x83	R	8	ADC result for adapter current measurements, LSB = 22.2mA	Table 17
DC ADC Results	0x84	R	8	ADC result for battery discharge current measurements, LSB = 44.4mA	Table 17
CC ADC Results	0x85	R	8	ADC result for battery charge current measurements, LSB = 22.2mA	Table 17
VSYS ADC Results	0x86	R	8	ADC result for CSOP (VSYS) measurements, LSB = 96mV	Table 17
VIN ADC Results	0x87	R	8	ADC result for CSIN (VIN) measurements, LSB = 144mV	Table 17
Information3 (Table 13)	0x90	R/W	13	Interrupt status - multiple events possible	0x0000h
Information4 (Table 13)	0x91	R/W	13	Interrupt real-time status	0x0000h
Information 5 (Table 16)	0x92	R/W	16	Indicates various charger status	0x0000h
Manufacturer ID	0xFE	R	8	Manufacturer ID register – 0x49. Read only	0x0049h
Device ID	0xFF	R	8	Device ID register. Read only	0x0016h

1. All values in this table are computed with R_{S1} = 20mΩ and R_{S2} = 10mΩ.

6.2 DAC Register Summary

Table 2. DAC Summary Table

ADDR	Charge Current Limit (R_{s2} = 10mΩ)	Max System Voltage	Min System Voltage	Adapter Current Limit1 (R_{s1} = 20mΩ)	Adapter Current Limit2 (R_{s1} = 20mΩ)	V_{IN} Voltage (ADP Min Voltage)	V_{IN} DAC for VSYS Regulation in Supplemental Mode	ACOK Reference for V_{IN} Comparison	ACProchot# (ACHOT) (R_{s1} = 20mΩ)	DCProchot# (DCHOT) (R_{s2} = 10mΩ)	OTG Voltage	OTG Current (R_{s1} = 20mΩ)
	0x14	0x15	0x3E	0x3F	0x3B	0x4B	0x4B	0x40	0x47	0x48	0x49	0x4A
[0]	-	-	-	-	-	-	-	-	-	-		-
[1]	-	-	-	-	-	-	-	-	-	-		-
[2]	4mA	-	-	4mA	4mA	-	-	-	-	-		-
[3]	8mA	8mV	-	8mA	8mA	-	-	-	-	-	18mV	-
[4]	16mA	16mV	-	16mA	16mA	-	-	-	-	-	36mV	-
[5]	32mA	32mV	-	32mA	32mA	-	-	-	32mA	-	72mV	32mA
[6]	64mA	64mV	64mV	64mA	64mA	128mV	85mV	144mV	64mA	64mA	144mV	64mA
[7]	128mA	128mV	128mV	128mA	128mA	256mV	171mV	288mV	128mA	128mA	288mV	128mA
[8]	256mA	256mV	256mV	256mA	256mA	512mV	341mV	576mV	256mA	256mA	576mV	256mA
[9]	512mA	512mV	512mV	512mA	512mA	1024mV	683mV	1152mV	512mA	512mA	1152mV	512mA
[10]	1024mA	1024mV	1024mV	1024mA	1024mA	2048mV	1365mV	2304mV	1024mA	1024mA	2304mV	1024mA
[11]	2048mA	2048mV	2048mV	2048mA	2048mA	4096mV	2731mV	4608mV	2048mA	2048mA	4608mV	2048mA
[12]	4096mA	4096mV	4096mV	4096mA	4096mA	8192mV	5461mV	9216mV	4096mA	4096mA	9216mV	4096mA
[13]	-	8192mV	8192mV	-	-	16384mV	10923mV	18432mV	-	8192mA	18432mV	-
[14]	-	16384mV	-	-	-	-	-	-	-	-	36864mV	-
[15]	-	-	-	-	-	-	-	-	-	-	-	-
Max	6140mA	18.304V	16.32V	6140mA	6140mA	24.576V	16.384V	36.72V	6400mA	12.8A	32.256V	6112mA

6.3 Control Registers

The Control registers configure the operation of the RAA489110. To change certain functions or options after POR, write a 16-bit control command to any control register address. See the Write-word protocol shown in Figure 32.

Table 3. Control0 Register 0x39H

Bit	Bit Name	Description
[15]	CSIN Sink/Discharge	Enables or turns on the discharge FET to pull down the CSIN. 0 = Disable, 10mA sink turned off (default) 1 = Enable, 10mA sink turned on
[14]	CSIN Auto Sink/Discharge	Enables or disables the discharge path for CSIN for 200ms on entering the ready state. 0 = Disable (default) 1 = Enable
[13]	CSOP Sink	Enables or turns on the discharge FET to pull down the CSOP. 0 = Disable, 10mA sink turned off (default) 1 = Enable, 10mA sink turned on
[12]	NGATE Off	0 = NGATE on (NGATE = CSOP + 5V); (default) 1 = NGATE off (NGATE = CSOP)
[11]	BYPASS On	0 = BYPSG off (BYPSG = BYPSRC) (default) 1 = BYPSG on (BYPSG = BYPSRC + 5V)
[10]	Force Forward BuckMode	0 = Normal modulator operations (default) 1 = Forward Force Buck/Reverse Force Boost
[9]	Bypass Mode transition	0 = Disable transition to Bypass mode (default) 1 = Enable transition to Bypass mode
[8]	ACHOT for PTM	0 = Disable AC PROCHOT# protection for Pass through mode (default) 1 = Enable AC PROCHOT# protection for Pass through mode
[7]	SMBus Timeout	Default time is 175s (see Control3 register Bits[12:11] and SMBus Timeout). 0 = Enable the SMBus timeout function (default) 1 = Disable the SMBus timeout function
[6]	Enable Charge Pumps to 100% Duty Cycle	Enables the charge pumps for BGATE and NGATE for 100% of the time. 0 = Normal operation (reduced supply current) (default) 1 = Enable charge pumps 100% of the time to ensure the charge pump good bit does not toggle due to gate leakage (see Table 14)
[5]	BYP $V_{IN} < V_{OUT}$ Comparator to turn off BYPSG	Enables or disables the bypass comparator and turns off the BYPSG when $V_{IN} < V_{OUT}$. 0 = Disable (default) 1 = Enable
[4:3]	DCProchot# Threshold in Battery Only Mode (Low Power Mode)	Configures the battery discharging current DCProchot# threshold in battery only Low Power mode indicated by the Information1 register 0x3A Bit[15]. If PSYS is enabled, the battery discharge current DCProchot# threshold is set by the DCProchot# register 0x48 setting.

Bits[4:3]	R_{S2} = 10mΩ (A)	R_{S2} = 20mΩ (A)	R_{S2} = 5mΩ (A)
00 (Default)	12	6	24
01	10	5	20
10	8	4	16
11	6	3	12

Table 3. Control0 Register 0x39H (Cont.)

Bit	Bit Name	Description
[2]	Input Voltage Regulation	Enables or disables the input voltage regulation loop. 0 = Enable (default) 1 = Disable
[1]	VSYS Regulation Offset Voltage Adder	Adds offset above the VSYSMAX register setting when not charging. 0 = 0mV (default) 1 = 384mV (384mV is always added to MinSystemVoltage in Trickle Charge mode - irrespective of this bit)
[0]	Reverse Turbo Boost	Reverse Turbo Boost when in hybrid/bypass configuration. If adapter current drawn exceeds the current limit, the modulator operates in reverse mode and takes energy from the battery to hold up the input. Not allowed while using Autonomous Charging mode or if battery capacity is low. 0 = Disable (default) 1 = Enable

Table 4. Control1 Register 0x3CH

Bit	Bit Name	Description
[15:14]	General Purpose Comparator Debounce Time	Configures the general purpose comparator assertion debounce time. 00 = 2µs (default) 01 = 12µs 10 = 2ms 11 = 720µs
[13]	Exit Learn Mode	Provides the option to Exit Learn mode when the battery voltage is lower than MinSystemVoltage register setting. 0 = Stay in Learn mode even if V_{BAT} < MinSystemVoltage register setting (default) 1 = Exit Learn mode if V_{BAT} < MinSystemVoltage register setting
[12]	Learn Mode	Enables or disables the Battery Learn mode used in NVDC mode only. (see Battery Learn Mode) 0 = Disable (default) 1 = Enable To enter Learn mode, the BATGONE pin needs to be low and a battery must be present.
[11]	OTG Function	Enables or disables the OTG function. 0 = Disable OTG (default) 1 = Enable OTG (adapter output power supply)
[10]	Disable CSIN OV in OTG Mode	0 = Enable CSIN Overvoltage protection in OTG mode (default) 1 = Disable CSIN Overvoltage protection in OTG mode
[9:7]	Switching Frequency	Configures the switching frequency and overrides the default switching frequency set by the PROG pin. 000 = 1420kHz 001 = 1180kHz 010 = 1020kHz 011 = 890kHz 100 = 808kHz 101 = 724kHz 110 = 656kHz 111 = 600kHz To keep the switching frequency set by the PROG pin resistor, leave Bits[9:7] as it is read.

Table 4. Control1 Register 0x3CH (Cont.)

Bit	Bit Name	Description
[6]	BGATE Force Off	Disables BGATE. This forces the BGATE FET to turn off and overwrite Turbo mode. See Table 22. 0 = Normal operation (default) 1 = Force BGATE Off (BGATE = VBAT) (also disables Turbo mode/Ideal Diode mode)
[5]	IMON Function in Battery Only Mode	Enables or disables the current monitor function AMON and BMON. 0 = Enable IMON (default) 1 = Disable IMON Bit[5] is valid only in Battery Only mode. When an adapter is present, IMON is automatically enabled and Bit[5] becomes invalid. Disables battery only DCHOT protection also.
[4]	IMON Selection	Selects AMON or BMON as the output of the AMON/BMON pin (see Control3[3] for direction). 0 = AMON (default) 1 = BMON
[3]	PSYS	Enables or disables the system power monitor PSYS function. 0 = Disable (default) 1 = Enable
[2]	Disable Digital OV Protection	0 = Enable Digital Overvoltage protection (Default) 1 = Disable Digital Overvoltage protection for VSYS and OTG modes See Control 7[7]
[1:0]	Not Used	Not used.

Table 5. Control2 Register 0x3DH

Bit	Bit Name	Description
[15:13]	Trickle Charging Current	Configures the charging current in Trickle Charging mode. [000] 32mA (do not use) [001] 64mA [010] 96mA [011] 128mA (default) [100] 160mA [101] 192mA [110] 224mA [111] 256mA
[12]	Two-Level Adapter Current Limit	Enables or disables the two-level adapter current limit function. (see Adapter Current Loop and One or Two-Level Current Limit) 0 = Disable (default) 1 = Enable
[11]	Fault Timer Debounce Time for OT and WOCP	Configures the debounce fault time for die Over Temperature (OT) or Way Overcurrent (WOC). 0 = 1.3s (default) 1 = 150ms
[10:9]	PROCHOT# Debounce	Configures the PROCHOT# debounce time before its assertion for ACProchot# and DCProchot#. 00: 7µs (default) 01: 100µs 10: 500µs 11: 1ms The Low_VSYS_Prochot# has a fixed 7µs debounce time.

Table 5. Control2 Register 0x3DH (Cont.)

Bit	Bit Name	Description
[8:6]	PROCHOT# Duration	Configures the minimum duration of the PROCHOT# signal when asserted. 000 = 10ms (default) 001 = 20ms 010 = 15ms 011 = 5ms 100 = 1ms 101 = 500µs 110 = 100µs 111 = 0s
[5]	Disable LowVsys PROCHOT#	0 = Enable Low Vsys PROCHOT# function (default) 1 = Disable Low Vsys PROCHOT# function
[4]	CMIN Reference	Configures the general purpose comparator reference voltage. 0 = 1.2V (default) 1 = 2V (this option is not available in Battery only mode)
[3]	General Purpose Comparator	Enables or disables the general purpose comparator. 0 = Enable (default) 1 = Disable (Interrupt Enabled - allows interrupt functionality on pin)
[2]	CMOUT Polarity	Configures the general purpose comparator output polarity when asserted. The comparator reference voltage is connected at the inverting input node. 0 = Not inverted, CMOUT is High when CMIN is higher than the reference (default) 1 = Inverted, CMOUT is Low when CMIN is higher than the reference
[1]	Internal Resistor Compensation for COMPR RCOMP	Changes the internal compensation resistor to speed up or slow down the loop response for reverse modulator operations (OTG). 0 = Faster (default) 1 = Slower
[0]	Internal Resistor Compensation for COMPF RCOMP	Changes the internal compensation resistor to speed up or slow down the loop response for forward modulator operations and Reverse Turbo Boost mode. 0 = Faster (default) 1 = Slower

Table 6. Control3 Register 0x4CH

Bit	Bit Name	Description
[15]	Disable OTG UV	0 = Normal operation (default) 1 = PPS operations; disables the undervoltage for OTG
[14]	ACLIM Reload	Reloads the AdapterCurrentLimit1 register with the value set by the last read of the PROG pin resistor on the falling edge of ACOK to prepare for a new adapter attaching. 0 = Reload AdapterCurrentLimit1 register (default) 1 = Do not reload
[13]	Autonomous Charging Termination Time	Configures the autonomous charging termination time. 0 = 20ms (default) 1 = 200ms

Table 6. Control3 Register 0x4CH (Cont.)

Bit	Bit Name	Description
[12:11]	SMBus Charger Timeout/ Autocharge Timer Options	Configures the SMBus Timeout time (see SMBus Timeout). 00 = 175s (default) 01 = 87.5s 10 = 43.75s 11 = 4.95s For autocharge mode, timer can be set to: 00 = 12h (default) 01 = 9h 10 = 6h 11 = 3h
[10]	DCM/CCM Hysteresis	0 = Disabled (default) 1 = Enables hysteresis for the DCM to CCM boundary
[9:8]	PSYS Gain	Configures the system power monitor PSYS output gain. (Default = 11) See PSYS GAIN values in the Electrical Specifications.
[7]	Charge Control	Enables Autonomous Charging mode (see Autonomous Charging Mode). 0 = SMBus Control, Battery charging current control through SMBus only (default) 1 = Enable Autonomous Charging mode (resets if 12-hour timer expires or a Fault occurs, PROCHOT# configured for autonomous charging mode indicator, End of Charge enabled)
[6]	AC and CC Current Feedback Gain	Configures AC and CC feedback gain for high current applications. 0 = x1.0 (default) 1 = x0.5
[5]	Input Current Limit Loop	Disables the input current limit loop. 0 = Enable input current limit loop (default) 1 = Disable input current limit loop
[4]	Input Current Limit Loop when BATGONE = 1	Disables the input current limit loop when BATGONE = 1. 0 = Enable ACLIM when BATGONE = 1 (default) 1 = Disable ACLIM when BATGONE = 1
[3]	IMON Direction	Configures the AMON/BMON direction (see Control1[4] for AMON/BMON selection). 0 = Adapter current monitor/battery charging current monitor (default) 1 = OTG output current monitor/battery discharging current monitor
[2]	Digital Reset	Resets all SMBus register values to the POR default value, including re-reading PROG settings. 0 = Idle (default) 1 = Reset
[1]	T2DCM	Buck-Boost T2 time in DCM (T2DCM), reduces input ripple. 0 = Reduced T2 time (increases switching frequency in DCM) (default) 1 = Normal T2 time
[0]	Enable ADC	0 = ADC is active only when adapter is plugged in and charging (default) 1 = Enables ADC for all modes

Table 7. Control4 Register 0x4EH

Bit	Bit Name	Description
[15]	BATGONE Disable	0 = Normal BATGONE input (default) 1 = Ignore BATGONE input
[14]	BGATE tristate	0 = Normal (default) 1 = Tri-state mode
[13]	Slew Rate Control	0 = Slew Rate Control Disabled (default) 1 = Slew Rate enabled to ramp DAC voltage; OTG 0.5625mV/µs and VSYS 0.25mV/µs; Not recommended in OTG mode until after establishing 5V to prevent OV issues. During DAC slew down, it is advisable to add the 10mA discharge current on CSOP so that OVP is not triggered.
[12]	Disable GP Comparator	0 = Enabled for all modes (default) 1 = Disabled for Battery Only mode (REF = 1.2V in Battery Only mode)
[11]	PSYS Rsense Ratio	R_{SENSE} (R_{s1}:R_{s2}) ratio for PSYS. 0 = 2:1 (default) 1 = 1:1
[10]	Enable AC loop in PTM	0 = Adapter Current Limit loop is disabled 4-7ms after PTM entry (default) 1 = Adapter Current Limit loop is always enabled in PTM mode
[9]	WOCP Function	0 = Enable way overcurrent detection (default) 1 = Disable
[8]	VSYS Short Check	Enables or disables VSYS short detection before enabling the modulator. 0 = Enable (default) 1 = Disable
[7]	Not Used	Not used
[6]	BATGONE PROCHOT#	Enables or disables trigger PROCHOT# with BATGONE. 0 = Disable (default) 1 = Enable
[5]	ACOK PROCHOT#	Enables or disables trigger PROCHOT# with ACOK. 0 = Disable (default) 1 = Enable
[4]	GP Comparator PROCHOT#	Enables or disables trigger PROCHOT# with general purpose comparator rising. 0 = Disable (default) 1 = Enable
[3:2]	ACOK Falling or BATGONE Rising Debounce	Configures the debounce time from ACOK falling or BATGONE rising to PROCHOT# trip. 00 = 2µs (default) 01 = 25µs 10 = 125µs 11 = 250µs
[1]	PROCHOT# Clear	Clears PROCHOT#. 0 = Idle (default) 1 = Clear PROCHOT#
[0]	PROCHOT# Latch	Manually resets PROCHOT#. 0 = PROCHOT# signal auto-clear (default) 1 = Hold PROCHOT# low when tripped, must be clear using Bit[1] above

Table 8. Control7 Register 0x38H

Bit	Bit Name	Description
[15:13]	t2 - Time corresponding to Adapter Current Limit 2 (Two level ACLIM enabled)	000 = 10µs (default) 001 = 100µs 010 = 500µs 011 = 1ms 100 = 300µs 101 = 750µs 110 = 2ms 111 = 10ms
[12:10]	t1 - Time Corresponding to AdapterCurrentLimit1 (Two level ACLIM enabled)	000 = 10ms (default) 001 = 20ms 010 = 15ms 011 = 5ms 100 = 1ms 101 = 0.5ms 110 = 0.1ms 111 = 0ms
[9:8]	End of Charge (EOC) Settings	End of charge settings when using Autonomous Charging mode. Also see Control3 [7] in Table 6. 00 = 105mA (default) 01 = 60mA 10 = 190mA 11 = 145mA
[7]	Analog OV Control	Analog overvoltage disable (also see Control1 [2] in Table 2). 0 = Normal, OV pulls down on comp and disables switching (default) 1 = Disable
[6:5]	AMON/BMON Gain	00 = 1x (default) 01 = 2x 10 = 4x 11 = 8x
[4]	PPS Mode support	0 = Normal operation (default) 1 = Enable PPS Mode support
[3]	Pass Through Mode	0 = Disable Pass through mode (default) 1 = Enable Pass through mode
[2]	Standby Mode	0 = Normal operation (default) 1 = Enable Standby mode
[1:0]	Buck-Boost Stretch CCM Period	Buck-boost stretch CCM period (T2 TIME). 00 = 0.6x (default) 01 = 1x 10 = 3x 11 = 2x

Table 9. Control8 Register 0x44H

Bit	Bit Name	Description
[15:13]	Supplemental Mode 3	000 = Disable (default) 111 = Enable
[12:10]	VSYSLO PROCHOT# Reference	Reference voltage for Low VSYS PROCHOT# (VSYSLO) 000: 5.3V, 001: 4.7V (Default), 010: 5.7V, 011: 5.9V 100: 6.1V, 101: 6.3V, 110: 6.5V, 111: 6.7V
[9:7]	Supplemental Mode 3 Compensation Settings	Supplemental Mode 3 Closed Loop Compensation Settings 000: 5kΩ, 001: 10kΩ, 010: 15kΩ, 011: 20kΩ 100: 25kΩ, 101: 30kΩ, 110: 35kΩ, 111: 50kΩ (default)
[6:5]	Adapter Low PROCHOT# (VADPLO) Reference	Reference voltage for Adapter Low PROCHOT# (VADPLO) 00 = 7.2V (default) 01 = 8.0V 10 = 8.8V 11 = 9.6V
[4]	GM_SUPN	Set Supplemental mode loop gain (GM_SUPN). 0 = 1x (default) 1 = 2x
[3]	T_SUP Multiplier (T_SUPM)	Set Supplemental mode period (T_SUPM) multiplier. 0 = 1x (default) 1 = 0.5x
[2:0]	T_SUP	Set Supplemental Buck mode period (T_SUP). 000 = Standard T_SUP (default) 001 = 7/6 × Standard T_SUP 010 = 8/6 × Standard T_SUP 011 = 9/6 × Standard T_SUP 100 = 10/6 × Standard T_SUP 101 = 11/6 × Standard T_SUP 110 = 12/6 × Standard T_SUP 111 = 13/6 × Standard T_SUP

Table 10. Control9 Register 0x45H

Bit	Bit Name	Description
[15]	BGATE Force On	0 = BGATE normal operation (default) 1 = BGATE forced ON (BGATE = VBAT + 5V)
[14]	Not Used	Not used
[13]	ACHOT Debounce for Exiting PTM	0 = 0ms (default) 1 = 20ms
[12:11]	Not Used	Not used
[10]	Clear CMOUT (General Purpose Comparator) Latch Data	0 = Do not clear CMOUT (General purpose comparator) latch data (default) 1 = Clear CMOUT (General purpose comparator) latch data
[9]	CMOUT (General Purpose comparator) Latch Enable	0 = Disable CMOUT (General purpose comparator) latch (default) 1 = Enable CMOUT (General purpose comparator) latch

Table 10. Control9 Register 0x45H (Cont.)

Bit	Bit Name	Description
[8]	Disable Auto-Recharge	In Autonomous charging mode, this control bit set to 1 disables charging from restarting once VBAT falls below MaxsysVoltage - 200mV/cell 0 = Auto-recharge enabled (default) 1 = Auto-recharge disabled
[7:6]	Refresh Time	00 = 500µs (default) 01 = 250µs 10 = 125µs 11 = 32µs
[5]	Force CCM Mode	0 = Disable Force CCM mode (default) 1 = Enable Force CCM mode
[4:2]	VSYS UV Protection	000 = Disable 001 = 3V 010 = 3.9V 011 = 4.8V (default) 100 = 5.7V 101 = 6.6V 110 = 7.5V 111 = 8.4V
[1:0]	Dither Enable	00 = Disable dither (default) 01 = Dither1x 10 = Dither2x 11 = Dither3x *Note:* The ADC must be enabled for Dither function to work.

