

## MAX15301

## InTune Automatically Compensated Digital PoL Controller with Driver and PMBus Telemetry

### General Description

The MAX15301 is a full-featured, highly efficient, digital point-of-load (PoL) controller with advanced power management and telemetry features. Unlike PID-based digital power regulators, the MAX15301 uses Maxim's patented InTune™ automatically compensated, state-space control algorithm. The InTune control law is valid for both the small- and large-signal response and accounts for duty-cycle saturation effects. These capabilities result in fast loop transient response and reduce the number of output capacitors compared to competing digital controllers.

The MAX15301 includes multiple features to optimize efficiency. An internal switch BabyBuck™ regulator generates the gate drive and the internal bias supplies for the controller with low power loss. An advanced, high-efficiency MOSFET gate driver has adjustable nonoverlap timing and load-variable gate-drive voltage to minimize switching losses over the full range of voltage, current, and temperature.

The MAX15301 was designed for end-customer's design environment. An on-board PMBus™-compliant serial bus interface enables communication with a supervisory controller for monitoring and fault management. A full suite of power management features eliminates the need for complicated and expensive sequencing and monitoring ICs. Basic DC-DC conversion operation can be set up via pin strapping and does not require user configuration firmware. This allows for rapid development of the power-supply subsystem before board-level systems engineering is completed. Maxim provides support hardware and software for configuring the MAX15301.

The MAX15301 is available in a 32-lead, 5mm x 5mm TQFN package and operates over the -40°C to +85°C temperature range.

*InTune and BabyBuck are trademarks of Maxim Integrated Products, Inc.*

*PMBus is a trademark of SMIF, Inc.*

*Maxim patents apply: 7498781, 7880454, 7696736, 7746048, 7466254, 798613, 7498781, 8,120,401, 8,014,879.*

*This product is subject to a license from Power-One, Inc., related to digital power technology patents owned by Power-One, Inc. This license does not extend to merchant market stand-alone power-supply products.*

### Features

- InTune Automatic Compensation Ensures Stability While Optimizing Transient Performance
- State-Space Compensation Results in Fast Transient Response with Reduced Output Capacitance
- Differential Remote Voltage Sensing Enables  $\pm 1\%$   $V_{OUT}$  Accuracy over Temperature (-40°C to +85°C)
- PMBus Interface for Configuration, Control, and Monitoring
- Supports Voltage Positioning
- High Output 2A/4A MOSFET Driver
  - Adjustable Nonoverlap Timing
  - Variable Gate-Drive Voltage
- Wide Input Range of 4.5V to 14V
- Efficient On-Chip BabyBuck Regulator for Self-Bias
- Output Voltage Range from 0.5V to 5.25V
- Startup into a Prebiased Output
- Configurable Soft-Start and Soft-Stop Time
- Fixed-Frequency Operation and Synchronization
- Flexible Sequencing and Fault Management
- Pin-Strappable Configuration
  - Output Voltage, SMBus Address, Switching Frequency, Current Limit
- Out-of-the-Box Operation Enables Fast Prototyping

### Applications

- Servers
- Storage Systems
- Routers/Switches
- Base-Station Equipment
- Power Modules

**Ordering Information and Typical Operating Circuit appear at end of data sheet.**

For related parts and recommended products to use with this part, refer to [www.maximintegrated.com/MAX15301.related](http://www.maximintegrated.com/MAX15301.related).

## Absolute Maximum Ratings

|                                |  |
|--------------------------------|--|
| INSNS to SGND                  | .....-0.3V to +14V   |
| LXSNS to SGND                  | .....-2V to +14V   |
| LXSNS (pulse < 10ns) to SGND   | .....-2V to +20V   |
| OUTP, OUTN, DCRP, DCRN to SGND | .....-0.3V to +5.5V  |
| PWR to PGND                    | .....-0.3V to +18V   |
| HLD to SGND                    | .....-0.3V to +4V  |
| 3P3 to SGND                    | .....-0.3V to the minimum of +4V<br>or ( $V_{GDRV} + 0.3V$ ) |
| GDRV to SGND                   | .....-0.3V to the minimum of +12V<br>or ( $V_{PWR} + 0.3V$ ) |
| LX to PGND                     | .....-2V to the minimum of +26V or ( $V_{BST} + 0.3V$ )      |
| DL to PGND                     | .....-0.3V to ( $V_{GDRV} + 0.3V$ )                          |
| LBI to PGND                    | .....-0.3V to ( $V_{PWR} + 0.3V$ )                           |
| LBO to PGND                    | .....( $V_{3P3} - 0.3V$ ) to ( $V_{GDRV} + 0.3V$ )           |
| DH to PGND                     | .....( $V_{LX} - 0.3V$ ) to ( $V_{BST} + 0.3V$ )             |
| BST to LX                      | .....-0.3V to +12V   |
| BST to PGND                    | .....-0.3V to +26V   |