Table 11. Control10 Register 0x46H

Bit	Bit Name	Description
[15:14]	Bin 5 Programmable Temperature CC Profile Control	Controls Charge current (as a percentage of set value) for Bin 5 (50°C to 60°C) 00 = 100% (default) 01 = 75% 10 = 50% 11 = 25%
[13:12]	Bin 4 Programmable Temperature CC Profile Control	Controls Charge current (as a percentage of set value) for Bin 4 (45°C to 50°C) 00 = 100% (default) 01 = 75% 10 = 50% 11 = 25%
[11:10]	Bin 3 Programmable Temperature CC Profile Control	Controls Charge current (as a percentage of set value) for Bin 3 (10°C to 45°C) 00 = 100% (default) 01 = 75% 10 = 50% 11 = 25%
[9:8]	Bin 2 Programmable Temperature CC Profile Control	Controls Charge current (as a percentage of set value) for Bin 2 (5°C to 10°C) 00 = 100% (default) 01 = 75% 10 = 50% 11 = 25%

Table 11. Control10 Register 0x46H (Cont.)

Bit	Bit Name	Description
[7:6]	Bin 1 Programmable Temperature CC Profile Control	Controls Charge current (as a percentage of set value) for Bin 1 (0°C to 5°C) 00 = 100% (default) 01 = 75% 10 = 50% 11 = 25%
[5:4]	Programmable Temperature CV Profile Control	Controls the CV profile voltage offset 00 = 0mV/cell (default) 01 = -48mV/cell 10 = -96mV/cell 11 = -144mV/cell
[3:2]	Force NTC Current	00 = Not forced (default) 01 = 1x 10 = 2x 11 = 4x
[1]	Enable Programmable Temperature Profile Hysteresis	0 = Disable Programmable temperature profile hysteresis (default) 1 = Enable Programmable temperature profile hysteresis
[0]	Enable Programmable Temperature Profile	0 = Disable Programmable temperature profile (default) 1 = Enable Programmable temperature profile

Table 12. Control11 Register 0x42H

Bit	Bit Name	Description
[2:15]	Not Used	Not used
[1]	VSYS ABS Overvoltage	0 = Enable (default) 1 = Disable
[0]	Buck-Boost Min T3 Time	0 = 150ns (default) 1 = 100ns

6.4 Interrupt Functionality

The INT# pin is shared with the CMOUT pin, so it must be enabled by setting Control2 Bit[3] = 1 (see Table 5). Setting the bit to 1 disables the comparator output function. After the INT# pin is enabled, configure the faults or flags to be masked or unmasked and have the INT# trigger. If the flag is a fault, it must be read to clear the INT#. Thirteen possible functions are supported by the interrupt control registers. INT# is an active low, open-drain output that is shared with the GP comparator. It pulls low to signal an interrupt event and requires a pull-up source to toggle.

Information4 provides the event real-time status and always shows the event flag, even if the interrupt is not enabled. This could be as small as a one clock pulse, and may not be useful without being latched, such as for Changed NTC Temperature Boundary.

If Control5 bit is set to 1, an interrupt is enabled to trigger. A 0 masks it and the event is ignored for triggering an interrupt.

Setting Control6 to a 1 means a 1 level triggers the interrupt. This interrupt function is not an edge trigger event.

If Control6 is set to a 1, an interrupt flag is set if the signal becomes a 1. If Control6 is set to 0, an interrupt flag is set when the signal becomes a 0. If Control6 is changed from a 1 to a 0 when the event is 0, this also triggers an interrupt on completion of the SMBus command.

The Information3 register shows results only for unmasked/enabled events. Interrupt flags are cleared by reading the status bit in the Information3 register but only if the fault condition has been removed or the level is changed. To catch the opposite edge, such as when leaving an event, toggle the appropriate bit in Control6.

The Information4 register shows the real-time status of the event. It is not affected by the mask/unmask bit and is not latched.

Table 13. Interrupt Control and Status Registers

Bit	Control Inputs			Flag Outputs			Description
	Control5 Interrupt Mask		Control6 Interrupt Trigger Level	Information3 Interrupt Status		Information4 Interrupt Real-Time Status	
	Address:0x4F		Address:0x43	Address:0x90		Address:0x91	
	0 = Not Enabled 1 = Enabled		0 = Event triggers when low 1 = Event triggers when high	0 = No event 1 = Event Set interrupt flag		0 = Not in state 1 = In this state	
	R/W	Default	Default	R/W	Default	Default	
[15]	R/W	0	0	R	0	0	Not used
[14]	R/W	0	0	R	0	0	Not used
[13]	R/W	0	1	R	0	0	Bypass mode status (interrupt generated when Bypass entry is completed/ Bypass mode is exited - due to Bypass bit reset or fault conditions)
[12]	R/W	0	1	R	0	0	SMBus timeout timer expired
[11]	R/W	0	1	R	0	0	3/6/9/12hours charge timer expired for Autonomous Charging mode only
[10]	R/W	0	1	R	0	0	SYS OV (CSOP OV)
[9]	R/W	0	1	R	0	0	ADP OV (CSIN OV)
[8]	R/W	0	1	R	0	0	ADP VMIN (selector info)

Table 13. Interrupt Control and Status Registers (Cont.)

Bit	Control Inputs			Flag Outputs			Description
	Control5 Interrupt Mask		Control6 Interrupt Trigger Level	Information3 Interrupt Status		Information4 Interrupt Real-Time Status	
	Address:0x4F		Address:0x43	Address:0x90		Address:0x91	
	0 = Not Enabled 1 = Enabled		0 = Event triggers when low 1 = Event triggers when high	0 = No event 1 = Event Set interrupt flag		0 = Not in state 1 = In this state	
	R/W	Default	Default	R/W	Default	Default	
[7]	R/W	0	1	R	0	0	ADP current (selector info)
[6]	R/W	0	1	R	0	0	Thermal warning (T_J > 120°C)
[5]	R/W	0	1	R	0	0	OTGPG (OTG output voltage not UV or OV)
[4]	R/W	0	1	R	0	0	Battery charging terminated for Autonomous Charging mode only
[3]	R/W	0	1	R	0	0	Battery charging changed from CC to CV
[2]	R/W	0	1	R	0	0	Switching FETs in fault state
[1]	R/W	0	1	R	0	0	Enter READY state
[0]	R/W	0	1	R	0	0	Changed NTC temperature boundary

6.5 Information Registers

The information registers contain SMBus readable information about manufacturing and Operating modes. Table 14 and Table 15 identify the bit locations of the information available.

Table 14. Information1 Register 0x3AH

Bit	Bit Name	Description
[0]	Diode Mode Status	0 = Diode mode is not active 1 = Diode mode is active
[1]	Reverse Turbo Mode Status	0 = Reverse turbo mode is not active 1 = Reverse turbo mode is active
[2]	Bypass Gate Power Good Status	0 = BYPSG charge pump is not good 1 = BYPSG charge pump is good[1]
[3]	NGATE Power Good Status	0 = NGATE charge pump is not good 1 = NGATE charge pump is good[1]
[4]	Trickle Charging Mode Status	0 = Trickle Charging mode is not active 1 = Trickle Charging mode is active
[5]	CSIN_CSOP Comparator Status	CSIN to CSOP comparator 0 = CSIN < CSOP 1 = CSIN > CSOP
[6]	BGATE Power Good Status	0 = BGATE charge pump is not good 1 = BGATE charge pump is good[1]
[7]	Bypass mode	0 = Bypass mode exited/ not entered 1 = Bypass mode entry completed
[8]	Pass through mode	0 = Pass through mode not active 1 = Pass through mode active
[9]	Not Used	Not used
[10]	Low_Vsys_PROCHOT# Status	Indicates if the Low_VSYS_Prochot# is tripped. 0 = Low_VSYS_Prochot# is not tripped 1 = Low_VSYS_Prochot# is tripped
[11]	DC PROCHOT# Status	Indicates if DCProchot# is tripped. 0 = DCProchot# is not tripped 1 = DCProchot# is tripped
[12]	AC PROCHOT# Status	Indicates if ACProchot#/OTGCURRENTProchot# is tripped. 0 = ACProchot#/OTGCURRENTProchot# is not tripped 1 = ACProchot#/OTGCURRENTProchot# is tripped
[14:13]	Active Control Loop	Indicates the active control loop. 00 = MaxSystemVoltage control loop is active 01 = Charging current loop is active 10 = Input adapter current limit loop is active 11 = Input voltage loop is active
[15]	Internal Reference Status	Indicates if the internal reference circuit is active. 0 = Reference is not active 1 = Reference is active

1. Depending on leakage on the pin, the bit may toggle unless set to 100% charge pump mode using Control0 [6] (see Table 3).

Table 15. Information2 Register 0x4DH

Bit	Bit Name	Description
[4:0]	PROG Resistor Read Out	Program Resistor read out (Table 18) Number of battery cells Switching frequency Adapter current limit PSYS/REFADJ Selection
[7:5]	Power Stage Operation Mode	Indicates the RAA489110 operation mode. 001 = Forward Boost mode 010 = Forward Buck mode 011 = Forward Buck-Boost mode 101 = Reverse Boost mode 110 = Reverse Buck mode 111 = Reverse Buck-Boost mode
[11:8]	State Machine	Indicates the RAA489110 state machine status. ▪ 0000 = RESET ▪ 0001,0011,0101,1000,1011 = STARTUP: The IC wakes up internal circuits biases, reads trim, and auto-zeros comparators; wait state for V_{DD} > 3.8V ▪ 0010 = ACHRG. Charge state. The system is charging the battery through the Auto-charge setting ▪ 0100 = BAT. Battery only mode with PSYS, ADC, and OTG disabled (ACOK is low) ▪ 0110 = CHRG. Charge state. Charging is enabled and the system is charging the battery through SMBus charging ▪ 0111 = FAULT. OTP or WOCP is triggered ▪ 1001 = OTG. Charger is operating in Reverse/OTG mode or Supplemental mode is enabled ▪ 1010 = READY. The charger is not switching but the circuits are biased and ready (for example, with the MaxSystemVoltage register set to 0). May also be reached by enabling PSYS or ADC in Battery Only mode (from BAT state) ▪ 1100 = VSYS. The charger is in the forward mode and switching, the system voltage or adapter current (or input voltage) can be regulated in this state.
[12]	BATGONE Pin Status	Indicates the BATGONE pin status. 0 = Battery is present 1 = No battery
[13]	General Purpose Comparator Status	Indicates the general purpose comparator output after debounce time. 0 = Comparator output is low 1 = Comparator output is high
[14]	ACOK Pin Status	Indicates the ACOK pin status. 0 = No adapter 1 = Adapter is present
[15]	Not used	Not used

Table 16. Information5 Register 0x92H

Bit	Bit Name	Description
[0]	Programmable temperature profile Bin 0	0 = Temperature profile does not correspond to Bin 0 1 = Temperature profile corresponds to Bin 0
[1]	Programmable temperature profile Bin 1	0 = Temperature profile does not correspond to Bin 1 1 = Temperature profile corresponds to Bin 1
[2]	Programmable temperature profile Bin 2	0 = Temperature profile does not correspond to Bin 2 1 = Temperature profile corresponds to Bin 2
[3]	Programmable temperature profile Bin 3	0 = Temperature profile does not correspond to Bin 3 1 = Temperature profile corresponds to Bin 3
[4]	Programmable temperature profile Bin 4	0 = Temperature profile does not correspond to Bin 4 1 = Temperature profile corresponds to Bin 4
[5]	Programmable temperature profile Bin 5	0 = Temperature profile does not correspond to Bin 5 1 = Temperature profile corresponds to Bin 5
[6]	Programmable temperature profile Bin 6	0 = Temperature profile does not correspond to Bin 6 1 = Temperature profile corresponds to Bin 6
[14:7]	Unused	Unused
[15]	NTC Out of range (Only when forcing NTC current)	When NTC currents are forced (does not apply to other modes) 0 = NTC voltage in range 1 = NTC voltage out of range

6.6 ADC Registers

Table 17. ADC Output Value Bits

ADDR	Description	LSB	Sample Window TIme	Polling Time
Control3 Reg 0x4C Bit[0]. See Table 6.	0 = Disables the ADC, except when required for charging the state machine 1 = Enables the ADC			
0x80	[9:0] NTC voltage If enabled as General Purpose ADC Voltage [9:2] 0 to 2.040V	8mV (Bit 2)	80µs	100ms
0x81	V_{BAT} voltage [13:6] 0 to 16.32V	64mV	80µs	100ms
0x82	Internal junction temperature [7:0] T_J voltage 0 to 2.040V	8mV	80µs	100ms
0x83	Input current (R_{s1} = 20mΩ) [7:0] 0 - 5.68A	22.2mA	80µs	400µs
0x84	Battery discharge current (R_{s2} = 10mΩ) [7:0] 0 - 11.37A	44.4mA	80µs	400µs
0x85	Battery charge current (R_{s2} = 10mΩ) [7:0] 0 - 5.68A	22.2mA	80µs	400µs
0x86	CSOP (VSYS) voltage [13:6] VSYS Voltage 0 to 24.48V	96mV	80µs	400µs
0x87	CSIN (V_{IN}) voltage [13:6] V_{IN} Voltage 0 to 36.72V	144mV	80µs	400µs

7. Application Information

7.1 Start-Up and ACOK

The RAA489110 includes a low power LDO with a nominal 4.5V output and an internal input OR-ed from the VBAT and CSIN inputs. The RAA489110 also includes a high power LDO with a nominal 5V output that has an input from the DCIN pin connected both to the adapter and the system bus through an external OR-ing diode circuit. The low power LDO must be active above 2.7V to enable the high power LDO. Both LDO outputs are tied to the VDD pin to provide the bias power and gate drive power for the RAA489110. The VDDP pin is the RAA489110 gate drive power supply input. Use an RC filter to generate the VDDP pin voltage from the VDD pin voltage.

The RAA489110 monitors the CSIN pin voltage to determine the presence of the adapter. When CSIN is higher than the ACOK threshold and after VDD POR releases, the charger is initialized for 150ms of debounce time from the first POR and no battery condition. Initialization takes about 4ms, and next the trim settings are read, the internal circuitry is auto-zeroed, and configuration is completed during the STARTUP state (see Table 15). During the first time an adapter is plugged in, while the 150ms debounce time is running, the RAA489110 uses a Renesas technique to check if the VSYS output is shorted (see System Voltage Rail Short Protection).

When V_{DD} > 2.7V with an additional 10ms delay, the RAA489110 digital block is activated and the SMBus register is ready to communicate with the master controller.

When the RAA489110 turns on the LDOs, it sources a current out of the PROG pin and reads the pin voltage to determine the PROG resistor value. The PROG resistor programs the RAA489110 configurations. See Table 18.

When V_{DD} > 3.8V, the RAA489110 allows the external circuit to pull up the ACOK pin. When ACOK is asserted, the RAA489110 starts switching.

ACOK is an open-drain output pin indicating the presence of the adapter and readiness of the adapter to supply power to the system bus. The RAA489110 actively pulls ACOK low in the absence of the adapter, for Way Overcurrent (WOCP), Over-Temperature (OTP), or VSYS Undervoltage (UV) fault.

Two thresholds affect ACOK. The higher threshold controls ACOK. One threshold is fixed at 3.6V rising and one programmable threshold using the DAC (see Table 2 for the ACOK Ref register). Register 0x40 value sets the threshold. The default register value is set to 0x0000h, which disables the programmable threshold detection. The programmable threshold is helpful for monitoring the input supply when targeting higher voltages with USB Power Delivery communications. To detect an unplugged adapter, the adapter voltage has to fall below the ACOK threshold (higher of 3.4V falling and ACOK Ref register value).

For switching to start and continue, the CSIN voltage should be higher than the ACOK threshold and VDD should be higher than 3.8V.

In Battery Only mode, the RAA489110 enters Low Power mode if only the battery is present. V_{DD} is 4.5V from the low power LDO to minimize the power consumption. V_{DD} becomes 5V when it exits Low Power mode, such as when PSYS or ADC are enabled.

7.2 Programming Resistor

A 1% resistor from the PROG pin to GND programs the configuration of the RAA489110.

The AdapterCurrentLimit2 register default value is 1.5A.

Table 18 shows the programming options.

Table 18. PROG Pin Programming Table

PROG-GND Resistance (Ω)			Cell Count	Default Switching Frequency (kHz)	PSYS or REFADJ Pin Selection	Default ACLimit1 Reg (A)	Information 2 (0x4D) [4:0] readout
Min	Nominal	Max					
305.91	309	312.09	2	724	REFADJ	1.5	00010
427.68	432	436.3	2	724	REFADJ	0.476	00011
556.38	562	567.6	2	724	PSYS	1.5	00100
674.19	681	687.8	2	724	PSYS	0.476	00101
797.94	806	814.06	2	1050	PSYS	0.476	00110
930.069[1]	931[1]	931.931[1]	2	1050	PSYS	0.2	00111
1089.0	1100	1111	2	724	PSYS	3.0	01000
1356.3	1370	1383.7	2	724	REFADJ	0.2	01001
1603.8	1620	1636.2	3	724	REFADJ	0.2	01010
1851.3	1870	1888.7	3	724	PSYS	3.0	01011
2187.9	2210	2232.1	3	724	PSYS	0.2	01100
2712.6	2740	2767.4	3	724	PSYS	1.5	01101
3207.6	3240	3272.4	3	1050	PSYS	1.5	01110
3702.6	3740	3777.4	3	1050	PSYS	0.476	01111
4375.8	4420	4464.2	3	724	REFADJ	0.476	10000
5435.1	5490	5544.9	3	724	REFADJ	1.5	10001
6425.1	6490	6554.9	4	724	REFADJ	0.2	10010
7425.0	7500	7575.0	4	724	REFADJ	0.476	10011
8365.5	8450	8534.5	4	1050	PSYS	0.476	10100
9216.9	9310	9403.1	4	1050	PSYS	0.2	10101
1089	11000	11110	4	724	PSYS	1.5	10110
12573	12700	12827	4	724	PSYS	0.476	10111

1. Tolerance is tighter for this selection, 0.1% required. Other selections are typically 1% tolerance.

An open or short on the PROG pin configures the charger output to a safe value of 4.2V. The RAA489110 uses the default number of cells in series as Table 18 shows and sets the default MaxSystemVoltage register value accordingly, but the default MinSystemVoltage register is 0V to prevent charging.

The switching frequency can be changed through SMBus Control1 register Bits[9:7] after POR. See Table 4 for a detailed description.

When VDD is turned on, the RAA489110 typically sources 130µA current out of the PROG pin and reads the PROG pin voltage to determine the resistor value. However, in some situations, application environmental noise can pollute the PROG pin voltage and cause an incorrect reading. If noise is a concern, Renesas recommends connecting a capacitor from the PROG pin to GND to provide filtering. The resistor and the capacitor R-C time

constant should be less than 40µs so the PROG pin voltage can rise to a steady state before the RAA489110 reads it.

By default, whenever the adapter is unplugged and ACOK goes from high to low, the RAA489110 resets the AdapterCurrentLimit1 register to the default setting determined by the PROG pin resistor. This current limit reloading can be disabled using Control3 register Bit [14] as shown in Table 6.

If PSYS is not enabled in Battery Only mode, the RAA489110 resets the MaxSystemVoltage register to the default value according to the PROG pin cell number setting. If PSYS is enabled, the RAA489110 keeps the value in the register.

The diagrams in this datasheet are based on current-sensing resistors R_{s1} = 20mΩ and R_{s2} = 10mΩ unless specified otherwise.

7.3 Charger Control Register Operations

7.3.1 System Voltage Regulation and Maximum Charging Voltage Regulation

If the battery is absent, or if a battery is present but BGATE is turned off, the RAA489110 regulates the system bus voltage at the MaxSystemVoltage register setting or optionally to the MaxSystemVoltage setting plus 384mV. The CSOP pin senses the system bus voltage. When a valid adapter voltage is not present and only the battery is present, the RAA489110 enters a low power state. In this state, the BGATE is turned on, and the charge current is not controlled if VSYS is raised above the battery voltage by an external source connected directly to VSYS. To set the maximum charging voltage or the system regulating voltage, write a 16-bit MaxSystemVoltage command to register address 0x15H using the Write-word protocol shown in Figure 32 and the data format shown in Table 2.

The MaxSystemVoltage register accepts any voltage command, but only the valid register bits are written to the register and the maximum value is clamped. A 0x0000H command in REG 0x15H causes the RAA489110 to stop switching and enter READY state.

When the device is not charging but is in the VSYS state and Control0 register Bit[1] is a 0, the system voltage is regulated to the same setting as the MaxSystemVoltage DAC. When Control0 register Bit[1] is a 1, system voltage is regulated to the DAC plus an offset of 384mV, which is useful to avoid discharging a full battery in VSYS state when there is a system load transient.

The MaxSystemVoltage register sets the battery full charging voltage limit. The MaxSystemVoltage register setting is also the system bus voltage regulation point when the battery is absent or present but not in Charging mode. The MinSystemVoltage register setting is the system voltage regulation point when the RAA489110 is in Trickle Charging mode. The CSOP pin is the system voltage regulation sense point in Trickle Charging mode. See Table 2 for more information about the Min System Voltage register.

The CSOP pin senses the battery voltage for maximum charging voltage regulation. The CSOP pin is also the system bus voltage regulation sense point and controls the VSYS operating voltage.

7.3.2 Normal/Fast Battery Charging and Charging Current Limit

To set the charging current limit, write a 16-bit ChargeCurrentLimit command to register address 0x14H (Table 2) using the Write-word protocol shown in Figure 32. Set ChargeCurrentLimit = 0 and MinSystemVoltage = 0 to stop charging. Set ChargeCurrentLimit and MinSystemVoltage to non zero to start trickle or fast/normal charging.

By default, the adapter current-sensing resistor, R_{s1}, is 20mΩ and the battery current-sensing resistor, R_{s2}, is 10mΩ. Using the R_{s1} = 20mΩ and R_{s2} = 10mΩ option results in a 4mA/LSB resolution in the SMBus current commands.

If the R_{s1} and R_{s2} values are different from the R_{s1} = 20mΩ and R_{s2} = 10mΩ option, scale the SMBus commands accordingly to obtain the correct current. Smaller current sense resistor values reduce the power loss and larger current sense resistor values give better accuracy. For example, if using a 5mΩ $R_{s2,}$ multiply each value in the DAC table by 2.

The RAA489110 limits the charging current by limiting the CSOP - CSON voltage, so halving the current sense resistor value doubles the current being regulated to. By using the recommended current sense resistor values R_{s1} = 20mΩ and R_{s2} = 10mΩ, the LSB of the register (ChargeCurrent register [2]) translates to 4mA of charging current. The ChargeCurrentLimit register accepts any charging current command, but only the valid register bits are written to the register.

If different current-sensing resistors are used, keep the R_{s1}:R_{s2} ratio as 2:1. If Control4 register Bit[11] is set, a 1:1 ratio is allowed but accuracy decreases. The PSYS output can be scaled accordingly to reflect the total system power correctly.

After POR, the ChargeCurrentLimit register is reset to 0x0000H, which disables fast charging and trickle charging. To enable fast charging the battery, write a non-zero number to the ChargeCurrentLimit register. Read the ChargeCurrentLimit register back to verify its content.

When charging, system voltage is regulated to VBAT plus some IR drop due to sense resistor and BFET ON-resistance. The system voltage is above the MinSystemVoltage DAC setting and below the MaxSystemVoltage DAC setting plus appropriate offsets.

7.3.3 Trickle Charging and Minimum System Voltage Regulation

Writing the MinSystemVoltage register 0x3EH to 0x0000h disables all battery charging.

The RAA489110 supports trickle charging to an overly discharged battery. It can activate the trickle charging function when the battery voltage is lower than the MinSystemVoltage setting. The VBAT pin is the battery voltage sense point for Trickle Charge mode. While trickle charging the battery, system regulation voltage is the MinSystemVoltage DAC setting plus 384mV. It can take up to 100ms (ADC polling time) to transition from trickle-to-fast charge or fast-to-trickle charge.

To set the minimum system voltage, write a 16-bit MinSystemVoltage command to register address 0x3EH using the Write-word protocol shown in Figure 32 and the data format shown in Table 2. To enable Trickle Charging, set the MinSystemVoltage and ChargeCurrent register to a non-zero value. If both registers have non-zero values and the battery voltage is below MinSystemVoltage, trickle charging is activated. To disable trickle charging, set the MinSystemVoltage and ChargeCurrent register to 0. Setting the MinSystemVoltage and ChargeCurrent register to 0x0000h disables all charging, which is the default and must be changed to allow any charging. The MinSystemVoltage register accepts any voltage command, but only the valid register bits are written to the register. Set the MinSystemVoltage register value lower than the MaxSystemVoltage register value.

See Table 22 for trickle charging control logic. When using the standard sense resistor, the trickle charging current can be programmed through SMBus Control2 register Bits[15:13] in Table 5.

In Trickle Charging mode, the RAA489110 regulates the system voltage to the MinSystemVoltage DAC setting with voltage sensed at the CSOP pin and regulates the charge current to the trickle charge current to the setting in the Control2 register Bits[15:13].

When the battery voltage is charged above the MinSystemVoltage register value, the RAA489110 enters Fast Charging mode by limiting the charging current at the ChargeCurrentLimit register setting using just the buck-boost switcher. The BFET is fully turned on. There may be a small amount of mode chatter at the trickle/fast charge boundary that stabilizes when trickle or fast charge mode is fully entered. The EOC flag may be set at the trickle-to-fast charge (or fast-to-trickle charge) boundary, so the flag needs to be reset before the actual EOC in autonomous mode.

The MinSystemVoltage register sets the battery voltage threshold to enter and exit Trickle Charging mode and Learn mode. The VBAT pin senses the battery voltage to compare with the MinSystemVoltage register setting. See Battery Learn Mode for details.

7.3.4 Autonomous Charging Mode

The RAA489110 supports Autonomous Charging mode and enables automatic end of charge termination. This mode can be enabled or disabled through SMBus Control3 register Bit[7] (Table 6). When Autonomous Charging mode is enabled, the SMBus timeout timer is disabled and Reverse Turbo Mode must be disabled. Autonomous mode is not disabled by writing SMBus ChargeCurrentLimit or MaxSystemVoltage commands. If Autonomous Charging mode is set and the battery does not terminate charging for 3/6/9/12 hours (Control3 register Bits[12:11]), Control3 register Bit[7] bit is reset, disabling Autonomous Charging and setting the interrupt (Bit [11]). When the 3/6/9/12 hour timer expires, the MaxSystemVoltage or the ChargeCurrent register has to be written first before charging can be started again. This Control3 register Bit[7] bit also resets if a fault occurs. Control7 register Bits[9:8] sets the End of Charging (EOC) current settings (Table 8), and the Control3 register Bit[13] sets the debounce time (Table 6).

The RAA489110 enters Autonomous Charging mode when the BGATE MOSFET is on and the battery voltage is lower than the MaxSystemVoltage by a certain threshold (See Auto Recharge Threshold Relative to Maximum System Voltage in the EC table) for 1ms debounce time.

In Autonomous Charging mode, the RAA489110 starts to charge the battery with the programmed value (REG0x14h). When Autonomous charging mode is enabled, charging begins if both Charge Current Limit register (0x14h) and MinSystemVoltage register (0x3Eh) are set to non-zero values.The PROCHOT# pin behaves as the Autonomous Charging mode indication pin and is pulled down to GND, and the SMBus timeout timer is disabled. The RAA489110 exits from Autonomous Charging mode when the battery charging current is less than the EOC setting for 20ms and 200ms in the CV loop. The autonomous charging termination time can be set by Control3 register Bit[13]. The RAA489110 enters/re-enters Autonomous charging mode when the battery voltage falls below the MaxSystemVoltage- Auto Recharge Threshold for 1ms debounce time and the BGATE MOSFET is on. This is called Auto-recharge function and can be disabled using Control9 register Bit[8]. The EOC flag may be set at the trickle-to-fast charge (or fast-to-trickle charge) boundary, so the flag needs to be reset before the actual EOC in autonomous mode.

When not in Autonomous Charging mode, the charger does not terminate charging but instead enters a CV charge state with a small charging current. The termination and start of another recharge cycle is controlled by the SMBus master. Enabling Autonomous Charge disables the SMBus Timeout Timer and sets PROCHOT# to be an Autonomous Charging indicator.

7.3.4.1 Auto Recharge Function

In autonomous charging mode, when the charger has fully charged and the EOC current is reached, charging is stopped and BGATE is turned off. When the battery voltage drops to MaxsysV below threshold, which is defined by the auto recharge threshold in the EC table (for 1ms), then charging starts again. This auto recharge function can be enabled or disabled using Control9 register Bit[8] and is enabled (0) by default.

If the auto recharge function is disabled, the charger does not start charging again even if the battery voltage drops below the MaxSystemVoltage auto recharge threshold. Charging can start again only by writing a non-zero value to the ChargeCurrent register (0x14).

7.3.5 SMBus Timeout

The RAA489110 includes a watchdog timer to ensure the SMBus master is active and to prevent overcharging the battery. The RAA489110 terminates charging by turning off the BGATE FET if the charger has not received a SMBus write command to the MaxSystemVoltage or ChargeCurrent register within 175s (default value in Control3 register Bits[12:11] = 00).

SMBus timeout time can be configured through SMBus Control3 register Bits[12:11].

When the charging is stopped by the SMBus timeout, the RAA489110 transitions from charging to the VSYS regulation state. The ChargeCurrent register retains its value instead of resetting to zero. When a timeout occurs, the MaxSystemVoltage or ChargeCurrent register must be written to re-enable charging.

Enabling Autonomous Charge disables the SMBus Timeout Timer. You can disable the SMBus timeout function through SMBus Control0 register Bit[7] as Table 3 shows. If SMBus timeout is disabled and a fault occurs, RAA489110 goes to a fault state and retries every 1.3s until the fault is cleared. After entering the FAULT state, there is no switching and the charger tries to start switching again after 1.3s.

7.3.6 BATGONE

The BATGONE pin is a dual-purpose pin that provides both an analog and a digital function. If pulled to VDD, the pin indicates a battery gone state, the digital function. In addition, an NTC can be connected from this pin to ground, the analog function.

A 1µA current pulls up on the BATGONE pin when not making an NTC ADC sample. A BATGONE condition is indicated if the pin voltage exceeds VDD minus a threshold (see Electrical Specifications for value).

If BATGONE is low, it indicates the presence of a battery. BATGONE needs to be low to enable OTG mode with BGATE on. When BATGONE is high the device exits Battery Learn mode.

7.3.7 NTC for Supporting Programmable temperature and JEITA Profiles

In addition to the internal die temperature, a thermistor for an NTC can be used on the BATGONE pin. The NTC is sensed using pulsed current source with three source current levels for reading the thermistor voltage on the pin.

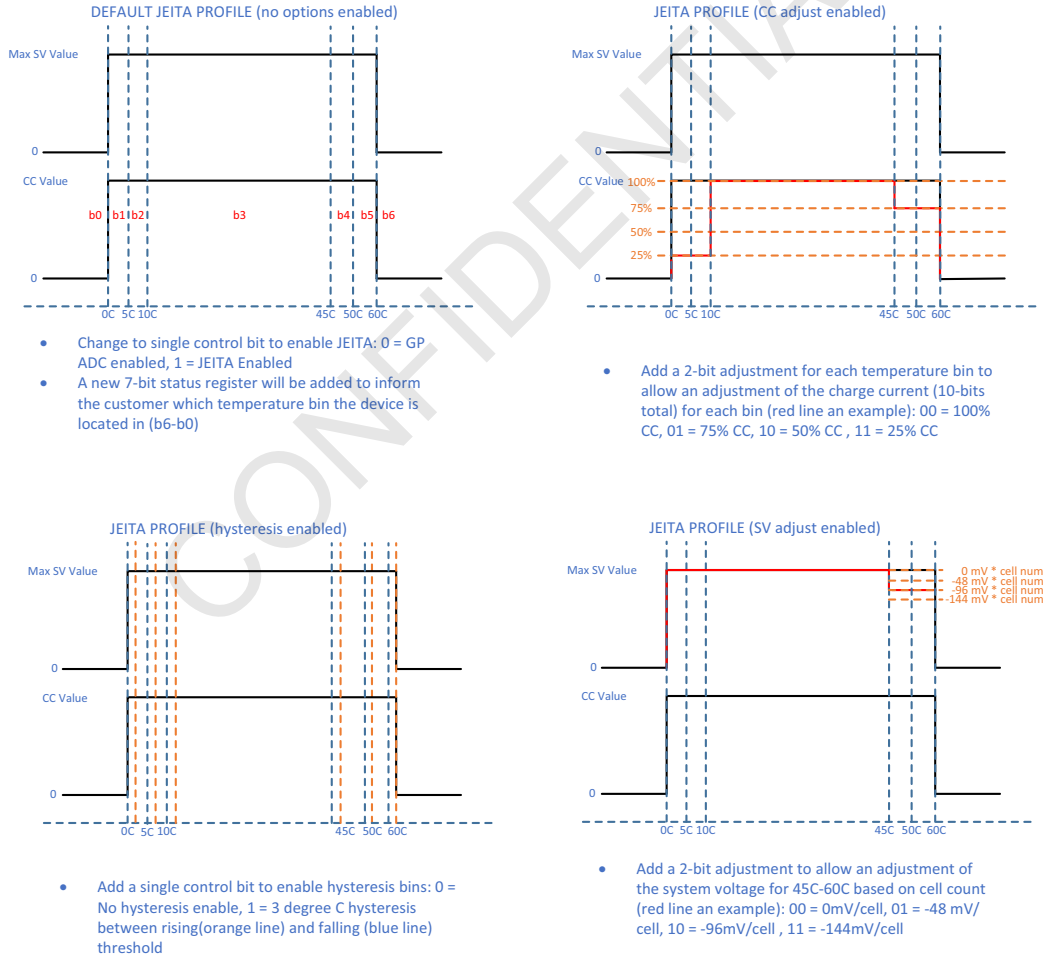


Figure 33. Programmable Temperature Profiles

7.3.8 Battery Learn Mode

The RAA489110 supports Battery Learn mode when in NVDC mode only. The RAA489110 enters Battery Learn mode when it receives the SMBus Control command.

Use Battery Learn mode to supply the system power from the battery even when the adapter is plugged in, such as calibration of the battery fuel gauge (so the name Battery Learn mode).

In Battery Learn mode, the RAA489110 turns on BGATE and turns off the buck-boost switcher regardless of whether the adapter is present.

The three ways of exiting Battery Learn mode are as follows:

- Receive the Battery Learn mode exit command through SMBus (Control1 Bit[12] setting)
- Battery voltage is less than the MinSystemVoltage register setting (Control1 Bit[13] setting)
- BATGONE pin voltage goes from logic LOW to HIGH

In all these cases, the RAA489110 resumes switching immediately to supply power to the system bus from the adapter to prevent system voltage collapse.

7.3.9 Battery Only Operation Mode

When the battery voltage V_{BAT} is higher than 2.7V and the adapter voltage V_{ADP} (CSIN) is less than 2.4V, the RAA489110 operates in Battery Only mode. During Battery Only mode, the RAA489110 turns on the BGATE and NGATE to connect the battery to the system. In Battery Only mode, the RAA489110 consumes very low power. The battery discharging current monitor BMON can be turned on during this mode to monitor the battery discharging current. If the battery voltage V_{BAT} is high enough to maintain VDD above 3.8V, the system power monitor PSYS or ADC functions can be turned on during this mode to monitor system power or other parameters. OTG mode can be enabled only if the battery voltage is above 5.2V.

Turning on additional functionality increases current consumed.

7.3.10 Battery Ship Mode

Battery Ship mode sets the lowest power state for the IC. Ship mode can only be entered from Battery Only mode. To achieve the lowest power, the following analog functions must be disabled. Many are disabled by default and do not need to be written, but all are listed for completeness. However, the power level can be customized for the system.

- Control0 0x39h (Table 3)
  - Bit[12] = 1 NGATE Off
  - Bit[11] = 0 BPYSG Off
  - Bit[6] = 0 Normal Charge Pump Operation
- Control1 0x3Ch (Table 4)
  - Bit[6] = 1 Force BGATE Off
  - Bit[5] = 1 Disable IMON
  - Bit[3] = 0 Disable PSYS
- Control3 0x4Ch (Table 6)
  - Bit[0] = 0 ADC active only if adapter is plugged in and charging is enabled
- Control4 0x4Eh (Table 7)
  - Bit[12] = 1 Disable GP Comparator for battery only mode
- Control8 0x44H (Table 9)
  - Bit[15] = 0 Disable Supplemental mode
- Control9 0x45H (Table 10)
  - Bit[15] = 0 BGATE Normal operation

To exit Ship mode, either plug in an adapter or use the SMBus to change these control bits.

In Standby mode, the charger enters BAT state even when an adapter is present to reduce current consumption on the adapter and battery. *Note:* Use only when the system is drawing minimal current. Before the Standby mode

control bit Control7 register Bit [2] is enabled, set the MaxSystemVoltage register to zero so that the charger is in READY state first. This can be followed by setting Control7 register Bit[2] = 1.

The same settings above for ship mode can be used to reduce the battery current consumption further in standby mode. The control bits for the functions above (such as PSYS) have to be re-enabled when the charger exits Standby/Ship mode.

7.3.11 Pass-Through Mode (PTM)

The Pass-Through Mode (PTM) is a feature on the RAA489110 where the input is connected to the output using Q1, Inductor and Q4. The output voltage (CSOP) is maintained at the input voltage. When the PTM is entered, Q1 and Q4 are continuously turned on except for refresh pulses (where Q2 and Q3 are turned on briefly to keep the BOOT capacitor charged). The refresh rate can be changed by using Control9 register Bits[7:6]. *Note:* Do not enable PTM and Programmable Power Supply (PPS) mode when Bypass mode is enabled.

Complete the following steps to enter PTM successfully:

1. Set Charge Current Limit (Reg 0x14) and MinSystemVoltage (Reg 0x3E) to 0.
2. Ensure that the system load is low enough that the adapter current is way below the AdapterCurrentLimit (Reg 0x3F).
3. Change MaxSystemVoltage (Reg 0x15) equal to adapter voltage. Check if the charger entered Forward Buck-Boost Mode (or Forward Boost Mode) by checking Information2 (REG 0x4D) Bits[7:5] = 011 (or 001). Alternatively, keep increasing the MaxSystemVoltage register by small steps until Forward Buck-Boost mode (or Forward Boost Mode) is entered and Information2 (REG 0x4D) Bits [7:5] = 011 (or 001).
   Note: In the application where CSIN voltage changes because of I×R drop constantly caused by load changes during this transition, the charger may go back to Forward Buck mode. Ensure that you set MaxSystemVoltage to make the charger work in Forward Buck-Boost mode (or Forward Boost Mode) after taking this into consideration when PTM enable command is sent.
   Note: The MaxSystemVoltage DAC maximum value is clamped at 18.304V. So, for adapter voltages higher than 18.304V, change MaxSystemVoltage DAC to maximum setting of 18.304V and then enable PTM.
4. Enable Pass Through Mode (PTM) Transition (Control7 register Bit[3]).
5. Check successful Pass Through Mode (PTM) entry through information bit (Information1 Bit[8]) after 7ms.

Renesas does not recommend using PTM when CSIP<VBAT. Renesas recommends disabling charging and learn mode before enabling PTM. When PTM is enabled, the charger ramps the CSOP voltage to the CSIN voltage (the reference voltage changes from MaxSystemVoltage DAC to the CSIN voltage). When the CSOP voltage is within a certain window of the input voltage (around 300mV), the charger enters Pass Through Mode. When the Pass Through Mode is entered, the information bit (Information 1[8]) is set high after 4-7ms.

If the Pass Through Mode Information bit is not set after 7ms, you are advised to reset the Pass through Mode control bit (Control7 register Bit[3]) manually and try again when needed.

The adapter current loop is disabled 4-7ms after PTM entry. If the load current exceeds Adapter current limit within this 4-7ms time, the charger switches from PTM to PWM switching until the charger is in the adapter current limit loop (without meeting any exit criteria). When the adapter current falls below the adapter current limit loop, the charger goes back to Pass Through Mode if no other exit conditions are met during this time.

After 4-7ms, the Adapter current loop is disabled while the charger is in PTM mode, if Control4 register Bit[10] = 0 (default). If Control4 register Bit[10] = 1, the Adapter current limit loop is not disabled and the load current and any current spikes in PTM should be below the Adapter current limit.

When the PTM is entered and Information bit goes high, the charger exits PTM when one of the following exit criteria are true:

- Control bit – When Control7 register Bit[3] PTM bit is disabled.

- ACHOT_DB – When the adapter current exceeds the AC PROCHOT# threshold for more than the debounce time set by Control9 register Bit[13]. This is blanked for the first 4ms of PTM enable (until PTM Information bit is set). If Control0 register Bit[8] is high, ACHOT_DB does not cause PTM exit, but PROCHOT# is still asserted.
- PTM OV – When the CSIN voltage exceeds the PTM Overvoltage threshold around 23.4V (see Electrical Specifications for accurate values).
- Battery discharge current >150mA – When the battery discharge current exceeds 150mA.
- V_{IN} loop – When the input voltage loop is selected due to CSIN dropping below the V_{IN} loop DAC (0x4B).
- ACOK – When the CSIN voltage drops below higher of regx40 (ACOKREF) and 3.6V (see Electrical Specifications for accurate values).
- IDM – If the charger enters Ideal Diode Mode (IDM), PTM mode is exited.
- $V_{IN} < V_{OUT}$ comparator – When Ctrl0[5] is enabled and CSIN falls below CSOP -120mV, PTM exits.

When the charger meets any of the exit criteria previously noted,

- CSOP starts regulating to the voltage set by the MaxSystemVoltage (the reference voltage changes back from CSIN to MaxSystemVoltage register).
- The Pass Through Mode (Control7 register Bit[3]), PPS (Control7 register Bit[4]), and Force Buck mode (Control0 register Bit[10]) bits are reset to 0 automatically.
- PTM mode information bit (Info 1[8]) is reset to 0.

Charging is not supported and is disabled during Pass through mode. Set ACOKREF 1V to 2V higher than the battery voltage (but lower than lowest adapter voltage considering tolerance, I*R drop) to detect adapter unplug under light-load conditions.

Note the following:

- Ensure only CV mode operation within PTM.
- Before entering PTM, enable the voltage slew rate control and ramp up the VSYS to close to VADP.
- Before entering PTM, to limit the adapter inrush current during PTM entry, set ACLIM DAC to a low value if necessary.
- If VADP is higher than 20V, use PTM or PPS only if CSOP absolute maximum is not violated.
- Although VSYS can follow the VADP up to PTM_OV = 23.4V, the slew rate control does not apply when the VSYS needs to go beyond 18.304V (Maximum System Voltage upper limit).
- Renesas recommends not enabling PTM mode when the adapter voltage is higher than PTM overvoltage threshold = 23.4V.

7.3.12 Programmable Power Supply (PPS)

Always use the Programmable Power Supply (PPS) function along with the Pass Through Mode function. If the PPS function is required, enable both PTM (Control7 register Bit[3]) and PPS (Control7 register Bit[4]) together.

When PPS is enabled, the same steps are carried out by the IC as PTM. In addition to these steps, BGATE is turned on. Set the charge current to the maximum charge current allowed into the battery (the actual charge current is generally controlled by the PPS source).

The following are the exit conditions for PPS in addition to all PTM exit conditions:

- CCHOT_DB – When the charge current exceeds the ChargeCurrentLimit register (0x14) for more than 1ms and ACHOT for PTM is enabled with Control0 register Bit[8] = 1. This is blanked for the first 4ms of PPS enable (until PTM Information bit is set).
- BAT_OV – When battery voltage exceeds MaxSystemVoltage + offset (Offset: 2-cell: 168mV, 3-cell: 252mV, 4-cell: 336mV). See the Battery Overvoltage Protection (For PPS Mode exit) section.
- Trickle charge – When the battery voltage falls below the MinSystemVoltage(0x3E) setting.

When PPS mode is exited, the charger goes to the NVDC state and continues switching and charging.

Control0 register Bit[8] = 1 disables PPS exit because of ACHOT_DB in addition to CCHOT_DB.

7.4 Reverse Modes

7.4.1 USB On The Go (OTG), USB - Power Delivery (PD)

When the OTG function is enabled with the SMBus command and the OTGEN pin and if the battery voltage V_{BAT} is higher than 5.2V, the RAA489110 operates in Reverse Buck, Reverse Boost, or Reverse Buck-Boost mode.

When the RAA489110 receives the command to enable the OTG function, it starts switching after a small delay. When the OTG output voltage reaches to the OTG output voltage set by register 0x49 Bits[14:3], OTG power-good OTGPG is internally set and can be observed on the INT# if the interrupt is enabled (Table 13).