|  |                      |
|--|----------------------|
| BST to GDRV  | .....-0.3V to +26V   |
| 1P8 to DGND  | .....-0.3V to +2.2V  |
| CIO, SET, PG, ADDR0, ADDR1, SYNC, TEMPX,<br>SALRT to DGND  | .....-0.3V to +4V    |
| EN, SCL, SDA to DGND                                       | .....-0.3V to +4V    |
| PGND to SGND   | .....-0.3V to +0.3V  |
| DGND to SGND   | .....-0.3V to +0.3V  |
| Electrostatic Discharge (ESD) Rating                       |                      |
| Human Body Model (HBM)                                     | .....±3500V          |
| Machine Model  | .....±200V           |
| Junction Temperature                                       | .....+125°C          |
| Operating Temperature Range                                | .....-40°C to +85°C  |
| Continuous Power Dissipation ( $T_A = +70^\circ\text{C}$ ) | .....                |
| TQFN (derate 34.5mW/°C above +70°C)                        | .....2758mW          |
| Storage Temperature Range                                  | .....-65°C to +150°C |
| Lead Temperature (soldering, 10s)                          | .....+300°C          |
| Soldering Temperature (reflow)                             | .....+260°C          |

Stresses beyond those listed under "Absolute Maximum Ratings" may cause permanent damage to the device. These are stress ratings only, and functional operation of the device at these or any other conditions beyond those indicated in the operational sections of the specifications is not implied. Exposure to absolute maximum rating conditions for extended periods may affect device reliability.

## Package Thermal Characteristics (Note 1)

TQFN

Junction-to-Ambient Thermal Resistance ( $\theta_{JA}$ ) .....29°C/W

Junction-to-Case Thermal Resistance ( $\theta_{JC}$ ) .....1.7°C/W

**Note 1:** Package thermal resistances were obtained using the method described in JEDEC specification JESD51-7, using a four-layer board. For detailed information on package thermal considerations, refer to [www.maximintegrated.com/thermal-tutorial](http://www.maximintegrated.com/thermal-tutorial).

## Electrical Characteristics

(All settings = factory default,  $V_{PWR} = V_{INSNS} = 12V$ ,  $V_{SGND} = V_{DGND} = V_{PGND} = 0V$ ,  $V_{OUT} = 1.2V$ ,  $f_{SW} = 600kHz$ . Specifications are for  $T_A = T_J = -40^\circ\text{C}$  to  $+85^\circ\text{C}$ , typical values are at  $T_A = T_J = +25^\circ\text{C}$ . See the [Typical Operating Circuit](#), unless otherwise noted.)(Note 2)

| PARAMETER                            | SYMBOL                 | CONDITIONS                                    | MIN  | TYP  | MAX  | UNITS |
|--------------------------------------|------------------------|---|------|------|------|-------|
| INPUT SUPPLY                         |                        |   |      |      |      |       |
| Input Voltage Range                  | V <sub>PWR</sub>       |   | 4.5  |      | 14   | V     |
| Input Supply Current                 | I <sub>PWR</sub>       | BabyBuck bias supply, driver not switching    | 10   |      |      | mA    |
|                                      |                        | Linear mode bias supply, driver not switching | 24   | 50   |      |       |
| Input Overvoltage Lockout Threshold  | V <sub>OVLO(PWR)</sub> | Input rising                                  | 14.3 | 15.2 | 16.0 | V     |
| Input Undervoltage Lockout Threshold | V <sub>UVLO(PWR)</sub> | Rising edge                                   | 3.8  | 4.1  | 4.4  | V     |
|                                      |                        | Hysteresis                                    | 0.24 |      |      |       |
| BIAS REGULATORS                      |                        |   |      |      |      |       |
| 3P3 Output Voltage                   | V <sub>3P3</sub>       | I <sub>LOAD(3P3)</sub> = 0mA                  | 3.3  |      |      | V     |
| 1P8 Output Voltage                   | V <sub>1P8</sub>       | I <sub>LOAD(1P8)</sub> = 0mA                  | 1.80 |      |      | V     |