Note: The OTGPG on RAA489110 is latched on the INT# pin and needs to be cleared. Information4 indicates the real-time status. In previous generations, the OTGPG pin indicated the real-time OTGPG status.

OTG Voltage DAC (0x49) needs to be at least 3.3V (SPR PPS Minimal Voltage in USB-PD Spec) before enabling OTG. The RAA489110 includes the OTG output undervoltage and overvoltage protection functions. The UVP threshold is OTG output voltage -1.8V and the OVP threshold is OTG output voltage +1.8V.

The UVP threshold can be disabled for USB-C Programmable Power Supply (PPS) support using Control3 register Bit[15](Digital OTG UV). When UV is detected, the RAA489110 de-asserts OTGPG. After 32ms, it stops switching. It resumes switching after the 1.3s or 150ms debounce time set by Control2 register Bit[11].

BATGONE needs to be low to enable OTG mode with BGATE on. OTG mode is not available if the battery voltage is below 5.2V.

Because the GPCOMP is shared with the same pin OTGEN, there is some logic to control how OTG mode is enabled.

If GPCOMP is enabled (Control2 register Bit[3] = 0), OTG function directly follows the OTG function register bit (Control1 register Bit[11]), the OTGEN pin becomes a don't care condition.

If GPCOMP is disabled (Control2 register Bit[3] = 1), if OTG function register bit is enabled (Control1 register Bit[11]), and OTGEN pin is enabled (Pin 26), OTG can be enabled.

7.4.1.1 OTG Voltage Register

The OTG voltage register contains SMBus readable and writable OTG mode output regulation voltage references. The default is 5.004V. OTG DAC max value is clamped to 32.256V, and the DAC register can be written as a higher value but is clamped as 32.256V.

OTG mode is allowed to be enabled only if the battery voltage is above 5.2V.

7.4.1.2 OTG Current Register

The OTG current register contains the SMBus readable and writable OTG current limit. The default is 512mA. This register accepts any current command, but only the valid register bits are written to the register and the maximum value is clamped at 6112mA when the current is sensed across R_{s1} = 20mΩ.

7.4.2 Fast Role Swap

The RAA489110 supports USB-C Power Delivery Fast Role Swap (FRS). FRS means quickly going from charging the battery to providing an OTG output voltage to provide power to accessories when another power source is disconnected. If FRS support is needed, enable OTG mode using the external pin, set up the OTG Voltage register for 5.004V, and toggle the external pin for OTGEN/CMIN to enable OTG mode when the FRS command is detected. If the adapter voltage is higher than 5V, the RAA489110 does not switch until CSIN is below the 5.004V DAC target.

7.4.3 Supplemental Mode (Intel VAP Support)

The RAA489110 supports Supplemental mode, also known as the Intel VMIN Active Protection (VAP) mode. The device supports the latest Intel VAP mode 3 that offers fast energy transfer to/from the adapter-side (input) capacitors to ensure the charger is ready to react to system load transients as quickly as possible, therefore, preventing system shutdown.

In the VAP mode 3 operation, when the load is not high and there is enough charge in the battery, the RAA489110 can operate the power stage in the reverse direction to charge the input capacitors up to the voltage defined by the OTGVoltage DAC (REG 0x49). When a heavy system load occurs, the system voltage sags. When the system voltage drops to a threshold determined by the Input Voltage DAC (REG 0x4B), the RAA489110 regulates the system voltage at that threshold level by operating the power stage in the forward direction and transferring energy from the input capacitors.

The load is supported by the input capacitors and the system voltage is regulated at Input Voltage DAC (REG 0x4B) value as long as there is energy in the input. As the charge is gradually depleted from the input capacitors, the input voltage drops. An Adapter Low PROCHOT# is asserted within 10µs of the input voltage crossing the threshold set by the VADPLO reference (Control8 register Bits[6:5]). When the load is removed, the charger starts to recharge the input capacitors using charge/energy from the battery. After receiving the command to exit Supplemental mode, the energy stored in the input capacitors can be discharged using an internal discharge path, so that an external power source can subsequently be safely connected.

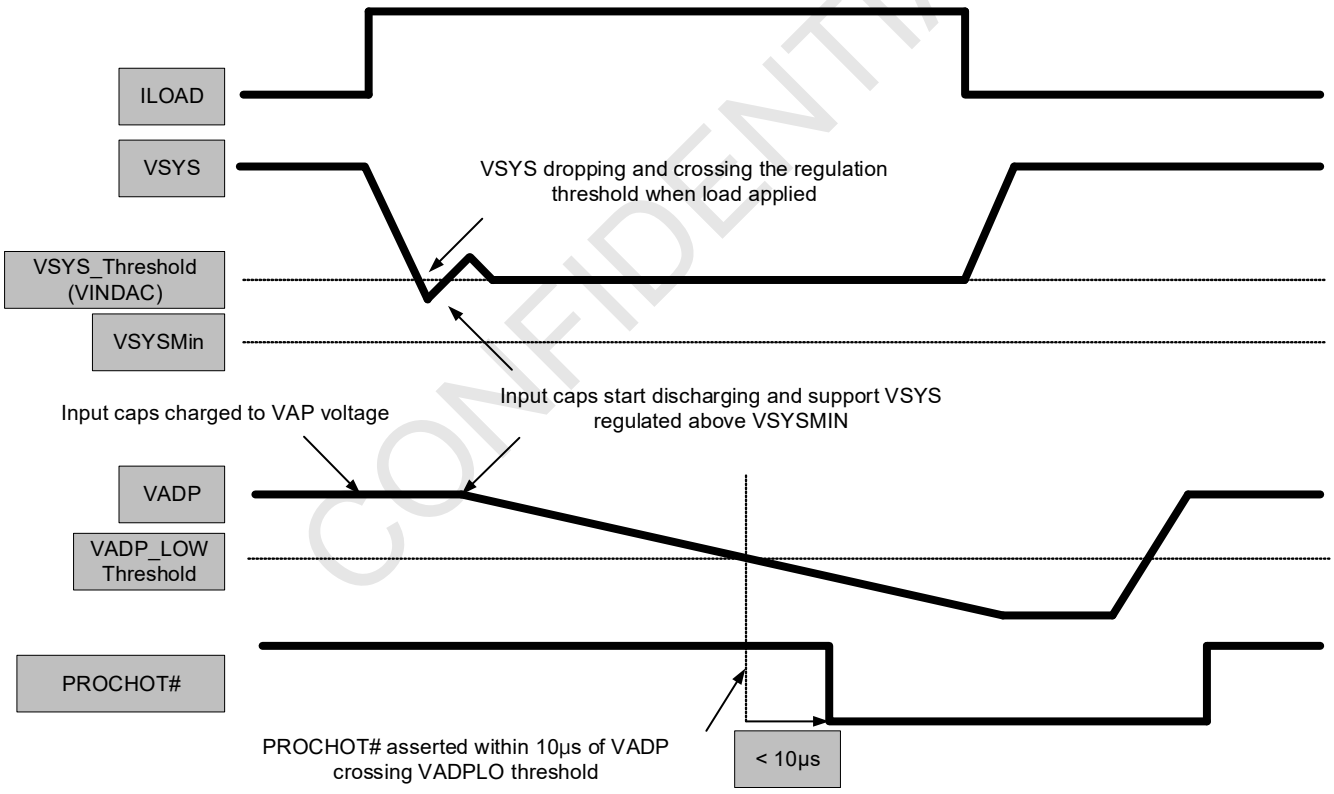


Figure 34. Supplemental Mode or Intel VAP Mode 3 Implementation

7.4.3.1 Entry Steps for Supplemental Mode or Intel VAP Mode 3

The following steps are required to enter Supplemental mode safely:

1. Set OTGEN pin to high.
2. (Optional) Set Charge current limit (Reg 0x14) to 1A.
3. Disable Slew Rate Control (Control4 register Bit[13]).
4. Disable General Purpose Comparator (Control2 register Bit[3]).
5. Disable CSIN overvoltage (OV) protection in OTG Mode (Control1 register Bit[10]).
6. Disable Analog OV Control (Control7 register Bit[7]).
7. (Optional) Set DC PROCHOT# DAC (Reg 0x48) to 8A.
8. Set OTGVoltage DAC (Reg 0x49) to desired voltage.
9. Set VinDAC (Reg 0x4B) for the minimum CSOP regulation point. The VinDAC voltage threshold must be lower than VBAT and higher than minimum allowable system voltage.
10. Set PROCHOT# duration to real time (Control2 register Bits[8:6] = 111).
11. Set PROCHOT# debounce to its minimum (Control2 register Bits[10:9] = 00).
12. Set VADPLO PROCHOT# reference to 7.2V (Control8 register Bits[6:5] = 00).
13. Enable VAP mode 3 (Control8 register Bits[15:13] = 111).

Note: An adapter low PROCHOT# is asserted when VAP mode 3 is initially enabled. When the charger recharges the input capacitors to OTGVoltage DAC value (Reg 0x49), PROCHOT# is de-asserted.

7.4.3.2 Exit Steps for Supplemental Mode or Intel VAP Mode 3

Supplemental mode can be exited when an adapter is plugged in and/or VAP support is not needed anymore to support the system demand.

The following steps are required to exit Supplemental mode and move to NVDC mode safely:

1. Set Charge Current Limit (Reg 0x14) and MinSysVoltage (Reg 0x3E) to 0.
2. Enable CSIN auto sink (Control0 register Bit[14]).
3. Disable VAP mode 3 (Control8 register Bits[15:13]=000).
4. Set VINDAC (REG 0x4B) to a value representing a required minimum adapter input voltage.
5. (Optional) Set DC PROCHOT# DAC (Reg 0x48) to required threshold.
6. (Optional) Set OTGVoltage DAC (Reg 0x49) to required voltage if OTG mode is to be used.
7. Set PROCHOT# duration/debounce time to required values (Control2 register Bits[8:6] and Control2 register Bits[10:9]).
8. Disable CSIN auto sink (Control0 register Bit[14]) after 200ms or after input caps are fully discharged.

When Supplemental mode is disabled, the input capacitors are still charged to the full OTGVoltage DAC (REG 0x49) voltage. The input capacitors need to be discharged before an adapter is connected to the charger. The RAA489110 has a CSIN auto sink feature, which automatically enables the 10mA discharge current on the CSIN node for 200ms when Supplemental mode exits. This brings the CSIN voltage down so that the adapter can be connected to the charger safely. This feature can be enabled/disabled by Control0 register Bit[14].

7.4.3.3 Input Voltage DAC (REG 0x48) for System Voltage Regulation in Supplemental Mode or Intel VAP Mode 3

The Input voltage DAC (REG 0x4B), also referred to as the VINDAC, is used in Supplemental mode as the system voltage regulation point. The VINDAC LSB is different when operating in the Supplemental mode, as compared to the regular input voltage loop control operation. Table 19 details the VINDAC resolution for Supplemental mode, which can be also cross-referred in register DAC summary table.

Table 19. Input Voltage DAC (REG 0x4B) when Operating in Supplemental Mode

	V_{IN} Voltage for System Voltage regulation in Supplemental Mode
ADDR	**0x4B**
[0]	-
[1]	-
[2]	-
[3]	-
[4]	-
[5]	-
[6]	85mV
[7]	171mV
[8]	341mV
[9]	683mV
[10]	1365mV
[11]	2731mV
[12]	5461mV
[13]	10923mV
[14]	-
[15]	-
Max	16.384V

7.4.3.4 Control Logic for OTG and Supplemental Mode

Table 20 describes the logical truth table for OTG and Supplemental Mode.

Table 20. Control Logic Truth Table for OTG and Supplemental Mode

Inputs				Outputs	
External Pin OTGEN/CMIN	**CTRL8[15:13] Supplemental Mode**	**CTRL2[3] GP Comparator**	**CTRL1[11] OTG Function**	**Logic Control Signal**	**Logic Control Signal**
	111 - Sup 000 - OTG	**1 - Disable 0 - Enable**	**1 - Enable 0 - Disable**	**OTG mode (OTG_EN)**	**Supplemental Mode (SUP_EN)**
0	111	1	0	0	0
0	000	1	0	0	0
0	000	1	1	0	0
1	111	1	0	0	1

Table 20. Control Logic Truth Table for OTG and Supplemental Mode (Cont.)

Inputs				Outputs	
External Pin OTGEN/CMIN	CTRL8[15:13] Supplemental Mode	CTRL2[3] GP Comparator	CTRL1[11] OTG Function	Logic Control Signal	Logic Control Signal
	111 - Sup 000 - OTG	1 - Disable 0 - Enable	1 - Enable 0 - Disable	OTG mode (OTG_EN)	Supplemental Mode (SUP_EN)
1	000	1	0	0	0
1	000	1	1	1	0
x	x	0	0	0	0
x	x	0	1	1	0

7.4.4 Reverse Mode Discharge Current Loop

When the charger is in OTG mode, in addition to the voltage regulation loop set by the OTGVoltage register and the current limit loop set by the OTGCurrent register, there is a discharge current limit loop that is set by 2xChargeCurrentLimit register (0x14). This function is disabled when the ChargeCurrent register (0x14) is set to zero. When the charge current is set to a non-zero value, the charger limits the battery discharge current to be less than the discharge current limit, which is set by 2xChargeCurrentLimit register setting. This function can be used to limit inrush current from battery when OTGVoltage ramps up or down (in addition to the slew rate function).

7.5 Monitoring

7.5.1 Current Monitor

The RAA489110 provides an adapter current monitor/OTG current monitor or a battery charging current monitor/battery discharging current monitor through the AMON/BMON pin. The AMON output voltage is 18x (CSIP - CSIN) and 18x (CSIN - CSIP) voltage. The BMON output voltage is 18x (CSON - CSOP) and 36x (CSOP - CSON) voltage.

The AMON and BMON functions can be enabled or disabled through SMBus Control1 register Bit[5], AMON or BMON can be selected through SMBus Control1 register Bit[4], and AMON/BMON direction can be configured through SMBus Control3 register Bit[3].

There are options to select 2x or 4x the output voltage on the AMON/BMON pin (to show 2x or 4x the adapter or battery current). This is chosen using Control7 register Bits[6:5].

7.5.2 PSYS Monitor

The RAA489110 PSYS pin provides a measure of the instantaneous power consumption of the entire platform. The PSYS pin outputs a current source described by Equation 1.

(EQ. 1) $$I_{PSYS} = K_{PSYS} \times (V_{ADP} \times I_{ADP} + V_{BAT} \times I_{BAT}) + Offset$$

K_{PSYS} is based on current-sensing resistor R_{s1} = 20mΩ and R_{s2} = 10mΩ. V_{ADP} (CSIN) is the adapter voltage in Volts, I_{ADP} is the adapter current in Amperes, V_{BAT} (CSON) is the battery voltage, and I_{BAT} is the battery discharging current. When the battery is discharging, I_{BAT} is a positive value; when the battery is being charged, I_{BAT} is a negative value. The battery voltage V_{BAT} is detected through the CSON pin to maximize the power monitor accuracy in NVDC configuration Trickle Charge mode.

The R_{s1} to R_{s2} ratio is 2:1 by default for a valid power calculation to occur. If the PSYS information is not needed, any R_{s1}:R_{s2} ratio is acceptable. Optionally, the R_{s1} to R_{s2} ratio can be 1:1 and for valid power calculation to occur, Control4 Bit[11] needs to be changed accordingly.

The overall gain KPSYS is affected by three parameters and is defined as follows:

(EQ. 2) $$K_{PSYS} = G_{PSYS} \times F_{RS2} \times H$$

- GPSYS is the PSYS gain set by Control3 register Bits[9:8].
- FRS2 is the value of the battery current sense resistor used (RS2) divided by 10mΩ. For example, a 5mΩ R_{S2} results in FRS2 = 5mΩ/10mΩ = 0.5.
- H is the current feedback gain bit and is set by Control3 register Bit[6]. Setting this bit to 0 is the default and results in H = 1. Setting this bit to 1 results in H = 0.5.

The PSYS gain can be configured through SMBus Control3 register Bits[9:8]. The default PSYS gain is set on VDD POR and three other settings for PSYS gain are available (see Table 6). This gain scaling selection allows a range of power to be sensed on PSYS.

The PSYS information includes the power loss of the charger circuit and the actual power delivered to the system. Resistor R_{PSYS} connected between the PSYS pin and GND converts the PSYS information from current to voltage.

The PSYS function can be enabled or disabled through SMBus Control1 register Bit[3] as shown in Table 4. Enabling the PSYS function increases the RAA489110 IC current consumption.

7.5.3 PROCHOT#

PROCHOT# is an open-drain output used to support IMVP protocols. On systems that do not need IMVP this pin can be used as an additional interrupt pin.

In Autonomous Charging mode, the RAA489110 starts to charge the battery with the programmed value (REG0x14h). The PROCHOT# pin behaves as Autonomous Charging mode indication pin and is pulled down to GND while charging.

7.5.3.1 Setting the PROCHOT# Threshold for Adapter Overcurrent Conditions

To set the PROCHOT# assertion threshold for adapter overcurrent conditions, write a 16-bit ACProchot# command to register address 0x47H using the Write-word protocol shown in Table 32 and the data format shown in Table 2. By using the recommended current sense resistor values, the LSB of the register translates to 32mA of adapter current. The ACProchot# register accepts any current command; however, only the valid register bits are written to the register, and the maximum value is clamped at 6400mA for R_{s1} = 20mΩ.

After POR, the ACProchot# register is reset to 0x0C00H. The ACProchot# register can be read back to verify its content.

If the adapter current exceeds the ACProchot# register setting, the PROCHOT# signal asserts after the debounce time programmed by the Control2 register Bits[10:9] and latches on for a minimum time programmed by Control2 register Bits[8:6].

7.5.3.2 Setting the PROCHOT# Threshold for Battery Over Discharging Current Conditions

To set the PROCHOT# signal assertion threshold for battery over discharging current conditions, write a 16-bit DCProchot# command to register address 0x48H using the Write-word protocol shown in Figure 32. By using the recommended current sense resistor values, the LSB of the register translates to 64mA of adapter current. The DCProchot# register accepts any current command; however, only the valid register bits are written to the register, and the maximum value is clamped at 12.8A for R_{s2} = 10mΩ.

After POR, the DCProchot# register is reset to 0x1000H. The DCProchot# register can be read back to verify its content.

If the battery discharging current exceeds the DCProchot# register setting, the PROCHOT# signal asserts after the debounce time programmed by the Control2 register Bits[10:9] and latches on for a minimum time programmed by Control2 register Bits[8:6].

In Battery Only and Low Power mode, the DCProchot# threshold is set by Control0 register Bits[4:3].

In Battery Only mode, the DCProchot# function using the DAC (0x48H) works only when PSYS, ADC, or OTG is enabled because the charger is in READY or OTG state (not BAT state) when these two functions are enabled. When the charger is in READY state, DC PROCHOT# works using the 0x48H register. When in BAT state, DC PROCHOT# is set by Control0 register Bit[4:3].

7.5.3.3 Low_VSYS_Prochot#

Low_VSYS is configured using Control8 register Bits[12:10] (Table 9); there are eight settings available. Low_VSYS_Prochot# works only when PSYS, ADC, or OTG is enabled.

7.5.3.4 Other PROCHOT# Configuration

Control4 register Bits[6:4] (see Table 7) can be used to configure the PROCHOT# to be asserted for the following triggers: BATGONE, ACOK, or General Purpose Comparator.

7.5.3.5 Setting PROCHOT# Debounce Time and Duration Time

Control2 register Bits[10:9] (see Table 5) configures the PROCHOT# signal debounce time before its assertion for ACProchot# and DCProchot#.

The low system (VSYS_LOW) voltage PROCHOT# has a fixed debounce time of 7µs.

Control2 register Bits[8:6] configures the minimum duration of the PROCHOT# signal when asserted for VSYS_LOW, ACPROCHOT#, and DCPROCHOT#.

For the ACOK and BATGONE, Control4 register Bits[3:2] (see Table 7) can configure the debounce time before PROCHOT# is asserted.

7.5.3.6 Setting PROCHOT# Clear and Latch Control Bits

Control4 register Bit[0] Table 7 can be used to configure the PROCHOT# to latch and hold its state. This configuration is helpful as an interrupt flag to allow the system to determine what happened. If this bit is set the Control4 register Bit[1] Table 7 must be used to clear the asserted PROCHOT#.

7.5.4 ADC Operation

The Analog to Digital Converter (ADC) is a successive-approximation 8-bit converter. Table 17 identifies the bit locations of the control and information available and also the sample and polling time. The ADC monitors measuring, battery voltage, current, temperature through NTC, input current, and internal die temperature. The ADC is always disabled if V_{DD} falls below 3.8V. When V_{DD} is above 3.8V, the ADC is enabled by default when the adapter is plugged in and the charger is charging the battery. To enable the ADC in all other modes, Control3 register Bit[0] needs to be set.

Data is always valid to be read as a raw number from the last completed sample, and it updates once per polling time. The equation for the ADC measurement for the junction temperature (T_J in °C) is given below. The measured code has a maximum value of 255.

(EQ. 3) $$Reg0x82(decimal) = 251.7 - 0.6154 \times T_J$$

Example timing windows are shown in Figure 35.

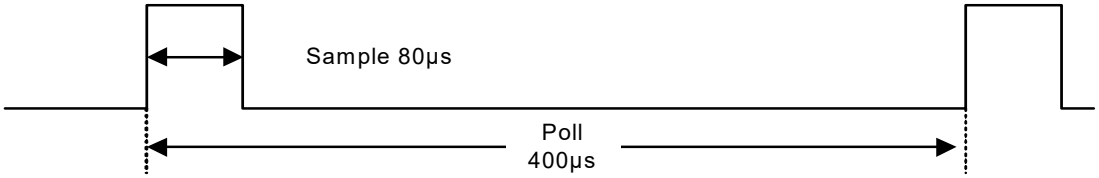


Figure 35. ADC Sample and Polling Time

7.6 Protection

7.6.1 Adapter Overvoltage Protection

If the adapter voltage sensed on the CSIN pin voltage exceeds 33.3V for more than 2µs, an adapter overvoltage condition occurs. The device stops switching to isolate the adapter from the system and BGATE turns on for the battery to support the system load. When the CSIN voltage drops below 32.8V for more than 2µs, it starts switching again. ACOK does not change states during this state.

7.6.2 Battery Protection

The battery is monitored by the ADC by reading register 0x81h and controlled using a NMOS FET (BFET). When battery voltage is below the MinSystemVoltage, the gate (BGATE) of the BFET operates in trickle mode to protect the battery. The RAA489110 controls the charging current using register 0x14h. An NTC input provides thermal protection to protect the battery from charging when outside of the normal operating region. For excessive voltage during constant current phase, the system overvoltage protection prevents excessive voltage on the battery.

When no valid adapter voltage is present (on CSIN) and only the battery is present, the RAA489110 enters a low power state. In this state the BGATE is turned on, but charge current is not controlled if VSYS is raised above the battery by an external source connected directly on VSYS (CSOP).

7.6.3 Battery Overvoltage Protection (For PPS Mode exit)

Battery Overvoltage condition arises when the voltage on VBAT pin exceeds MaxSystemVoltage register + offset (Offset: 2-cell: 168mV, 3-cell: 252mV, 4-cell: 336mV). Battery overvoltage condition goes away when the battery voltage falls below the above threshold with a 1ms debounce time.

Battery overvoltage protection is only for PPS mode and is one of the exit conditions for PPS Mode.

7.6.4 System Voltage Rail Short Protection

The RAA489110 has a system rail short protection to prevent powering on the system rail into a short-circuit before start of switching. When the VSYS voltage is below 0.6V, the RAA489110 sources 10mA current from VDDP to charge VSYS before the switching can start. When the VSYS pin is charged above 0.6V, an internal timer starts to count. After 10µs debounce time of the VSYS voltage being above 0.6V, the RAA489110 stops sourcing 10mA current and allows the RAA489110 to start switching. Any time a transition occurs from the READY state (disable switching with MaxSystemVoltage = 0V) back to the VSYS state (switching enabled by setting MaxSystemVoltage > 0V), the 10mA turns on again and CSOP voltage has to be charged above 0.6V to allow switching again.

7.6.5 System Voltage Undervoltage Protection (for Short-Circuit Protection)

The charger has an undervoltage protection on the system side that can be configured using Control9 register Bits[4:2]. When the CSOP voltage falls to the VSYS UV threshold set by Control9 register Bits[4:2], there is a 100ms debounce before the charger enters FAULT state. After entering FAULT state, there is no switching and charger tries to start switching again after 1.3s (configurable by Control2 register Bit[11]). ACOK is asserted low when the CSOP voltage falls to the VSYS undervoltage (UV) threshold.

7.6.6 System Voltage Overvoltage Protection

If the system voltage VSYS is 800mV higher than the MaxSystemVoltage register set value, the RAA489110 declares the system overvoltage and stops switching. It resumes switching without debounce when VSYS drops 400mV below the system overvoltage threshold (check EC table for the accurate values).

7.6.7 Way Overcurrent Protection (WOCP)

If the system bus is shorted (either a MOSFET short or an inductor short) the input current could be high. The RAA489110 includes input overcurrent protection to turn off the BYPSG and stop switching.

The RAA489110 provides adapter current and battery discharging current Way Overcurrent Protection (WOCP) function against MOSFET shorts, system bus shorts, and inductor shorts. The RAA489110 monitors the CSIP - CSIN voltage and CSON - CSOP voltage, and compares them with the WOCP threshold (12A for adapter current and 18A for battery discharge current).

When the WOC comparator is tripped, the RAA489110 increments a timer every 10µs. Whenever the timer reaches 7 counts, the charger stops switching immediately. The timer is reset every 50ms. After the 1.3s or 150ms debounce time set by Control2 register Bit[11], it goes through the start-up sequence to retry.

The WOCP function can be disabled through Control4 register Bit[9].

7.6.8 Over-Temperature Protection

The RAA489110 stops switching for self protection when the junction temperature exceeds +150°C.

When the temperature falls below +120°C for 100µs and after the 1.3s or 150ms delay, the RAA489110 resumes switching.

Internal die temperature can be monitored using the ADC, and firmware can update parameters to avoid thermal shutdown.

In addition to the internal die temperature, you can use a thermistor for an NTC on the BATGONE pin to control charging in accordance to the Programmable temperature profiles. See BATGONE for more details.

7.7 Additional Features

7.7.1 Stand-Alone Comparator

The RAA489110 includes a general purpose stand-alone comparator. The OTGEN/CMIN pin is the comparator input. The internal comparator reference is connected to the inverting input of the comparator and is configured by Control2 register Bit[4] as 1.2V or 2V (Table 5). The comparator output is the CMOUT/INT# pin, and the output polarity when the comparator is tripped can be configured through the SMBus register bit.

When Control2 register Bit[2] = 0 for normal comparator output polarity and if CMIN > Reference, CMOUT = High; if CMIN < Reference, CMOUT = Low.

When Control2 register Bit[2] = 1 for inversed comparator output polarity and if CMIN > Reference, CMOUT = Low; if CMIN < Reference, CMOUT = High.

By default in Battery Only mode, the stand-alone comparator is enabled. This comparator can be enabled/disabled in Battery Only mode using Control4 register Bit[12] (Table 7); however, the reference is set to 1.2V. Also, ensure Control2 register Bit[3] = 0 to enable the General purpose comparator in Battery only mode.

The general purpose comparator and INT# share the same pin, so either of them can pull the pin low if interrupts or GPCOMP is enabled. If all interrupts are disabled, the CMOUT/INT# pin shows the output of the GPCOMP. If GPCOMP is disabled, the pin indicates an interrupt status only.

The general purpose comparator output can be latched high using Control9 register Bit[9]. If the latch data needs to be cleared, Control9 register Bit[10] can be set to 1.

Figure 36 shows the Interrupt and the stand-alone comparator implementation.

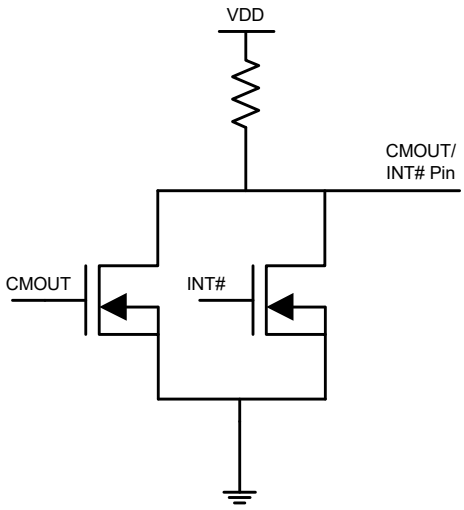


Figure 36. INT# and CMOUT Implementation

7.7.2 REFADJ Feedback Mode

The RAA489110 can support an external feedback resistor on the REFADJ pin. REFADJ mode allows the OTG output voltage to be controlled with an external feedback resistor. This mode is determined by the PROG resistor on power up (see Table 18) and is mutually exclusive to PSYS pin functionality.

One design method can be used to support Qualcomm quick charge feedback devices. These devices decode the D+/D- inputs and send a current into the resistor divider to make an adjustment in the OTG output voltage.

The schematic shown in Figure 37 shows how the REFADJ pin is tied to the feedback (FB node) resistor divider node off the VADP node for a quick charge protocol IC. This schematic sets up the FB node to use the reference voltage of 0.278V from RAA489110, but the output on the VADP node can be set up to any voltage over the standard operating range using the R_1/R_2 ratio.

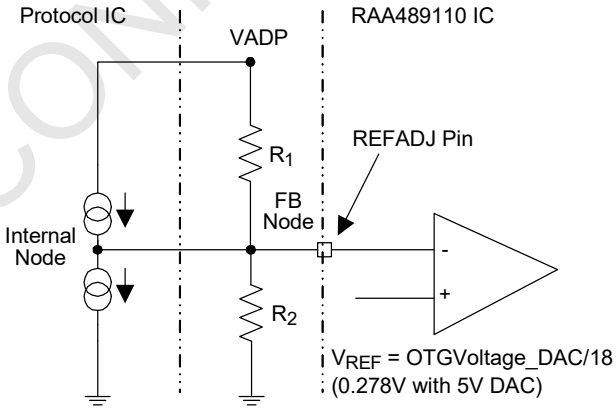


Figure 37. Simplified REFADJ Application

8. Modulator Information

8.1 Buck-Boost Charger Modes of Operation

The RAA489110 buck-boost charger drives an external N-channel MOSFET bridge made up of two transistor pairs as shown in Figure 38. The first pair, Q_1 and Q_2, is a buck arrangement with the transistor center tap connected to an inductor input, as is the case with a buck converter. The second transistor pair, Q_3 and Q_4, is a

boost arrangement with the transistor center tap connected to the output of the same inductor, as is the case with a boost converter. This arrangement supports bucking from a voltage input higher than the battery and also boosting from a voltage input lower than the battery.

Note: In OTG mode the output sensing point is the CSIN pin.

Table 21. Operation Mode

Mode	Q_1	Q_2	Q_3	Q_4
Buck	Control FET	Sync. FET	OFF	ON
Boost	ON	OFF	Control FET	Sync. FET
Buck-Boost	Control FET	Sync. FET	Control FET	Sync. FET
OTG Buck	ON	OFF	Sync. FET	Control FET
OTG Boost	Sync. FET	Control FET	OFF	ON
OTG Buck-Boost	Sync. FET	Control FET	Sync. FET	Control FET

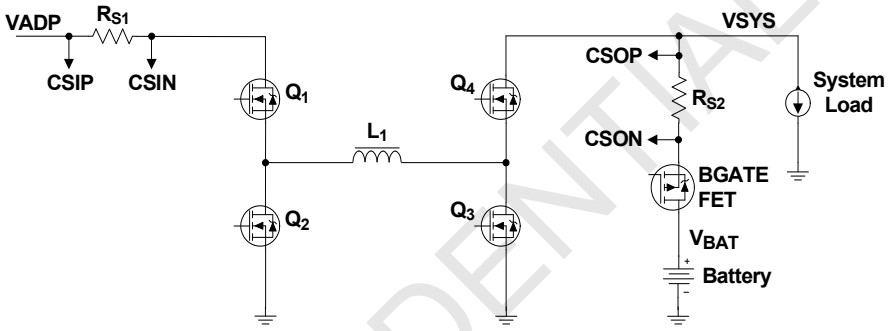


Figure 38. Buck-Boost Charger Topology

The RAA489110 optimizes the Operation mode transition algorithm by considering the input and output voltage ratio and the load condition. When the adapter voltage V_{ADP} is rising and is higher than 90% of the system bus voltage VSYS, the RAA489110 transitions from Boost mode to Buck-Boost mode; if V_{ADP} is higher than 114% of VSYS, the RAA489110 is forced to transition from Buck-Boost mode to Buck mode regardless of other conditions. At heavier load, the mode transition point changes accordingly to accommodate the duty cycle change due to the power loss on the charger circuit.

When the adapter voltage V_{ADP} is falling and is lower than 109% of the system bus voltage VSYS, the RAA489110 transitions from Buck mode to Buck-Boost mode; if V_{ADP} is lower than 86% of VSYS, the RAA489110 transitions from Buck-Boost mode to Boost mode.

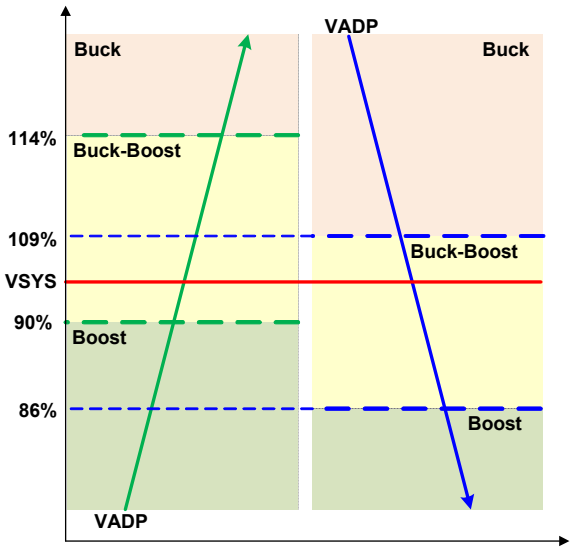


Figure 39. Operation Mode[1]

1. Mode transition boundaries are established by characterization and are not production tested.

When the OTG function is enabled with the SMBus command and OTGEN pin and if the battery voltage V_{BAT} is higher than 5.2V, the RAA489110 operates in OTG mode. Fast role swap is similar to OTG but uses shorter filters that allow a quick response to hold up the input when the adapter is detected as unplugged.

8.2 Modulator Control Loops

The four main control loops for the modulator are shown in Figure 40. Each loop has a DAC register to provide settings as needed for each system.

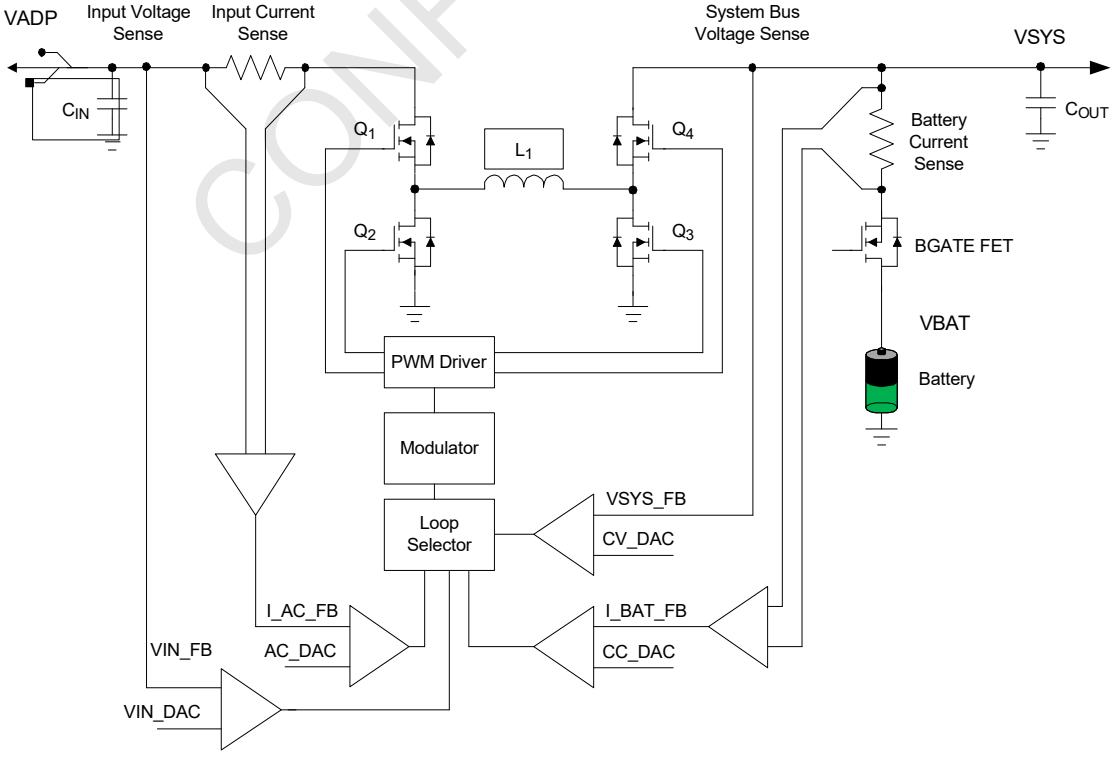


Figure 40. Charger Control Loops

8.2.1 Adapter Current Loop and One or Two-Level Current Limit

To set the adapter current limit, write a 16-bit AdapterCurrentLimit1 command to register address 0x3FH and/or AdapterCurrentLimit2 command to register address 0x3BH using the Write-word protocol shown in Figure 32 for a 20mΩ R_{s1}. For the DAC summary of values, see Table 2. When the AdapterCurrentLimit1 (0x3F) is set to 0, charger stops switching and goes to READY state.

The RAA489110 limits the adapter current by limiting the CSIP - CSIN voltage. By using the recommended current sense resistor values, the LSB of the register translates to 4mA of adapter current. Any adapter current limit command is accepted; however, only the valid register bits are written to the AdapterCurrentLimit1 and AdapterCurrentLimit2 registers, and the maximum value is clamped.

After adapter POR, the AdapterCurrentLimit1 register is reset to the value programmed through the PROG pin resistor. The AdapterCurrentLimit2 register is set to its default value of 1.5A or keeps the value that is written to it previously if the battery is present first. The AdapterCurrentLimit1 and AdapterCurrentLimit2 registers can be read back to verify their content. By default, the two level adapter current limit is disabled.

The AdapterCurrentLimit2 register has the same specification as the AdapterCurrentLimit1 register.

The two-level adapter current limit function can be enabled and disabled through SMBus Control2 register Bit[12], and the t1, t2 settings are configured by Control7 register (Table 8). When the two-level adapter current limit function is disabled, only the AdapterCurrentLimit1 value is used as the adapter current limit and AdapterCurrentLimit2 value is ignored

In a real system, a Turbo event usually does not last very long. It is often no longer than milliseconds, a time during which the adapter can supply current higher than its DC rating. The RAA489110 employs a two-level adapter current limit to fully take advantage of the surge capability of the adapter and minimize the power drawn from the battery.

Figure 41 shows the two SMBus programmable adapter current limit levels, AdapterCurrentLimit1 and AdapterCurrentLimit2, as well as the durations t1 and t2. The two-level adapter current limit function is initiated when the adapter current is less than 100mA lower than the AdapterCurrentLimit1 register setting. The adapter starts at AdapterCurrentLimit2 for t2 duration and changes to AdapterCurrentLimit1 for t1 duration before repeating the pattern. These parameters can set the adapter current limit with an envelope that allows the adapter to temporarily output surge current without requiring the charger to enter Turbo mode. This operation maximizes battery life.

If AdapterCurrentLimit1 is set to 0A, the charger stops switching and goes to READY state.

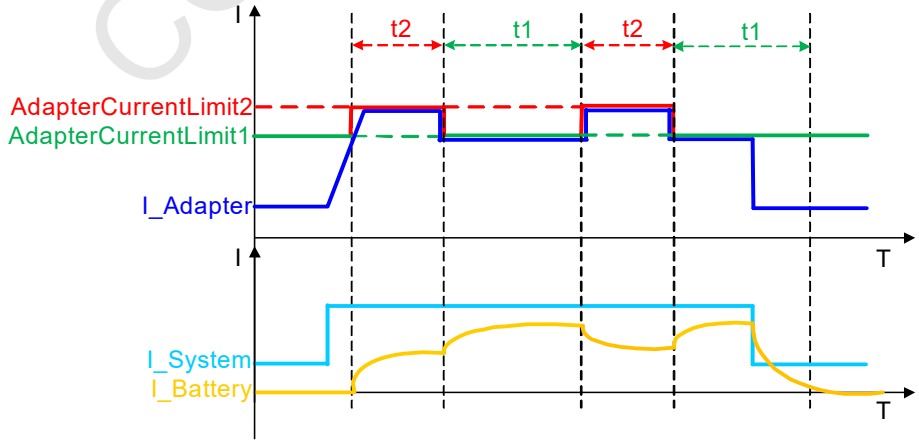


Figure 41. Two-Level Adapter Current Limit

8.2.1.1 USB-PD On-the-Go Output Current

The OTG output current regulation register DAC (Table 2) contains the SMBus readable and writable current that the current sense loop tries to regulate. This loop reuses the input current sense amplifier. If USB-PD Programmable Power Supply is needed, this is the current limit loop. Note that the OTG_UV needs to be disabled (see CTRL3 Bit[15] in Table 6).

This register accepts any current command, but only the valid register bits are written to the register. The maximum value is clamped.

8.2.2 Input Voltage Regulation Loop

8.2.2.1 Adapter Support Voltage

The input voltage regulation register DAC (Table 2) contains the SMBus readable and writable input voltage limit at which the input voltage loop tries to regulate when the input voltage is dropping. When the ADP is browning out or weak, the input voltage can droop and the input voltage loop tries to regulate to this setting by reducing battery charging current and then system power to try to hold up the input voltage. The system voltage may start to drop if the input power is not high enough to support the system.

This register accepts any voltage command but only the valid register bits are written to the register The maximum value is clamped.

8.2.2.2 USB-PD On-the-Go Output Voltage

The OTG output voltage regulation register DAC (Table 2) contains the SMBus readable and writable voltage that the voltage loop tries to regulate. This loop reuses the input voltage sense amp.

This register accepts any current command, but only the valid register bits are written to the register. The maximum value is clamped.

8.2.3 System Voltage Regulation Loop

This loop works for two different voltage settings: MaxSystemVoltage and MinSystemVoltage.

If the battery is absent, or is present but BGATE is turned off or not charging and if Control0 register Bit[1] is a 0, the system voltage is regulated to the same setting as the MaxSystemVoltage DAC. When Control0 register Bit[1] is a 1, the system voltage is regulated to the DAC plus an offset of 384mV (Table 3). This additional offset is useful to avoid discharging a full battery in the VSYS state when there is a system load transient.

To set the maximum charging voltage or the system regulating voltage, write a 16-bit MaxSystemVoltage command to register address 0x15H using the Write-word protocol shown in Figure 32. A 0V command causes the RAA489110 to stop switching and enter the READY state.

The RAA489110 supports trickle charging to an overly discharged battery. It can activate the trickle charging function when the battery voltage is lower than the MinSystemVoltage setting. The VBAT pin is the battery voltage sense point for Trickle Charge mode. While trickle charging the battery, the system regulation voltage is the MinSystemVoltage DAC setting plus 384mV.

To enable Trickle Charging, set the MinSystemVoltage and ChargeCurrent register to a non-zero value higher than the battery voltage. To disable trickle charging, set the MinSystemVoltage and ChargeCurrent register to 0. See Table 22 for trickle charging control logic.

The CSOP pin senses the system voltage for MaxSystemVoltage and MinSystemVoltage during trickle charging and controls the VSYS operating voltage.

8.2.4 Charging Current Loop

The charging current loop uses the charge current DAC (see Table 26) to set the fast charging current limit. In Trickle Charging mode, the RAA489110 regulates the CSOP to the MinSystemVoltage register value through the buck-boost switcher. Another independent control loop controls the BGATE FET so the charging current is regulated to the trickle charge current value set by Control2 register Bits[15:13].

To set the normal/fast charging current, write a 16-bit ChargeCurrentLimit command to register address 0x14H (Table 2) using the Write-word protocol shown in Figure 32.

The RAA489110 limits the charging current by limiting the CSOP - CSON voltage, so halving the current sense resistor value doubles the current being regulated to. By using the recommended current sense resistor values R_{s1} = 20mΩ and R_{s2} = 10mΩ, the LSB of the register translates to 4mA of charging current. The ChargeCurrentLimit register accepts any charging current command, but only the valid register bits are written to the register.