**Electrical Characteristics (continued)**

(All settings = factory default,  $V_{PWR} = V_{INSNS} = 12V$ ,  $V_{SGND} = V_{DGND} = V_{PGND} = 0V$ ,  $V_{OUT} = 1.2V$ ,  $f_{SW} = 600kHz$ . Specifications are for  $T_A = T_J = -40^{\circ}C$  to  $+85^{\circ}C$ , typical values are at  $T_A = T_J = +25^{\circ}C$ . See the [Typical Operating Circuit](#), unless otherwise noted.)(Note 2)

| PARAMETER                              | SYMBOL              | CONDITIONS  | MIN  | TYP  | MAX                   | UNITS |
|--|---------------------|---|------|------|-----------------------|-------|
| STARTUP/SHUTDOWN TIMING                |                     |   |      |      |                       |       |
| Firmware Initialization                | t <sub>1</sub>      | From V <sub>IN</sub> > V <sub>UVLO(PWR)</sub> , until ready to enable (Figure 2)            | 25   |      | ms                    |       |
| Minimum t <sub>ON_DELAY</sub>          | t <sub>2</sub>      | (Figure 2, Note 4)  | 1    |      | ms                    |       |
| Turn-On Rise Time                      | t <sub>3</sub>      | (Figure 2, Note 4)  | 1    |      | ms                    |       |
| Adaptive Tuning Time                   | t <sub>4</sub>      | From V <sub>OUT</sub> = V <sub>OUT</sub> command to assertion of power good (PG) (Figure 2) | 12   |      | ms                    |       |
| OUTPUT VOLTAGE                         |                     |   |      |      |                       |       |
| Output Voltage Range                   | V <sub>OUT</sub>    | Measured from OUTP to OUTN (Notes 4 and 5)  | 0.5  | 5.25 |                       | V     |
| LX Bias Current                        | I <sub>LX</sub>     | Not switching, current out of device pin  | 200  |      | μA                    |       |
| Duty-Cycle Range                       |                     | (Notes 3 and 4)   | 5    | 95   |                       | %     |
| Regulation Set-Point Accuracy          |                     | T <sub>A</sub> = +25°C, I <sub>OUT</sub> ≤ 20A (Notes 4, 8, 9)                              | -0.5 | +0.5 |                       | %     |
|  |                     | -40°C ≤ T <sub>A</sub> ≤ +85°C (Notes 4, 8, 9)  | -1   | +1   |                       |       |
| V <sub>OUT</sub> Sense Bias Current    | I <sub>OUTP</sub>   | Current flowing into OUTP   | 50   |      | μA                    |       |
|  | I <sub>OUTN</sub>   | Current flowing out of OUTN   | 35   |      | μA                    |       |
| DCR Sense Bias Current                 | I <sub>DCRP</sub>   | Current flowing into DCR, V <sub>DCRP</sub> - V <sub>DCRN</sub> = 150mV                     | 120  |      | nA                    |       |
|  | I <sub>DCRN</sub>   |   | 4    |      | μA                    |       |
| PWM CLOCK (Note 4)                     |                     |   |      |      |                       |       |
| Switching Frequency Range              | f <sub>SW</sub>     |   | 300  | 1000 |                       | kHz   |
| Switching Frequency Set-Point Accuracy |                     | T <sub>A</sub> = +25°C  | -5   | +5   |                       | %     |
|  |                     |   | -10  | +10  |                       |       |
| External Clock to SYNC Frequency Range | f <sub>SYNC</sub>   |   | 300  | 1000 |                       | kHz   |
| External Clock to SYNC Duty Cycle      | D <sub>EXTCLK</sub> |   | 40   | 60   |                       | %     |
| SYNC Frequency Drift Tolerance         |                     | From nominal lock frequency (Note 6)  | -10  | +10  |                       | %     |
| PROTECTION (Note 4)                    |                     |   |      |      |                       |       |
| Current-Sense Common-Mode Voltage      |                     | V <sub>ISP</sub> , V <sub>ISN</sub>   | -0.1 | +5.5 |                       | V     |
| Overcurrent Fault Threshold Accuracy   |                     | T <sub>A</sub> = +25°C, exclusive of sensor error   | ±3   |      | %                     |       |
| Output Overvoltage Fault Threshold     |                     | Output rising   | 115  |      | %<br>V <sub>OUT</sub> |       |
| Output Undervoltage Fault Threshold    |                     | Output falling  | 85   |      | %<br>V <sub>OUT</sub> |       |

**Electrical Characteristics (continued)**

(All settings = factory default,  $V_{PWR} = V_{INSNS} = 12V$ ,  $V_{SGND} = V_{DGND} = V_{PGND} = 0V$ ,  $V_{OUT} = 1.2V$ ,  $f_{SW} = 600kHz$ . Specifications are for  $T_A = T_J = -40^{\circ}C$  to  $+85^{\circ}C$ , typical values are at  $T_A = T_J = +25^{\circ}C$ . See the [Typical Operating Circuit](#), unless otherwise noted.)(Note 2)

| PARAMETER                              | SYMBOL          | CONDITIONS   | MIN                    | TYP                   | MAX              | UNITS                 |
|--|-----------------|--|------------------------|-----------------------|------------------|-----------------------|
| Thermal Shutdown Threshold Accuracy    |                 |  |                        | ±20                   |                  | °C                    |
| Thermal Shutdown Hysteresis            |                 |  |                        | 20                    |                  | °C                    |
| Power-Good Threshold                   |                 | V <sub>OUT</sub> rising  |                        | 90                    |                  | %<br>V <sub>OUT</sub> |
|  |                 | V <sub>OUT</sub> falling   |                        | 85                    |                  |                       |
| POWER MANAGEMENT (Note 4)              |                 |  |                        |                       |                  |                       |
| STARTUP/SHUTDOWN TIMING                |                 |  |                        |                       |                  |                       |
| Firmware Initialization                | t <sub>1</sub>  | From V <sub>IN</sub> > V <sub>UVLO(PWR)</sub> , until ready to enable (Figure 2)     |                        | 25                    |                  | ms                    |
| TON_DELAY, TOFF_DELAY Range            | t <sub>2</sub>  | Minimum delay (Figure 2, Note 4)   |                        | 1                     |                  | ms                    |
|  |                 | Maximum delay (Figure 2, Note 4)   |                        | 145                   |                  |                       |
| TON_DELAY, TOFF_DELAY Resolution       |                 | Delay timing step size   |                        | 0.6                   |                  | ms                    |
| TON_DELAY, TOFF_DELAY Command Accuracy |                 | Command value sent vs. readback  |                        |                       | ±0.3             | ms                    |
| TON_DELAY, TOFF_DELAY Timing Accuracy  |                 | Command readback value vs. actual delay time   |                        | ±0.8                  |                  | ms                    |
| TON_RISE, TOFF_FALL Range              | t <sub>3</sub>  | Minimum (Figure 2, Note 4)   |                        | 1                     |                  | ms                    |
|  |                 | Maximum (Figure 2, Note 4)   |                        | 255 x t <sub>RR</sub> |                  |                       |
| TON_RISE, TOFF_FALL Resolution         | t <sub>RR</sub> | Ramp timing step size (varies with V <sub>OUT_COMMAND</sub> )                        |                        | 0.4 -1.0              |                  | ms                    |
| TON_RISE, TOFF_FALL Command Accuracy   |                 | Command value sent vs. readback  |                        |                       | ±0.5             | ms                    |
| TON_RISE, TOFF_FALL Timing Accuracy    |                 | Command readback value vs. actual ramp duration                                      |                        | ±10                   |                  | µs                    |
| Adaptive Tuning Time                   | t <sub>4</sub>  | From end of soft-start ramp to PG assertion (varies with FREQUENCY_SWITCH (Figure 2) |                        | 12                    |                  | ms                    |
| Tracking Error                         |                 | 200mV < V <sub>IN</sub> < (V <sub>OUT_SET</sub> - 200mV) (Note 7)                    | -100                   |                       | +100             |                       |
| Temperature Measurement Accuracy       |                 | External   |                        | ±5                    |                  | °C                    |
|  |                 | Internal   |                        | ±5                    |                  |                       |
| DIGITAL I/O                            |                 |  |                        |                       |                  |                       |
| Power-Good Logic-High Leakage Current  |                 | Open-drain output mode, open-drain connected to 5.5V, V <sub>3P3</sub> = 3.3V        |                        |                       | 10               | µA                    |
| Output Logic-High                      |                 | CMOS mode, I <sub>SOURCE</sub> = 4mA   | V <sub>3P3</sub> - 0.4 |                       | V <sub>3P3</sub> | V                     |