8.3 Buck Boost Configurable Charger

The RAA489110 is a Buck-Boost battery charger that can support both Narrow Voltage DC (NVDC) charging or Bypass mode. NVDC is the initial start up state for the RAA489110, and firmware from a controller using the I^2C interface is used to change the configuration to Bypass mode.

The RAA489110 allows the system to be optimized for both types of configurations. For lower power systems, the NVDC mode may be appropriate and reduces system complexity. For higher power systems, the Bypass mode may be the best choice to allow a smaller inductor but support higher system power with improved efficiency.

Because the system power does not pass through the inductor, Bypass mode allows high power systems to size the inductor for just the maximum charging current or the turbo boost current. Because main power goes directly from the adapter to the system, the system efficiency improves and the inductor is smaller, which saves board area. For NVDC mode configuration, the inductor has to support the full system power and needs to be a larger size because it supports both charging and system power.

This mode allows the whole switch circuit to be bypassed only when the ADP is greater than the battery voltage. It connects the ADP to the VSYS through two N-MOSFETs using an internal charge pump for the gate drive. This mode is primarily controlled by firmware to ensure flexibility and has only fault protections for safety. Ensure that ADP > VBAT either by guaranteeing that ADP > VBAT or by enabling the VIN > VOUT bypass comparator (Control0 register Bit[5] (Table 3) to automatically turn off the BYPSG gate.

OTG and Fast role swap must not be allowed while in Bypass mode, and the system must prevent the toggling of the OTGEN pin and/or setting the OTG enable register. Bypass mode must be enabled to allow reverse turbo boost operation.

See the RAA489110 device page for firmware documentation.

8.3.1 NVDC Charger

In NVDC mode, the inductor supports the full system power and the power for charging the battery; therefore, the inductor typically needs to be a larger size because it supports both charging and system power.

The RAA489110 automatically selects the adapter and/or the battery as the source for system power. The BGATE pin drives an N-channel MOSFET (NFET) gate that connects or disconnects the battery from the system and the switcher.

8.3.1.1 Normal Charging

In NVDC mode, the charging current is selected for the charge rate into the battery. However, set the input current limit for the total system plus battery charging current.

If VDD is higher than 3.8V, the RAA489110 enters Forward Buck, Forward Boost, or Forward Buck-Boost mode depending on the adapter and system voltage VSYS duty cycle ratio. The system bus voltage is regulated at the voltage set on the MaxSystemVoltage register. If the ChargeCurrent register is programmed (non-zero), the RAA489110 charges the battery either in Trickle Charging mode or Fast Charging mode as long as BATGONE is low.

8.3.1.2 Turbo Support/ Ideal Diode Mode (IDM)

In NVDC charger configuration and Turbo mode (also known as Ideal Diode Mode, IDM), the RAA489110 turns on the BGATE FET to limit the adapter current at the adapter current limit set point while the battery supplies the rest of the power required by the system. To turn on BGATE in Turbo mode, the CSON pin voltage needs to be 180mV lower than the VBAT pin voltage. If the RAA489110 detects 165mA charging current or if the battery discharging current is less than 125mA for 40ms, it turns off BGATE to exit Turbo mode.

See Table 22 for BGATE operation. BGATE Force off control bit has the highest priority for BGATE operation over BGATE force on control bit and Charging enabled. BGATE Force off control bit and BATGONE pin high have the same effect on BGATE operation. BGATE Force on control bit has the next highest priority over Charging enabled.

Regulation to charge current limit and trickle charge function can be done only when BGATE force off and BGATE force on control bits are both set to 0 and charging is enabled. ‘x’ denotes a Don’t care condition in the table.

In most systems, a Turbo event usually does not last very long. It is often no longer than milliseconds, a time during which the adapter can supply current higher than its DC rating. The RAA489110 employs a two-level adapter current limit to fully take advantage of the surge capability of the adapter and minimize the power drawn from the battery.

Table 22. NVDC Charger Behavior Truth Table

BGATE Force Off Control Bit Control1 Register Bit[6]	BGATE Force On Control bit Control9 Register Bit[15]	Charging Enabled CC ≠ 0; VSYSMIN ≠ 0	BGATE Status - On/Off	
0 = Normal 1 = BGATE Force Off	0 = Normal 1 = BGATE Force On	0 = Disabled Charging 1 = Enabled Charging	System Load Not In Turbo Mode Range	System Load In Turbo Mode Range
0	0	0	Off	On
0	0	1	ON for fast charge; trickle charge enabled	On
0	1	x	On	On
1	x	x	Off	Off

8.3.2 Bypass Mode

The RAA489110 can operate in Bypass configuration when the adapter voltage is higher than the battery voltage by sufficient margin to account for tolerance and I*R drop. Bypass refers to both passing the adapter power directly to the system and bypassing the inductor and charger. Bypass can be combined with charging when the adapter power is higher than the system plus charging power. If the input power is not enough for the system, Reverse Turbo-Boost mode can take power from the battery and provide it to the system. If the device was charging but the input power droops, the RAA489110 can automatically switch from charging to reverse turbo-boost. OTG, FRS, AC PROCHOT, and learn mode are not supported in Bypass mode. Do not toggle the OTGEN pin in Bypass mode.

The following are four operation modes within bypass operation:

- Bypass – A zero forward power flow and reverse power flow in Buck-Boost power stage.
- Bypass + Charge – Only forward power flow in Buck-Boost power stage.
- Reverse Turbo Boost – Only reverse power flow in Buck-Boost power stage.
- Reverse Turbo Boost + Charge – Forward power flow or reverse power flow in Buck-Boost power stage depending on system loading.

8.3.2.1 Bypass

The BYPSG pin drives a pair of back-to-back common source N-MOSFETs to connect or disconnect the adapter from the system and the battery. When the N-MOSFETs are turned on, it bypasses the switching FETs and

inductor to provide a higher efficiency path from the adapter input to the system output. At the same time, the battery path is isolated by turning off the NGATE NFET.

The V_{IN} > V_{OUT} (CSIN > CSOP) comparator can be used to turn off the Bypass gate and exit Bypass mode when the CSIN falls below CSOP -180mV. This comparator can be enabled and used with ACOK threshold to detect an adapter unplug event. The rising threshold for the comparator is CSOP + 180mV. Because ACOKREF and the V_{IN} > V_{OUT} comparator are critical protections for the charger, Renesas recommends enabling both features and setting them at appropriate values.

Use of the BYPSG/BYPSRC/NGATE pins is optional. Tie the BYPSRC pin to VDDP if not used.

When both CC (0x14 = 0) and Reverse Turbo Boost (ctrl0[0] = 0) are disabled, MaxVsysVoltage DAC (0x15) needs be set as 0 in Bypass mode.

8.3.2.2 Bypass + Charging

When in Bypass mode, normal battery charging is similar to normal charging.

8.3.2.3 Reverse Turbo-Boost Mode

Turbo mode refers to the system drawing more power than the power rating of the adapter. Turbo mode prompts the need for the switcher to change from Forward mode of operation to Reverse mode of operation to reverse the energy flow from going into the battery to going out of the battery. This mode of operation enables the battery to help the adapter provide the required system power. This operation has been widely used in many systems, such as Sun mode and Eclipse mode for bidirectional battery charger/discharger used on satellites with solar panels as the power source acting as the adapter (reference *A zero voltage switching bidirectional battery charger/discharger for the NASA EOS Satellite, Dan M. Sable, Fred C. Lee and Bo H. Cho, APEC 1992 Conference Proceedings*). To use the various HPBB/bypass charger configuration, follow the steps from Transitioning Between Modes (NVDC/Bypass/RTB).

The RAA489110 automatically selects the adapter and/or the battery as the source for system power. When the adapter power is not enough for the system as detected by the input current limit loop, the battery needs to supplement the adapter. As a result, the charger operates in the reverse direction and takes energy from the battery to hold up the input voltage.

The Control0 register Bit[0] enables or disables the Reverse Turbo-Boost function. See Table 3 for details. Use caution when enabling reverse Turbo because the BFET is held on and there is potential to have excessive current into the battery. Autonomous Charging must be disabled before enabling the Reverse Turbo-Boost function.

In Reverse Turbo-Boost mode, the RAA489110 operates the switcher in reverse mode to pull energy from the battery and give energy to the adapter voltage rail so that the adapter current is limited at the adapter current limit set point, while the battery supplies the additional power required by the system.

8.3.2.4 Reverse Turbo Boost Mode + Charging

When in Bypass mode with Reverse Turbo Enabled, battery charging is similar to normal NVDC charging, unless the adapter power is not enough for the system as detected by the input current limit loop. If there is not enough adapter power, the battery needs to supplement the adapter. When this occurs, first the charging stops, and if the power demand increases, the RAA489110 operates in the reverse direction and takes energy from the battery to hold up the input voltage.

The RAA489110 automatically enters Reverse Turbo mode when all of the following three criteria are met:

- The adapter current is within 80mA of the AdapterCurrentLimit1 (or AdapterCurrentLimit2 if two-level adapter current limit function is enabled) register setting.
- The battery charging current is less than 150mA.
- The COMP pin voltage is lower than 1.4V.

Meeting these three criteria means that the RAA489110 enters Reverse Turbo mode only when it is absolutely necessary.

For example, assume the adapter voltage is 20V, the adapter current limit is 4A (80W rating), and the RAA489110 is charging an 8V battery at a 5A rate (40W charging power). If the system load increases from 0W to 79W instantaneously, the adapter current increases from 2A to 5.95A instantaneously and exceeds the 4A current limit level. However, the adapter current loop takes control and decreases the charging current to limit the adapter current at 4A, eventually providing 79W of system power and 1W of battery charging power. In this case, the RAA489110 does not need to enter Turbo mode adapter and can conserve battery energy. In the same example, if the system load increases from 0W to 81W instantaneously, the adapter current increases from 2A to 6.05A instantaneously and exceeds the 4A current limit level. The adapter current loop takes control and decreases the charging current to limit the adapter current at 4A. Therefore, the RAA489110 eventually determines that it needs to enter Turbo mode, so that the adapter provides 80W, and the battery provides 1W to provide 81W to the system.

The interaction of the control loops within the RAA489110, including the adapter current loop, the charging current loop, and the battery full charging voltage loop, determines the timing of the Reverse Turbo mode entry. The timing strongly depends on the control loop compensation design and the interaction among the loops. In the previous example, compared with system power instantaneously increasing from 0W to 81W, system power instantaneously increasing from 0W to 160W causes the RAA489110 to enter Reverse Turbo mode much faster because the loops drive the circuit parameters to meet the three Turbo mode entry criteria much quicker when the adapter is more severely overloaded.

The RAA489110 exits Reverse Turbo mode when one of the following three criteria are met:

- The battery charging current exceeds 150mA (R_{s2} = 10mΩ).
- The adapter current is less than the AdapterCurrentLimit register setting and the COMP voltage is lower than 1.4V.
- The battery discharging current is less than 125mA (for R_{s2} = 10mΩ) for 40ms.

Table 23 shows the RAA489110 charger behavior truth table in Bypass mode.

Table 23. Charger Behavior Truth Table in Bypass mode

Reverse Turbo Boost Mode Control Bit	Enable Charging Control Bit (VSYSMIN ≠ Zero)	ChargeCurrent Register	Charge?	Boost?
0 = Enable Turbo 1 = Disable Turbo	0 = Disable Charging 1 = Enable Charging	0 = 0h Command 1 = Non-Zero Valid Command		
0	0	0	No	Yes
0	0	1	Do not set[1]	Yes
0	1	0	Do not set[1]	Yes
0	1	1	Yes (Fast charge and trickle charge enabled)	Yes
1	0	0	No	No
1	0	1	Do not set[1]	No
1	1	0	Do not set[1]	No
1	1	1	Yes (Fast charge and trickle charge enabled)	No

1. Set MinSystemVoltage and ChargeCurrent register both to zero or non zero. Setting only one register to zero is not recommended.

8.3.3 Transitioning Between Modes (NVDC/Bypass/RTB)

Firmware commands can be used to configure the RAA489110 to transition between the different modes. Figure 42 shows the major and minor states that the RAA489110 can operate in and the transitions between them.

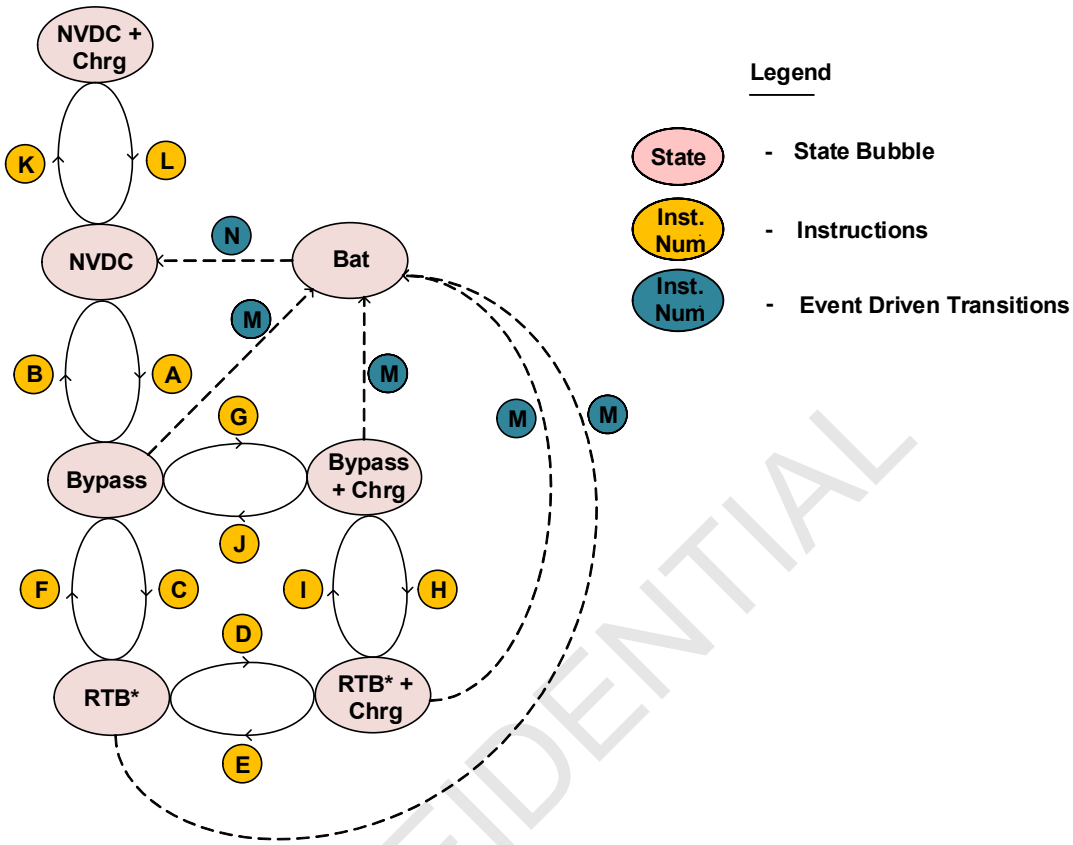


Figure 42. Transition State Diagram

The following commands are merely suggestions/recommendations for a typical application. Renesas recommends using these commands for an initial implementation/evaluation, but the specific steps must be validated in the specific application to ensure proper operation.

Bypass State – Set up the system with the Bypass gates ON to make VSYS = VADP and allow flow of current from the adapter directly to the load. In this state, the adapter is connected directly to the system, but the RAA489110 is not switching, so the charging and reverse turbo boost functions are disabled.

(BYPSG = on, NGATE = off, BGATE = off, MaxSystemVoltage = 0, RTB bit = 0, CC = 0, MinSystemVoltage = 0)

Bypass + Charging State – The adapter is connected directly to the system (Bypass) and charging is enabled, but the turbo boost function is disabled. Use this state when the adapter can support the entire system load.

(BYPSG = on, NGATE = off, BGATE = on, MaxSystemVoltage = non-zero, RTB bit = 0, CC = non-zero, MinSystemVoltage = non-zero)

Reverse Turbo-Boost State (RTB) – The Bypass gates are ON and Reverse Turbo Boost is enabled and primed to meet any load requirements. The battery can supplement the adapter to provide power in this mode. Charging is disabled.

(BYPSG = on, NGATE = off, BGATE = on, MaxSystemVoltage = non-zero, RTB bit = 1, Force Forward Buck bit = 1, CC = 0, MinSystemVoltage = 0)

RTB + Charging State: An extension of RTB, but with battery charging enabled.

(BYPSG = on, NGATE = off, BGATE = on, MaxSystemVoltage = non-zero, RTB bit = 1, Force Forward Buck bit = 1, CC = non-zero, MinSystemVoltage = non-zero)

Bat State – Reached when the adapter is unplugged and ACOK goes low. The system load is supported by the battery.

(BYPSG = off, NGATE = on, BGATE = on, MaxSystemVoltage = non-zero, RTB bit = 0, CC = 0, MinSystemVoltage = 0)

8.3.3.1 Transitioning from NVDC or NVDC + CHRG to Bypass

To transition from NVDC mode to Bypass mode, turn off charging first. The system load must be reduced so that the RAA489110 input current does not exceed the Adapter Current Limit as the mode switches from NVDC to Bypass, thereby ensuring smooth transition.

8.3.3.1.1 Enter Bypass mode with protection

The RAA489110 uses one single bit to transition from NVDC to Bypass mode. Complete the following steps to ensure that the bypass mode transition and subsequent operation are safe and smooth.

1. Set Charge Current Limit (Reg 0x14) and MinSystemVoltage (Reg 0x3E) to 0.
2. Ensure that the adapter voltage is less than 23.4V and ensure the system load is low enough that the adapter current is below the AdapterCurrentLimit (Reg 0x3F).
3. Set ACOKREF (Reg 0x40) higher than the battery full charge voltage (Vbat + 180mV + ADC tolerance)[1]
4. Enable Bypass Mode Transition (Control0 register Bit[9]).
5. Check successful Bypass mode entry through information bit (Information1 Bit[7]) after 7ms.
6. If Information1 Bit[7] is high, enable V_{IN} < V_{OUT} Comp (Control0 register Bit[5]).
7. Set MaxSystemVoltage (Reg 0x15) to 0 (Required when operating Bypass mode only without RTB or Charging).

If Bypass mode is not entered after 7ms, manually reset Control0 register Bit[9] and try again when needed.

Renesas recommends keeping the adapter voltage lower than the Bypass/PTM overvoltage threshold of 23.4V before enabling Bypass mode. If Bypass mode is enabled with an adapter voltage higher than 23.4V, the RAA489110 waits until the voltage drops below 23.4V and enters Bypass mode automatically. Such a sequence may cause some unexpected behavior. Additionally, there is risk of violating the VSYS absolute overvoltage protection threshold of 23.4V in Bypass mode because the adapter and system are connected. Therefore, Renesas recommends entering Bypass mode with an adapter voltage lower than 23.4V.

Renesas also recommends keeping the system load well below the ACLIM threshold when enabling Bypass mode. If the charger is operating in AdapterCurrentLimit mode and Bypass mode is enabled, Bypass mode is likely not entered properly resulting in unexpected behavior.

If Bypass mode is entered, do not enable charging (0x14 and 0x3E) until the CSOP voltage ramps down to the battery voltage.

When these steps are completed, charging can be enabled or disabled.

The steps in Table 24 ensure that the transition and subsequent operation are smooth.

1. If the adapter voltage is higher than the battery voltage by sufficient margin to account for adapter voltage tolerance and cable I*R drop, ACOKREF can be set higher than (Vbat +180mV + ADC tolerance). If the margin between the adapter voltage including its tolerance and the maximum battery voltage is too small for ACOKREF to be set, ACOKREF can be set to a voltage lower than the maximum battery voltage. In this case, when the adapter is removed, CSIN voltage starts to drop and when the CSIN < Vbat or CSIN < CSOP (if enabled by Control0 register Bit[5]) exit condition is met, the RAA489110 exits bypass mode. When the CSIN voltage drops further below the ACOKREF threshold, RAA489110 de-asserts ACOK to indicate the adapter removal.

Table 24. Transitioning from NVDC (or NVDC + CHRG) Mode to Bypass Mode

Transition / Step Number	Function Description	Register Name	Value (Decimal)	Read/ Write	Register Address
L	NVDC + CHRG to NVDC				
1	Set Charge current register to 0 to disable fast charging	ChargeCurrentLimit	0	Write	0x14
2	Set MinSystemVoltage register to 0 to disable trickle charging	MinSystemVoltage	0	Write	0x3E
A	NVDC to Bypass				
1	Ensure that the adapter voltage is less than 23.4V				
2	Ensure that the adapter current is below the AdapterCurrentLimit	AdapterCurrentLimit			0x3F
3	Set ACOKREF higher than the battery full charge voltage	ACOKREF	> (V_{bat} + 180mV + ADC tolerance)	Write	0x40
4	Enable Bypass Mode Transition	Control0 register Bit[9]	1	Write	0x39
5	After 7ms, check successful Bypass mode entry. (If Bypass mode is not entered, please manually reset Control0 register Bit[9] and try again from the step 1.)	Information 1 Bit[7]		Read	0x3A
6	If Information 1 Bit[7] is high, enable $V_{IN} < V_{OUT}$ comparator	Control0 register Bit[5]	1	Write	0x39
7	Set MaxSystemVoltage to 0 (This is required when operating Bypass mode only without RTB or Charging)	MaxSystemVoltage	0	Write	0x15

8.3.3.1.2 Steps Automatically Performed by Charger when Bypass Enabled

The following steps are performed by the RAA489110 automatically when Control0 register Bit[9] is enabled to transition from NVDC to Bypass.

1. The CSOP voltage is ramped up to the CSIN voltage.
2. The Bypass FET is turned on and the NGATE is turned off.
3. After a few milliseconds (4-7ms) of wait time, the Information1 Bit[7] is set high to indicate that Bypass mode has been entered successfully.

8.3.3.1.3 Bypass Mode Interrupts

The following are interrupts that are available to detect Bypass mode entry and exit:

- Set Control5 register Bit[13] to enable bypass mode detection.
- Set Control6 register Bit[13] to detect entry completion.
- Reset Control6 register Bit[13] to detect bypass mode exit because of fault conditions.

8.3.3.2 Transitioning from Bypass to NVDC or NVDC + CHRG

To transition from Bypass mode to NVDC, turn off charging and RTB mode first. The system load must be reduced so that the system current does not exceed the RAA489110 Adapter Current Limit value during the transition.

8.3.3.2.1 Exit Bypass mode with protection

The RAA489110 transitions from Bypass to NVDC mode when the Bypass control bit Control0 register Bit[9] is disabled or any of the Bypass mode exit criteria are met. The following steps are required to ensure safe and smooth exit from bypass mode through control bit.