**Electrical Characteristics (continued)**

(All settings = factory default,  $V_{PWR} = V_{INSNS} = 12V$ ,  $V_{SGND} = V_{DGND} = V_{PGND} = 0V$ ,  $V_{OUT} = 1.2V$ ,  $f_{SW} = 600kHz$ . Specifications are for  $T_A = T_J = -40^{\circ}C$  to  $+85^{\circ}C$ , typical values are at  $T_A = T_J = +25^{\circ}C$ . See the [Typical Operating Circuit](#), unless otherwise noted.)(Note 2)

| PARAMETER                                  | SYMBOL         | CONDITIONS   | MIN | TYP  | MAX     |
|--|----------------|--|-----|------|---------|
| Output Logic-Low                           |                | $I_{SINK} = 4mA$   |     | 0.4  | V       |
| Input Bias Current                         |                |  | -1  | +1   | $\mu A$ |
| Rise/Fall Slew Rate                        |                | $C_{LOAD} = 15pF$  | 2   |      | ns      |
| EN, SYNC Input-Logic Low Voltage           |                | Input voltage falling  |     | 0.8  | V       |
| EN, SYNC Input-Logic High Voltage          |                | Input voltage rising   | 2   |      | V       |
| EN, SYNC Input Leakage Current             |                |  | -10 | +10  | $\mu A$ |
| <b>SMBus (Note 4)</b>                      |                |  |     |      |         |
| SDA, SCL Input Logic-Low Voltage           |                | Input voltage falling  |     | 0.8  | V       |
| SDA, SCL Input Logic-High Voltage          |                | Input voltage rising   | 2   |      | V       |
| SDA, SCL, SALRT Logic-High Leakage Current |                | $V_{SCL}$ , $V_{SDA} = 0V$ , and $V_{SALRT}$ tested at 0V and 3.3V |     | 10   | $\mu A$ |
| SDA, SCL, SALRT Logic-Low Output Voltage   |                | $I_{SINK} = 4mA$   |     | 0.4  | V       |
| PMBus Operating Frequency                  | $f_{SMB}$      |  | 400 |      | kHz     |
| Bus Free Time (STOP - START)               | $t_{BUF}$      |  | 1.3 |      | $\mu s$ |
| START Condition Hold Time from SCL         | $t_{HD:STA}$   |  | 0.6 |      | $\mu s$ |
| START Condition Setup Time from SCL        | $t_{SU:STA}$   |  | 0.6 |      | $\mu s$ |
| STOP Condition Setup Time from SCL         | $t_{SU:STO}$   |  | 0.6 |      | $\mu s$ |
| SDA Hold Time from SCL                     | $t_{HD:DAT}$   |  | 300 |      | ns      |
| SDA Setup Time from SCL                    | $t_{SU:DAT}$   |  | 100 |      | ns      |
| SCL Low Period                             | $t_{LOW}$      |  | 1.3 |      | $\mu s$ |
| SCL High Period                            | $t_{HIGH}$     |  | 0.6 |      | $\mu s$ |
| <b>DRIVER BIAS REGULATOR</b>               |                |  |     |      |         |
| GDRV Output Voltage Range                  | $V_{GDRV}$     | GCTRLDAC = 0   | 5.2 |      | V       |
|  |                | GCTRLDAC = 15  | 8.7 |      |         |
| GDRV Undervoltage Lockout                  | $V_{GDRVUVLO}$ | GDRV falling, 200mV (typ) hysteresis                               | 3.5 | 3.75 | V       |
| LBI, LBO Current Limit                     |                |  | 0.7 |      | A       |

**Electrical Characteristics (continued)**

(All settings = factory default,  $V_{PWR} = V_{INSNS} = 12V$ ,  $V_{SGND} = V_{DGND} = V_{PGND} = 0V$ ,  $V_{OUT} = 1.2V$ ,  $f_{SW} = 600kHz$ . Specifications are for  $T_A = T_J = -40^{\circ}C$  to  $+85^{\circ}C$ , typical values are at  $T_A = T_J = +25^{\circ}C$ . See the [Typical Operating Circuit](#), unless otherwise noted.)(Note 2)

| PARAMETER                              | SYMBOL           | CONDITIONS  | MIN | TYP | MAX | UNITS       |
|--|------------------|---|-----|-----|-----|-------------|
| <b>HIGH-SIDE DRIVER</b>                |                  |   |     |     |     |             |
| Driver Source Current                  | $I_{DH\_SOURCE}$ | $V_{PWR} = 12V$ , $V_{DH} = 0V$ , 3.0nF load                                      |     | 2   |     | A           |
| Driver Sink Current                    | $I_{DH\_SINK}$   | $V_{PWR} = 12V$ , $V_{DH} = 0V$ , 3.0nF load                                      |     | 4   |     | A           |
| DH Driver On-Resistance (Sourcing)     | $R_{ON(DH)}$     | $V_{PWR} = 12V$ , $V_{BST} - V_{LX}$ forced to 5V                                 |     | 1   |     | $\Omega$    |
| DH Driver On-Resistance (Sinking)      | $R_{ON(DH)}$     | $V_{PWR} = 12V$ , $V_{BST} - V_{LX}$ forced to 5V                                 |     | 0.4 |     | $\Omega$    |
| <b>LOW-SIDE DRIVER</b>                 |                  |   |     |     |     |             |
| Driver Source Current                  | $I_{DL\_SOURCE}$ | $V_{PWR} = 12V$ , $V_{DL} = 0V$ , 5.0nF load                                      |     | 2   |     | A           |
| Driver Sink Current                    | $I_{DL\_SINK}$   | $V_{PWR} = 12V$ , $V_{DL} = 5V$ , 5.0nF load                                      |     | 4   |     | A           |
| DL Driver On-Resistance (Sourcing)     | $R_{ON(DL)}$     | $V_{PWR} = 12V$ , $V_{LX} - V_{PGND}$ forced to 5V                                |     | 1   |     | $\Omega$    |
| DL Driver On-Resistance (Sinking)      | $R_{ON(DL)}$     | $V_{PWR} = 12V$ , $V_{LX} - V_{PGND}$ forced to 5V                                |     | 0.4 |     | $\Omega$    |
| <b>DRIVER TIMING AND RESISTANCE</b>    |                  |   |     |     |     |             |
| DL Transition Time                     | $t_{F\_DL}$      | Falling, 5.0nF load, $V_{GDRV} = 5V$  |     | 10  |     | ns          |
|  | $t_{R\_DL}$      | Rising, 5.0nF load, $V_{GDRV} = 5V$   |     | 15  |     |             |
| DH Transition Time                     | $t_{F\_DH}$      | Falling, 3.0nF load, $V_{GDRV} = 5V$  |     | 8   |     | ns          |
|  | $t_{R\_DH}$      | Rising, 3.0nF load, $V_{GDRV} = 5V$   |     | 10  |     |             |
| DH Driver Pulldown Resistance          | $R_{PD(DH)}$     | Not switching, $V_{EN} = 0V$  | 100 |     | 300 | k $\Omega$  |
| DL Driver Pulldown Resistance          | $R_{PD(DL)}$     | Not switching, $V_{EN} = 0V$  | 100 |     | 300 | k $\Omega$  |
| Boost On-Resistance                    | $R_{ON(BST)}$    | $V_{GDRV} = 5V$ , $V_{DH} = V_{LX} = V_{PGND}$ (pulldown state), $I_{BST} = 10mA$ |     | 1.5 |     | $\Omega$    |
| <b>THERMAL PROTECTION</b>              |                  |   |     |     |     |             |
| Gate-Driver Thermal Shutdown Threshold | $T_{SHDN}$       | Hysteresis = $20^{\circ}C$  |     | 150 |     | $^{\circ}C$ |

**Note 2:** Limits are 100% production tested at  $T_A = +25^{\circ}C$ . Maximum and minimum limits over temperature are guaranteed through correlation using statistical quality control (SQC) methods. Typical values are expressed as factory-default values also for configurable specifications within a range.

**Note 3:** Can go to 100% during a transient.

**Note 4:** Design guaranteed by bench characterization. Limits are not production tested.

**Note 5:** The settable output voltage range is 0.6V to 5.0V. This range expands to 0.5V to 5.25V when the voltage margining function is enabled.

**Note 6:** Once the MAX15301 locks onto an external synchronizing clock, the tolerance on the capture range is  $\pm 10\%$ .