1. Set Charge Current Limit (Reg 0x14) and MinSystemVoltage (Reg 0x3E) to 0 to disable charging.
2. Ensure that the power drawn by the system load is low enough that the adapter current remains below the AdapterCurrentLimit (Reg 0x3F).
3. Disable Bypass Mode (Control0 register Bit[9]).
4. Set MaxSystemVoltage (Reg 0x15) to the maximum battery full charge voltage.
5. Enable the CSOP sink (Control0 register Bit[13]).
6. Wait ~200ms or until VSYS ramps down to the MaxSystemVoltage DAC level, and then disable the CSOP sink (Control0 register Bit[13]).
7. Set Charge Current Limit (Reg 0x14) and MinSystemVoltage (Reg 0x3E) to required values when needed to enable charging.

When Bypass mode is exited, Control0 register Bit[9], Control0 register Bit[0], Control0 register Bit[5], and Control0 register Bit[10] bits are reset and the Bypass-mode information bit (Information1 Bit[7]) changes to 0. When Bypass mode is exited, either by the control bit or by any of the exit criteria, Renesas recommends reducing the system voltage to the MaxSystemVoltage DAC level before enabling charging. This minimizes the potential battery inrush current and reduces the risk of damage. The VSYS voltage can be safely reduced by enabling the CSOP current sink (Control0 register Bit[13]). When this is enabled, a 10mA discharge current is sunk into the CSOP pin, thereby reducing the VSYS voltage because the NGATE FET is automatically turned on. The time required to bring the VSYS voltage down is calculated using Equation 4:

(EQ. 4) $$T = \frac{C_{OUT} \times (Vsys - MaxSysV)}{Idischarge}$$

The steps in Table 25 ensure that the transition and subsequent operation are smooth.

Table 25. Transitioning from Bypass Mode to NVDC (or NVDC + CHRG) Mode

Transition / Step Number	Function Description	Register Name	Value (Decimal)	Read/ Write	Register Address
B	Bypass to NVDC	-	-	-	-
1	Set Charge current register to 0 to disable fast charging	ChargeCurrentLimit	0	Write	0x14
2	Set MinSystemVoltage register to 0 to disable trickle charging	MinSystemVoltage	0	Write	0x3E
3	Ensure that the adapter current remains below the AdapterCurretLimit	AdapterCurrentLimit	-	-	0x3F
4	Disable Bypass Mode	Control0 register Bit[9]	0	Write	0x39
5	Set MaxSystemVoltage to the maximum battery full charge voltage	MaxSystemVoltage	Battery specific	Write	0x15
6	Enable CSOP Sink	Control0 register Bit[13]	1	Write	0x39
7	Wait for 200ms or until V_{sys} ramps down to the MaxSystemVoltage DAC level, and then disable CSOP Sink	Control0 register Bit[13]	0	Write	0x39
K	NVDC to NVDC + CHRG	-	-	-	-

Table 25. Transitioning from Bypass Mode to NVDC (or NVDC + CHRG) Mode (Cont.)

Transition / Step Number	Function Description	Register Name	Value (Decimal)	Read/ Write	Register Address
1	Set MinSystemVoltage to non-zero value to enable trickle charging	MinSystemVoltage	Battery specific	Write	0x3E
2	Set Charge Current Limit to non-zero value to allow charging	ChargeCurrentLimit	Battery speficif	Write	0x14

8.3.3.2.2 Exit criteria for Bypass mode

The RAA489110 exits Bypass mode and transitions to NVDC mode when any of the following exit conditions are met.

- Control Bit – Disable Control0 register Bit[9] exits Bypass mode. Charging must be disabled before making transition from Bypass mode to NVDC mode when using the control bit option.
- Battery Discharge Current > 150mA – Part exits Bypass mode if the discharge current from the battery exceeds 150mA with RTB disabled.
- ACOK – If the adapter voltage drops below the ACOK reference threshold, such as on adapter removal, Bypass mode is exited. The ACOK reference threshold for the CSIN Pin is set to the higher of Reg 0x40 (ACOKREF) and 3.6V (check EC table for the accurate value).
- Bypass/PTM Overvoltage – The adapter or input voltage exceeds the maximum value of 23.4V (check EC table for accurate value).
- VIN Loop – If charger enters Input voltage regulation loop because of a high-load condition or large adapter voltage drop. Debounce is 100µs.
- CSIN > VBAT Comparator – Bypass Mode is only active if $V_{ADP} > V_{BAT}$. Part exits Bypass mode if this condition is violated.
- CSIN > CSOP comparator – When Control0 register Bit[5] is set by user instruction after Bypass mode with protection is entered, the charger exits Bypass mode if the CSIN < CSOP.

8.3.3.2.3 Steps Automatically Performed by Charger when Bypass Mode Exits

When any of the exit conditions previously described are met, the RAA489110 performs the following steps automatically to transition from Bypass mode to NVDC mode. The Bypass FET is latched off, the NGATE FET is turned on automatically if certain conditions are met and important control/information bits are changed by the RAA489110 to indicate Bypass mode exit.

1. Charger turns off Bypass Gate. It can take ~200µs to fully turn off Bypass Gate.
2. The RAA489110 waits for any of the following conditions to be true before turning on NGATE:
   a. BGATE is Off.
   a. Battery discharge current > 150mA.
   b. Part in BAT state.
3. Part turns on NGATE within ~1ms.
4. Information1[7] indicates that Bypass Mode is deactivated.
5. Control0 register Bit[9], Control0 register Bit[0], Control0 register Bit[5], and Control0 register Bit[10] bits are reset.

8.3.3.2.4 Automatic NGATE FET Turn-On when Bypass Mode Exits

The RAA489110 can automatically turn on the NGATE FET when bypass mode is exited, and certain conditions are met. In particular, the NGATE FET is turned on automatically in response to any one of the following conditions:

- BGATE is Off.
- Battery discharge current > 150mA.
- Part in BAT state.

When charging is enabled in Bypass mode and bypass mode is exited through an exit condition with the adapter present, the NGATE FET is not automatically turned on as none of the previously mentioned conditions are met. The RAA489110 continues charging the battery through the power stage and VSYS is clamped at a voltage determined by the NGATE FET body diode and the CSOP voltage, which is approximately the same as the battery voltage. If any load is applied to the system during this stage, the load current flows through the NGATE FET body diode. Therefore, Renesas recommends disabling charging before exiting Bypass mode. After Bypass mode is successfully exited and the NGATE FET is turned on, charging can be re-enabled.

8.3.3.3 Transitioning to Charging and Reverse Turbo Boost (RTB) states in Bypass mode

When the RAA489110 has transitioned completely into Bypass mode, enable the charging and/or Reverse Turbo Boost (RTB) modes using the commands in Table 26.

Table 26. Transitioning Between Bypass Mode and Charging and Reverse Turbo Boost States

Transition	From State	To State	Step	Function Description	Register Name	Value (Decimal)	Register Address
C	Bypass	RTB (Reverse Turbo Boost)	1	Reduce system load below ACLIM	-	-	-
			2	Enable Reverse Turbo Boost function and Force Forward Buck Mode	Control0 register Bit[0] and Control0 register Bit[10]	1	0x39
			3	Set MaxSystemVoltage register to full battery charge voltage	MaxSystemVoltage	Battery specific	0x15
D	RTB	RTB + CHRG	1	Set MinSystemVoltage to non-zero value to enable trickle charging	MinSystemVoltage	Battery specific	0x3E
			2	Set charge current limit to non-zero value to allow charging	ChargeCurrentLimit	Battery specific	0x14
E	RTB + CHRG	RTB	1	Disable fast charging	ChargeCurrentLimit	0	0x14
			2	Disable trickle charging	MinSystemVoltage	0	0x3E
F	RTB	Bypass	1	Reduce system load below ACLIM	-	-	-
			2	Set MaxSystemVoltage register to zero	MaxSystemVoltage	0	0x15
			3	Disable reverse turbo boost function and force forward buck mode	Control0 register Bit[0] and Control0 register Bit[10]	0	0x39
G	Bypass	Bypass + CHRG	1	Set MinSystemVoltage to a non-zero value to enable trickle charging	MinSystemVoltage	Battery specific	0x3E
			2	Set charge current limit to a non-zero value to allow charging	ChargeCurrentLimit	Battery specific	0x14
			3	Set MaxSystemVoltage register to full battery charge voltage	MaxSystemVoltage	Battery specific	0x15

Table 26. Transitioning Between Bypass Mode and Charging and Reverse Turbo Boost States

Transition	From State	To State	Step	Function Description	Register Name	Value (Decimal)	Register Address
H	Bypass + CHRG	RTB + CHRG	1	Reduce system load below ACLIM	-	-	-
			2	Enable Reverse Turbo Boost function and Force Forward Buck Mode	Control0 register Bit[0] and Control0 register Bit[10]	1	0x39
I	RTB + CHRG	Bypass + CHRG	1	Reduce system load below ACLIM	-	-	-
			2	Disable reverse turbo boost function and force forward buck mode	Control0 register Bit[0] and Control0 register Bit[10]	0	0x39
J	Bypass + CHRG	Bypass	1	Set MaxSystemVoltage register to zero	MaxSystemVoltage	0	0x15
			2	Disable fast charging	ChargeCurrentLimit	0	0x14
			3	Disable trickle charging	MinSystemVoltage	0	0x3E

8.3.3.4 Adapter Removal Events

When the RAA489110 operates in NVDC mode, it can automatically detect adapter removal and operate in Battery Only mode independently. When the RAA489110 is in Bypass mode (with or without charging and Reverse Turbo Boost), it can still detect the adapter removal event. In the case of adapter removal (transitions M in the Figure 6) where the adapter voltage is lower than ACOKREF DAC value, RAA489110 automatically resets Bypass Mode Transition (Control0 register Bit[9]), Reverse Turbo Boost (RTB) (Control0 register Bit[0]), V_{IN} < V_{OUT} Comp (Control0 register Bit[5]), and Force Forward Buck Mode (Control0 register Bit[10]) bit. It turns off Bypass FETs and turn on the NGATE FETs so it can deliver full power from the battery with minimal voltage drop and loss. If an adapter is re-plugged (transition N in the Figure 42), the RAA489110 automatically transitions into NVDC state after ACOK goes high. Because the Bypass mode enable control bits are reset, the Bypass mode needs to be re-enabled following the instructions provided in the Table 24.

Table 27 summarized the adapter removal and re-plugging events during bypass mode operation. The register values shown are an example. Modify these values for your platform.

Table 27. Adapter Removal Events

Transition	From State	To State	Step	Function Description	Register Name	Value (Decimal)	Register Address
M	Bypass/ Bypass+ Chrg/ RTB/ RTB+ Chrg	BAT	-	Monitor ACOK – when ACOK goes low, complete the following steps before connecting another adapter	-	-	-
			1	Check Reverse Turbo Boost, Bypass Mode Transition, V_{IN} < V_{OUT} Comp, Force Forward Buck Mode bits are reset	Control0 register Bit[0], Control0 register Bit[5], Control0 register Bit[9], Control0 register Bit[10]	0	0x39
			2	Set Charge current register to 0 to disable fast charging (Optional for transitioning from Bypass / RTB state)	ChargeCurrent Limit	0	0x14
			3	Set MinSysVoltage register to 0 to disable trickle charging (Optional for transitioning from Bypass / RTB state)	MinSysVoltage	0	0x3E
			4	Set MaxSysVoltage register to full battery charge voltage (Optional for transitioning from Bypass+Chrg/RTB/RTB+Chrg state)	MaxSysVoltage	Battery specific	0x15
			5	Reset ACOKREF register to normal value to detect low voltage (5V or 9V) adapter during next plug in event	ACOKREF	3.6V or required level	0x40
N	BAT	NVDC	-	Monitor ACOK – when ACOK goes high, automatically transition to NVDC	-	-	-

8.4 R3 Modulator

The RAA489110 uses the Renesas Robust Ripple Regulator (R3) modulation scheme. The R3 modulator combines the best features of fixed frequency PWM and hysteretic PWM while eliminating many of their shortcomings. Figure 43 conceptually shows the R3 modulator circuit and Figure 44 shows the operation principles in steady state.

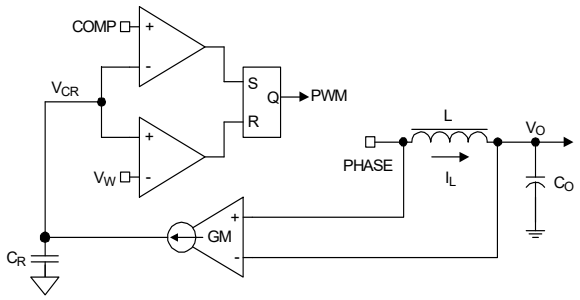


Figure 43. R3 Modulator

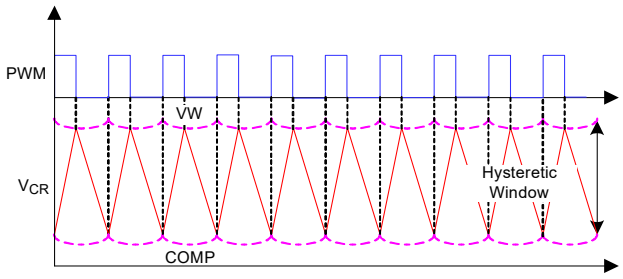


Figure 44. R3 Modulator Operation Principles in Steady State

A fixed voltage window (VW window) exists between VW and COMP. The modulator charges the ripple capacitor C_R with a current source equal to $g_m(V_{IN} - V_O)$ during PWM on-time and discharges the ripple capacitor C_R with a current source equal to $g_m V_O$ during PWM off-time where g_m is a gain factor. The C_r voltage V_{CR} therefore emulates the inductor current waveform. The modulator turns off the PWM pulse when V_{CR} reaches VW and turns on the PWM pulse when it reaches COMP.

Because the modulator works with V_{CR}, which is a large amplitude and noise free synthesized signal, it achieves lower phase jitter than conventional hysteretic mode modulators.

Figure 45 shows the operation principles during dynamic response. The COMP voltage rises during dynamic response, temporarily turning on PWM pulses earlier and more frequently, which allows for higher control loop bandwidth than conventional fixed frequency PWM modulators at the same steady state switching frequency.

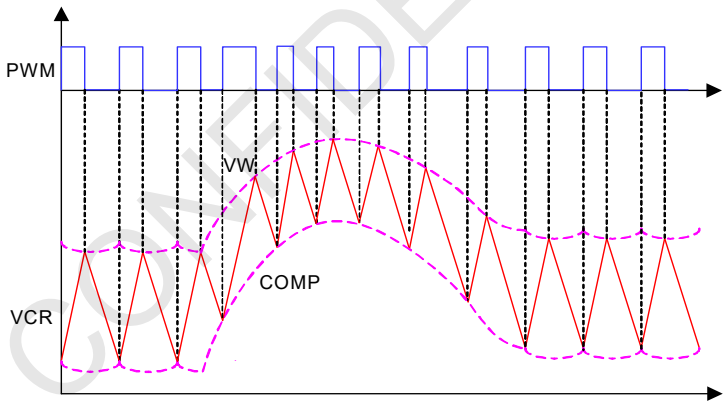


Figure 45. R3 Modulator Operation Principles in Dynamic Response

8.4.1 DE (Diode Emulation) Operation

In Diode Emulation (DE) mode, the RAA489110 uses a phase comparator to monitor the PHASE node voltage during the low-side switching FET on-time to detect the inductor current zero crossing. The phase comparator needs a minimum on-time of the low-side switching FET for it to recognize inductor current zero crossing. If the low-side switching FET on-time is too short for the phase comparator to successfully recognize the inductor zero crossing, the RAA489110 can lose diode emulation ability. To prevent this scenario, the RAA489110 uses a minimum low-side switching FET on-time. When the intended low-side switching FET on-time is shorter than the minimum value, the RAA489110 stretches the switching period to keep the low-side switching FET on-time at the minimum value, which causes the CCM switching frequency to drop below the set point.

The R3 modulator can operate in DE mode to increase light-load efficiency. In DE mode, the low-side MOSFET emulates a diode by conducting when the current is flowing from source-to-drain and not allowing reverse current. As Figure 46 shows, when LGATE is on, the low-side MOSFET carries current and creates negative voltage on

the phase node because of the voltage drop across the ON-resistance. The IC monitors the current by monitoring the phase node voltage. It turns off LGATE when the phase node voltage reaches zero to prevent the inductor current from reversing the direction and creating unnecessary power loss.

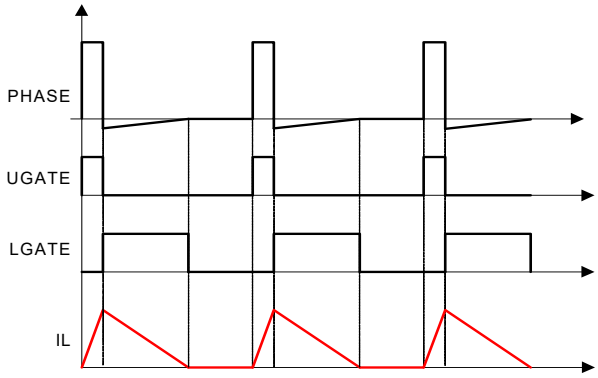


Figure 46. Diode Emulation

If the load current is light enough, as Figure 46 shows, the inductor current reaches and stays at zero before the next phase node pulse, and the regulator is in Discontinuous Conduction Mode (DCM). If the load current is heavy enough, the inductor current never reaches 0A, and the regulator is in Continuous Conduction Mode (CCM) although the controller is in DE mode. RAA489110 has the option to stay in Continuous Conduction Mode (Forced Continuous Conduction Mode - FCCM) and disable the Diode emulation operation using Control9 register Bit[5]. DCM to FCCM or FCCM to DCM transition should only be made when the system load current is high enough such that charger operates in CCM before and after the control bit change.

Figure 47 shows the operation principle of DE mode at light load. The load gets incrementally lighter in the three cases from top to bottom. The PWM on-time is determined by the VW window size and therefore is the same, making the inductor current triangle the same in the three cases. The R3 modulator clamps the ripple capacitor voltage V_{CR} in DE mode to make it mimic the inductor current. The COMP voltage takes longer to reach V_{CR}, which naturally stretches the switching period. The inductor current triangles move farther apart from each other so that the inductor current average value is equal to the load current. The reduced switching frequency helps increase light-load efficiency.

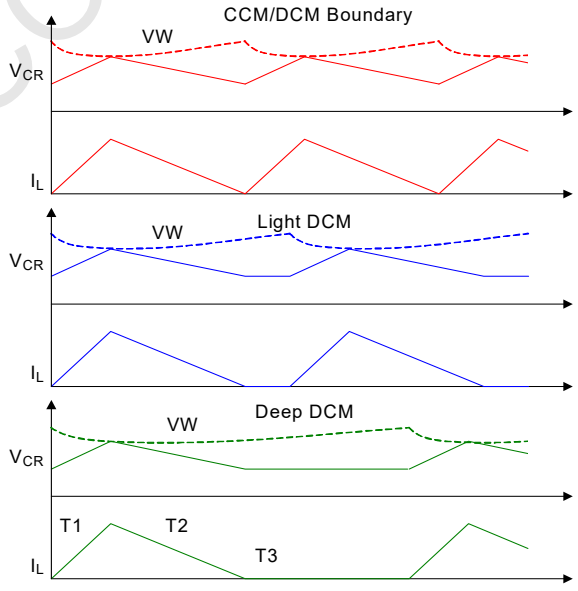


Figure 47. Period Stretching

9. Design Guide

This design guide provides a high-level explanation of the steps necessary to design a single-phase power converter. It is assumed that the reader is familiar with many of the basic skills and techniques referenced in the following section. In addition, complete reference designs are provided that include schematics, bills of materials, and example board layouts.

9.1 Selecting the Sense Resistors

Sense resistors are the easiest and most flexible method of monitoring/controlling current in the battery charge, discharge path, or the adapter input/output current. Most of the electrical specifications in this datasheet used R_{s1} = 20mΩ and R_{s2} = 10mΩ. However, any value can be selected because it is the voltage across the CSIN/CSIP and CSON/CSOP pins that are used for the control loops.

A sense resistor can introduce significant voltage drop and power loss to the load. In an application with high current requirements, the sense resistors require the use of low value sense resistor or a parallel combination of multiple sense resistors to support the higher power.

Appropriate scaling of the current values should be based on the voltage across the CSIN/CSIP and CSON/CSOP.

For example, if DAC is set for 2A at R = 20mΩ, V_{sx} = 40mV; with R = 10mΩ, which is half the previous value, the DAC setting ends up being doubled to 4A to preserve V_{sx} = 40mV.

9.1.1 Adapter Sense Resistor

The adapter sense resistor (R_{s1}) controls the current being pulled from an adapter when in forward mode, and senses the maximum current for ACProchot#. In Reverse mode, the sense resistor regulates the output current for OTG mode.

9.1.2 Battery Sense Resistor

The battery sense resistor (R_{s2}) controls the battery charging current when in Forward mode. In Reverse mode, the sense resistor senses the battery discharging current for DCProchot#.

9.2 Selecting the LC Output Filter

The duty cycle of an ideal buck converter in CCM is a function of the input and the output voltage. The relationship is written by Equation 5:

(EQ. 5) $$D = \frac{V_{OUT}}{V_{IN}}$$

The output inductor peak-to-peak ripple current is written by Equation 6:

(EQ. 6) $$I_{P-P} = \frac{V_{OUT} \cdot (1 - D)}{f_{SW} \cdot L}$$

A typical step-down DC/DC converter has an I_{P-P} of 20% to 40% of the maximum DC output load current for a practical design. The value of I_{P-P} is selected based on several criteria such as MOSFET switching loss, inductor core loss, and the resistive loss of the inductor winding.

The DC copper loss of the inductor can be estimated by Equation 7 where I_{LOAD} is the converter output DC current.

(EQ. 7) $$P_{COPPER} = I_{LOAD}^{2} \cdot DCR$$

The copper loss can be significant so attention has to be given to the DCR selection. Another factor to consider when choosing the inductor is its saturation characteristics at elevated temperatures. A saturated inductor can destroy circuit components.