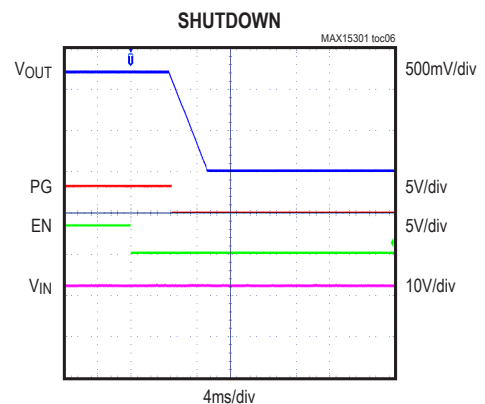
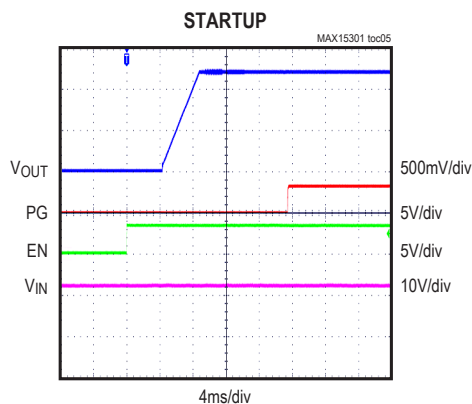
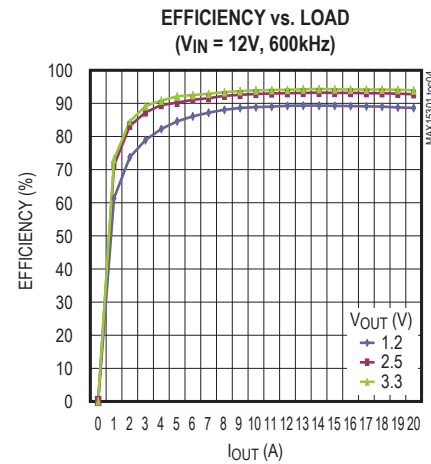
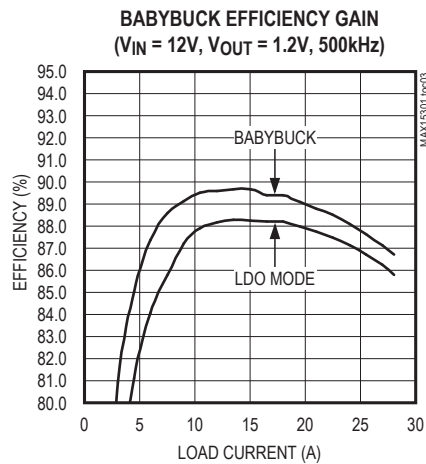
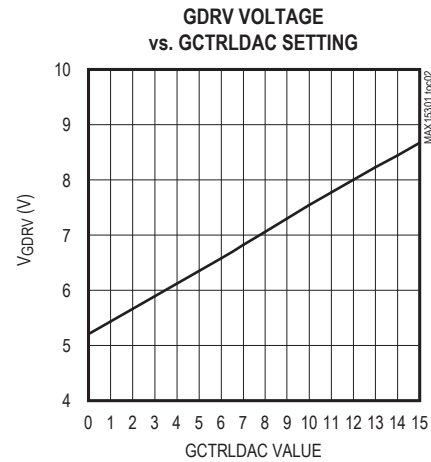
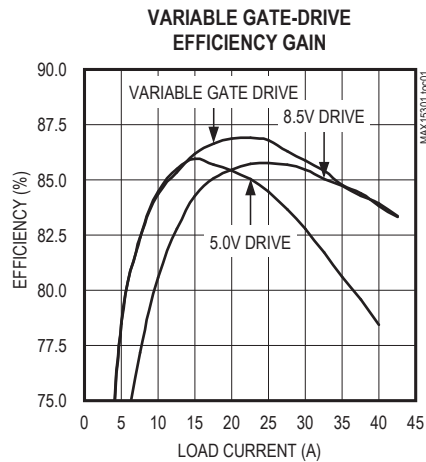
**Note 7:** See the [Voltage Tracking](#) section.