A DC/DC buck regulator must have output capacitance C_O into which ripple current I_{P-P} can flow. Current I_{P-P} develops a corresponding ripple voltage V_{P-P} across C_O, which is the sum of the voltage drop across the capacitor ESR and of the voltage change stemming from charge moved in and out of the capacitor. These two voltages are written by Equation 8 and Equation 9:

(EQ. 8) $$\Delta V_{ESR} = I_{P-P} \cdot ESR$$

(EQ. 9) $$\Delta V_C = \frac{I_{P-P}}{8 \cdot C_O \cdot f_{SW}}$$

If the output of the converter has to support a load with high pulsating current, several capacitors need to be paralleled to reduce the total ESR until the required V_{P-P} is achieved. The inductance of the capacitor can cause a brief voltage dip if the load transient has an extremely high slew rate. Consider low inductance capacitors in this scenario. A capacitor dissipates heat as a function of RMS current and frequency. Be sure that I_{P-P} is shared by a sufficient quantity of paralleled capacitors so that they operate below the maximum rated RMS current at f_{SW}. Take into account that the effective capacitance of a capacitor can fade as much as 50% or even more as the DC voltage across it increases.

9.3 Adapter Input Filter

The adapter cable parasitic inductance and capacitance can cause some voltage ringing or an overshoot spike at the adapter connector node when the adapter is hot plugged in. This voltage spike can damage the BYPSG MOSFET or the RAA489110 pins connecting to the adapter connector node. One low cost solution is to add an RC snubber circuit at the adapter connector node to clamp the voltage spike as shown in Figure 48. A practical value of the RC snubber is 2.2Ω to 2.2µF while the appropriate values and power rating should be carefully characterized based on the actual design. However, do not add a pure capacitor at the adapter connector node, which can cause an even bigger voltage spike due to the adapter cable or the adapter current path parasitic inductance. A TVS diode can also be added to clamp voltage spike on the adapter side.

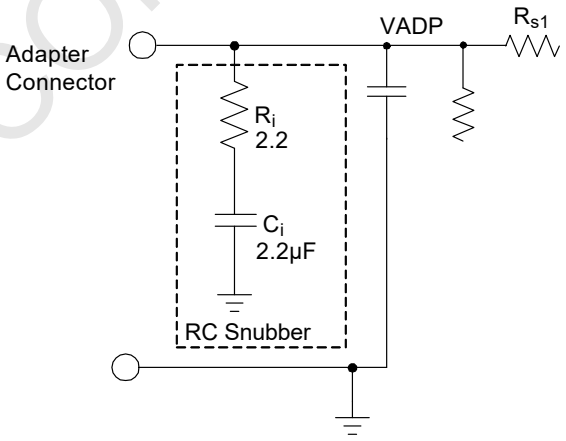


Figure 48. Adapter Input RC Snubber Circuit

9.4 Selecting the Input Capacitor

The important parameters for the input capacitance are the voltage rating and the RMS current rating. For reliable operation, select capacitors with voltage and current ratings above the maximum input voltage and capable of supplying the RMS current required by the switching circuit. Their voltage rating should be at least 1.25 times greater than the maximum input voltage, while a voltage rating of 1.5 times is a preferred rating. Figure 49 is a graph of the input capacitor RMS ripple current normalized relative to output load current as a function of duty cycle and is adjusted for converter efficiency. The normalized RMS ripple current calculation is written as Equation 10.

(EQ. 10)
$$I_{C_{IN}(RMS,NORMALIZED)} = \frac{I_{MAX} \cdot \sqrt{D \cdot (1 - D) + \frac{D \cdot k^2}{12}}}{I_{MAX}}$$

where:

- I_{MAX} is the maximum continuous I_{LOAD} of the converter
- k is a multiplier (0 to 1) corresponding to the inductor peak-to peak ripple amplitude expressed as a ratio of I_{MAX} (0 to 1)
- D is the duty cycle that is adjusted to take into account the efficiency of the converter, which is written as Equation 11:

(EQ. 11)
$$D = \frac{V_{OUT}}{V_{IN} \cdot EFF}$$

In addition to the capacitance, some low ESL ceramic capacitance is recommended to decouple between the drain of the high-side MOSFET and the source of the low-side MOSFET.

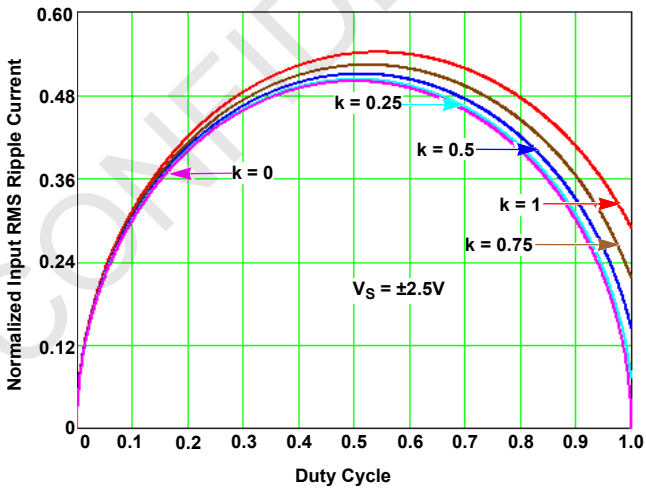


Figure 49. Normalized RMS Input Current at EFF = 1

9.5 Selecting the Switching Power MOSFET

9.5.1 Switching Power MOSFET Gate Capacitance

The RAA489110 includes an internal 5V LDO output at VDD pin, which can provide the switching MOSFET gate driver power through the VDDP pin with an RC filter. The 5V LDO output overcurrent protection threshold is 90mA, minimal (check EC table for the accurate value). When selecting the switching power MOSFET, carefully consider the MOSFET gate capacitance to avoid overloading the 5V LDO, especially in Buck-Boost mode when four MOSFETs are switching at the same time. For one MOSFET, the gate drive current can be estimated by Equation 12:

(EQ. 12) $$I_{driver} = Q_g \cdot f_{SW}$$

where:

- Q_g is the total gate charge in the MOSFET datasheet
- f_{SW} is switching frequency

9.5.2 Switching Power MOSFET Power

Typically, a MOSFET cannot tolerate even brief excursions beyond its maximum drain-to-source voltage rating. The MOSFETs used in the power stage of the converter should have a maximum VDS rating that exceeds the sum of the upper voltage tolerance of the input power source and the voltage spike that occurs when the MOSFET switches off.

Several power MOSFETs are readily available that are optimized for DC/DC converter applications. The preferred high-side MOSFET emphasizes low gate charge so that the device spends the least amount of time dissipating power in the linear region and does not exceed the VDDP current rating. Unlike the low-side MOSFET, which has the drain-to-source voltage clamped by its body diode during turn off, the high-side MOSFET turns off with a VDS of approximately V_{IN} - V_{OUT} plus the spike across it. The preferred low-side MOSFET emphasizes low $r_{DS(ON)}$ when fully saturated to minimize conduction loss. *Note:* This is an optimal configuration of MOSFET selection for low duty cycle applications (D < 50%). For higher output and low input voltage solutions, a more balanced MOSFET selection for high-side and low-side devices may be warranted.

For the Low-Side (LS) MOSFET, the power loss can be assumed to be conductive only and is written as Equation 13:

(EQ. 13) $$P_{CON\_LS} \approx I_{LOAD}^{2} \cdot r_{DS(ON)\_LS} \cdot (1 - D)$$

For the High-Side (HS) MOSFET, the conduction loss is written by Equation 14:

(EQ. 14) $$P_{CON\_HS} = I_{LOAD}^{2} \cdot r_{DS(ON)\_HS} \cdot D$$

For the High-Side MOSFET, the switching loss is written as Equation 15:

(EQ. 15) $$P_{SW\_HS} = \frac{V_{IN} \cdot I_{VALLEY} \cdot t_{SWON} \cdot f_{SW}}{2} + \frac{V_{IN} \cdot I_{PEAK} \cdot t_{SWOFF} \cdot f_{SW}}{2}$$

where:

- I_{VALLEY} is the difference of the DC component of the inductor current minus 1/2 of the inductor ripple current.
- I_{PEAK} is the sum of the DC component of the inductor current plus 1/2 of the inductor ripple current.
- $t_{SW(ON)}$ is the time required to drive the device into saturation.
- $t_{SW(OFF)}$ is the time required to drive the device into cut-off.
- Renesas recommends using a 4.7µF (10V) VDD/VDDP capacitor, which has an effective capacitance higher than 0.4µF at 5V and x1.6 effective capacitance at the BOOT pin at 5V.

9.6 Selecting the Bootstrap Capacitor

The selection of the bootstrap capacitor is written by Equation 16:

(EQ. 16) $$C_{BOOT} = \frac{Q_g}{\Delta V_{BOOT}}$$

where:

- Q_g is the total gate charge required to turn on the high-side MOSFET.
- ΔV_{BOOT} is the maximum allowed voltage decay across the boot capacitor each time the high-side MOSFET is switched on.

As an example, suppose the high-side MOSFET has a total gate charge Q_g, of 25nC at V_{GS} = 5V, and a ΔV_{BOOT} of 200mV. The calculated bootstrap capacitance is 0.125µF; for a comfortable margin, select a capacitor that is double or more the calculated capacitance. Use an X7R or X5R ceramic capacitor.

Renesas recommends using a bootstrap capacitor of 0.47µF (25V), which has an effective capacitance higher than 0.25µF at 5V and x50 effective high-side MOSFET gate capacitance.

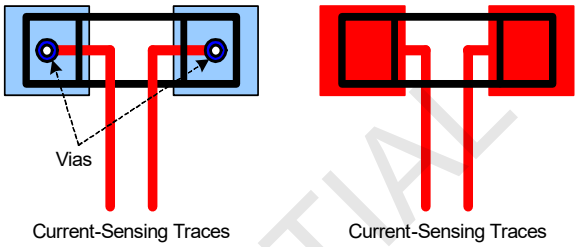
One additional consideration is the gate charge power loss written by Equation 17 and the VDDP current consumption. Keep the Pg below the VDDP overcurrent threshold.

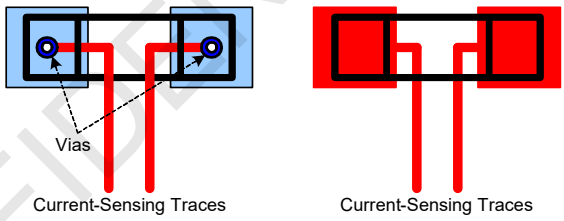
(EQ. 17) $$Pg = (Q_g(LS)) + (Q_g(HS)) \bullet V_{GS} \bullet f_{SW}$$

9.7 DCIN Filter

An RC filter is connected at the DCIN pin. Renesas recommends connecting a 10Ω DCIN resistor between the DCIN pin and the VADP/VSYS diodes, and connecting a 4.7µF (50V) DCIN capacitor to GND, which has an effective capacitance higher than 0.4µF at 20V.

10. Layout

Pin #	Pin Name	Layout Guidelines
Bottom Pad	GND	Connect this ground pad to the ground plane through a low impedance path. Renesas recommends using at least five vias to connect to ground planes in the PCB to ensure sufficient thermal dissipation directly under the IC.
1	CSON	CSOP is the sense line for output voltage. Route using a thick, short length plane on one single layer from the drain of Q4 to the CSOP pin to minimize inductance. Run two dedicated traces with sufficient width in parallel (close to each other to minimize the loop area) from the two terminals of the battery current-sensing resistor to the IC. Place the differential mode and common-mode R-C filter components in the general proximity of the controller. Route the current-sensing traces through vias to connect the center of the pads or route the traces into the pads from the inside of the current-sensing resistor. The following drawings show the two preferred ways of routing current-sensing traces. 
2	CSOP	
3	NGATE	Switching pin. Run the NGATE trace to the NGATE N-type MOSFET Gate node. Use sufficient width. Avoid any sensitive analog signal trace from crossing over or getting close.
4	BOOT2	Switching pin. Place the bootstrap capacitor in the general proximity of the controller. Use sufficiently wide trace. Avoid any sensitive analog signal trace from crossing over or getting close.
5	UGATE2	Run these two traces in parallel fashion with sufficient width. Avoid any sensitive analog signal trace from crossing over or getting close. Renesas recommends routing the PHASE2 trace to the high-side MOSFET source pin instead of general copper. Place the IC close to the switching MOSFETs gate terminals and keep the gate drive signal traces short for a clean MOSFET drive. The IC can be placed on the opposite side of the switching MOSFETs. Place the output capacitors as close as possible to the switching high-side MOSFET drain and the low-side MOSFET source; and use shortest PCB trace connection. Place these capacitors on the same PCB layer as the MOSFETs instead of on different layers and using vias to make the connection. Place the inductor terminal to the switching high-side MOSFET source and low-side MOSFET drain terminal as close as possible. Minimize this phase node area to lower the electrical and magnetic field radiation but make this phase node area large enough to carry the current. Place the inductor and the switching MOSFETs on the same layer of the PCB.
6	PHASE2	
7	LGATE2	Switching pin. Run the LGATE2 trace in parallel with the UGATE2 and PHASE2 traces on the same PCB layer. Use sufficient width. Avoid any sensitive analog signal trace from crossing over or getting close.
8	VDDP	Place the decoupling capacitor in the general proximity of the controller. Run the trace connecting to the VDD pin with sufficient width.
9	LGATE1	Switching pin. Run the LGATE1 trace in parallel with the UGATE1 and PHASE1 traces on the same PCB layer. Use sufficient width. Avoid any sensitive analog signal trace from crossing over or getting close.

Pin #	Pin Name	Layout Guidelines
10	PHASE1	Run these two traces in parallel fashion with sufficient width. Avoid any sensitive analog signal trace from crossing over or getting close. Renesas recommends routing the PHASE1 trace to the high-side MOSFET source pin instead of general copper. Place the IC close to the switching MOSFETs gate terminals and keep the gate drive signal traces short for a clean MOSFET drive. The IC can be placed on the opposite side of the switching MOSFETs. Place the input capacitors as close as possible to the switching high-side MOSFET drain and the low-side MOSFET source; and use shortest PCB trace connection. Place these capacitors on the same PCB layer as the MOSFETs instead of on different layers and using vias to make the connection. Place the inductor terminal to the switching high-side MOSFET source and low-side MOSFET drain terminal as close as possible. Minimize this phase node area to lower the electrical and magnetic field radiation but make this phase node area large enough to carry the current. Place the inductor and the switching MOSFETs on the same layer of the PCB.
11	UGATE1	
12	BOOT1	Switching pin. Place the bootstrap capacitor in the general proximity of the controller. Use sufficiently wide trace. Avoid any sensitive analog signal trace from crossing over or getting close.
13	BYPSRC	Run this trace with sufficient width to the bypass N-type MOSFET sources/reference node.
14	CSIN	Run two dedicated traces with sufficient width in parallel (close to each other to minimize the loop area) from the two terminals of the adapter current-sensing resistor to the IC. Place the Differential mode and common-mode R-C filter components in general proximity of the controller. Keep the CSIN node near the Q_1 drain. Route the current-sensing traces through vias to connect the center of the pads; or route the traces into the pads from the inside of the current-sensing resistor. The following drawings show the two preferred ways of routing current-sensing traces. 
15	CSIP	
16	BYPSG	Run this trace with sufficient width to the bypass N-type MOSFET gates.
17	DCIN	Place the OR diodes and the R-C filter in the general proximity of the controller. Run the VADP trace and VSYS trace to the OR diodes with sufficient width.
18	VDD	Place the R-C filter connecting with VDDP pin in the general proximity of the controller. Run the trace connecting to the VDDP pin with sufficient width.
19	PROG	Signal pin. Place the PROG programming resistor in the general proximity of the controller.
20	OTGEN/CMIN	Digital pins. No special consideration.
21	SDA	Digital pins. No special consideration. Run the SDA and SCL traces in parallel.
22	SCL	
23	PROCHOT#	Digital pin, open-drain output. No special consideration.
24	ACOK	Digital pin, open-drain output. No special consideration.
25	BATGONE/NTC	Digital pin (BATGONE), analog pin (NTC). Place the 10kΩ resistor series in the BATGONE signal trace and the optional decoupling capacitor in the general proximity of the controller.
26	CMOUT/INT#	Digital pin, open-drain output. No special consideration.
27	COMPR	Place the compensation components in the general proximity of the controller. Avoid any switching signal from crossing over or getting close.
28	COMPF	Place the compensation components in the general proximity of the controller. Avoid any switching signal from crossing over or getting close.

Pin #	Pin Name	Layout Guidelines
29	AMON/BMON	No special consideration. Place the optional R-C filter in the general proximity of the controller.
30	PSYS(REFADJ)	Signal pin, current source output. No special consideration. REFADJ is an analog signal pin for feedback of the output voltage. Place near the controller and run a dedicated trace for each resistor divider node (TOP, MIDDLE, BOTTOM). Do not inject noise or additional capacitance.
31	VBAT	Place the optional R-C filter in the general proximity of the controller. Run a dedicated trace from the battery positive connection point to the IC.
32	BGATE	Use a sufficiently wide trace from the IC to the BGATE N-type MOSFET gate. Place the capacitor from BGATE to ground close to the MOSFET.

11. Package Outline Drawing

The package outline drawing is located at the end of this document and is accessible from the Renesas website. The package information is the most current data available and is subject to change without revision of this document.

12. Ordering Information

Part Number[1][2]	Part Marking	Package Description (RoHS Compliant)	Pkg. Dwg. #	Carrier Type[3]	Temp. Range (°C)
RAA489110ARGNP#AA0	489110 ARGNPA	32 Ld 4x4 TQFN	L32.4x4D	Tube	-10 to +100
RAA489110ARGNP#HA0				Reel, 6k	
RAA489110A3GNP#AA0	489110 A3GNP	32 Ld 4x4 TQFN	L32.4x4D	Tube	-40 to +105
RAA489110A3GNP#HA0				Reel, 6k	
RTKA489110DE0000BU	Evaluation board				

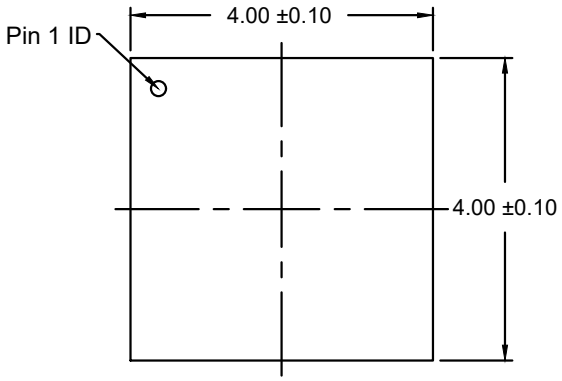
1. These Pb-free plastic packaged products employ special Pb-free material sets, molding compounds/die attach materials, and 100% matte tin plate plus anneal (e3 termination finish, which is RoHS compliant and compatible with both SnPb and Pb-free soldering operations). Pb-free products are MSL classified at Pb-free peak reflow temperatures that meet or exceed the Pb-free requirements of IPC/JEDEC J-STD-020.
2. For Moisture Sensitivity Level (MSL), see the RAA489110 device page. For more information about MSL, see TB363.
3. See TB347 for details about reel specifications

13. Revision History

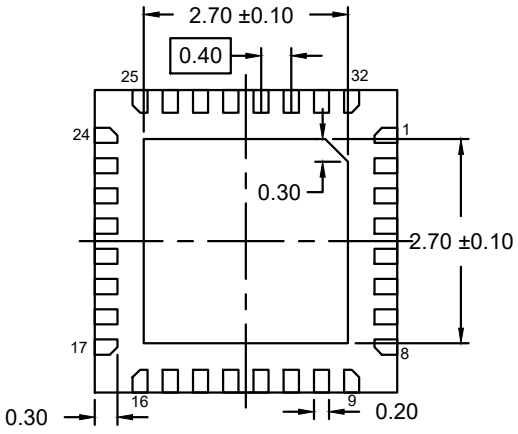
Revision	Date	Description
2.01	Jul 21, 2026	▪ Updated the Start-Up and ACOK section. ▪ Updated the System Voltage Undervoltage Protection (for Short-Circuit Protection) section.
2.00	Oct 27, 2025	▪ Updated θ_{JA} from 37°C/W to 38°C/W. ▪ Updated θ_{JC} from 1.5°C/W to 2.5°C/W.
1.04	Aug 27, 2025	Updated the maximum BGATE Gate Drive Current from 220µA to 250µA in the Electrical Specifications.
1.03	Jan 24, 2025	▪ Updated PHASE1 minimum in the Abs Max section. ▪ Updated POD to the latest version; changes are as follows: • Converted to the new format • Corrected typos on notes • Added four dimensions to the Land Pattern
1.02	Aug 30, 2024	▪ Updated the maximum for PHASE1 in the Abs Max section. ▪ Updated third paragraph in Trickle Charging and Minimum System Voltage Regulation.
1.01	Aug 10, 2023	▪ Added footnote to Figure 39. ▪ Updated section 8.3.2.1. Bypass.
1.00	May 26, 2023	Initial release.

Package Outline Drawing

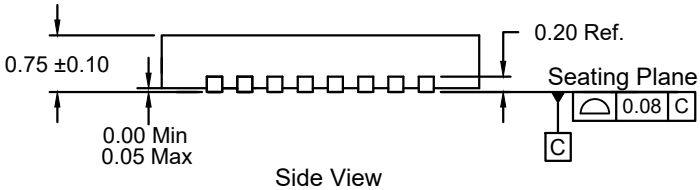
L32.4x4D
QW0032AA
32-QFN 4.0 x 4.0 x 0.75 mm Body, 0.40 mm Pitch
Rev04, Mar 26, 2025



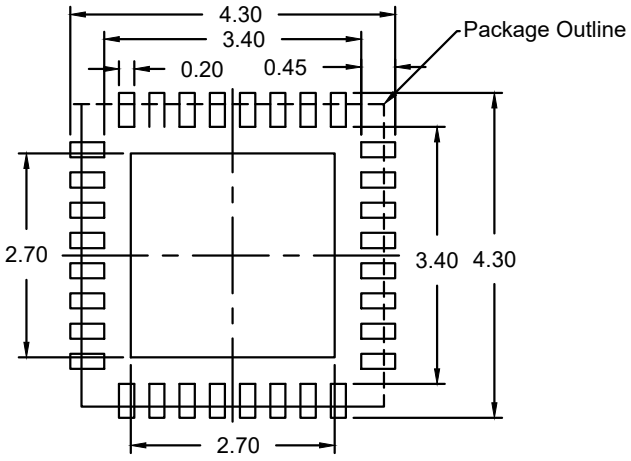
Top View



Bottom View



Side View



Typical Recommended Land Pattern

NOTES:

1. JEDEC compatible.
2. All dimensions are in mm and angles are in degrees.
3. Use ±0.05 mm for the non-toleranced dimensions.
4. Numbers in ( ) are for references only.

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