**Note 8:** Excluding tracking mode.

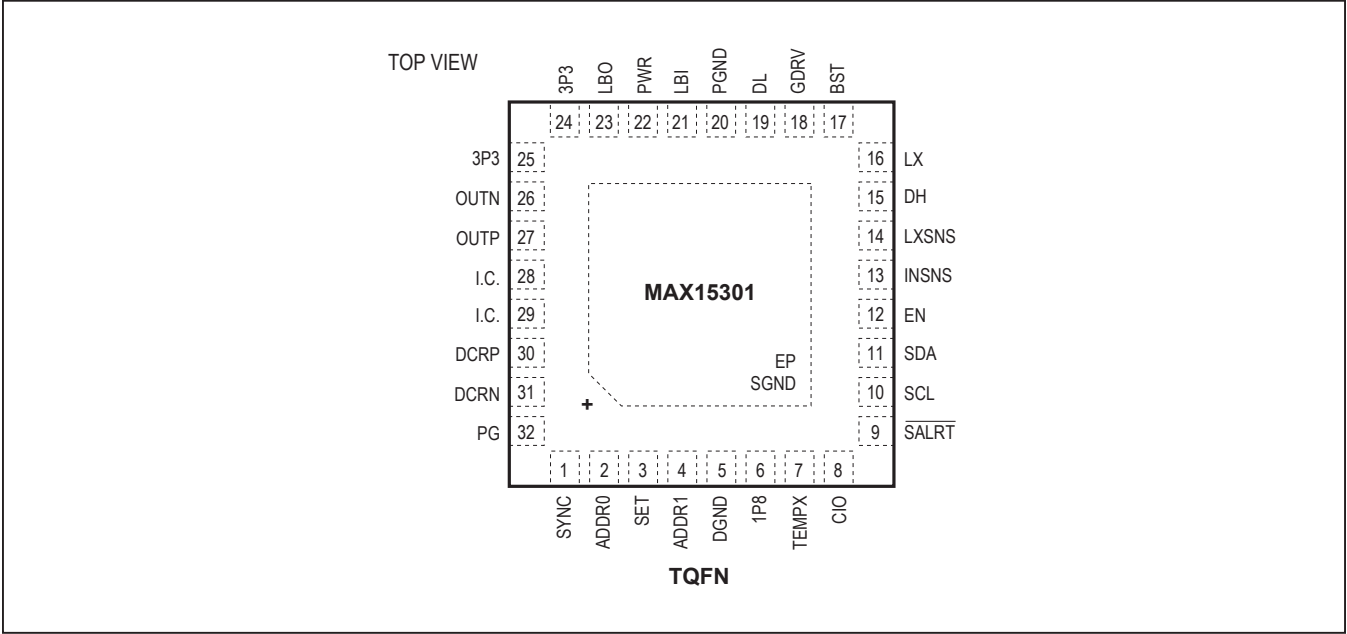
**Note 9:** Voltage regulation accuracy is power-stage dependent; adherence to all data sheet design recommendations is required to achieve specified accuracy.

## Typical Operating Characteristics

( $T_A = +25^\circ\text{C}$ ,  $V_{IN} = 12\text{V}$ ,  $V_{OUT} = 1.2\text{V}$ ,  $f_{SW} = 600\text{kHz}$ , unless otherwise noted. See the Typical Operating Circuit and Application 1 in Table 8).



Pin Configuration



Pin Description

| PIN | NAME  | FUNCTION  |
|-----|-------|---|
| 1   | SYNC  | External Switching Frequency Synchronization Input. Connect a resistor between SYNC and SGND to set the switching frequency of the DC-DC converter (see Table 2). The MAX15301 can also synchronize with an external clock applied at SYNC. |
| 2   | ADDR0 | SMBus Address Select Input 0. Used with ADDR1 to assign a unique SMBus address to the device.   |
| 3   | SET   | Output Voltage Set Input. Connect a resistor between SET and SGND to set the output voltage. Shorting this pin to ground selects tracking mode (see Table 1).   |
| 4   | ADDR1 | SMBus Address Select Input 1. Used with ADDR0 to assign a unique SMBus address to the device and set the current limit for MAX15301.  |
| 5   | DGND  | Digital Ground. Connect to DGND and PGND using short, wide PCB traces.  |
| 6   | 1P8   | Internal 1.8V Regulator Output. 1P8 is the supply rail for the internal digital circuitry. Bypass 1P8 to DGND with a 10µF ceramic capacitor. This pin may not be used to power any circuitry external to the MAX15301.                      |
| 7   | TEMPX | Connection for the External Temperature Sensor. Connect an npn transistor junction from TEMPX to SGND to measure the temperature at any point on the PCB. Place a 100pF ceramic capacitor in parallel with the temperature sense junction.  |
| 8   | CIO   | Configurable Input/Output Pin. This is a voltage-tracking input when SET is connected to SGND to select tracking mode. CIO must be grounded when not in tracking mode.  |



## Pin Description (continued)

| PIN    | NAME                      | FUNCTION  |
|--------|---------------------------|---|
| 9      | $\overline{\text{SALRT}}$ | SMBus Alert. Interrupt to the SMBus master. Open-drain output that pulls low when SMBus interaction is required.  |
| 10     | SCL                       | SMBus Clock Input   |
| 11     | SDA                       | SMBus Data Input/Output   |
| 12     | EN                        | Enable Input. Do not leave unconnected. By default, driving EN high enables output regulation, and driving EN low disables output regulation.   |
| 13     | INSNS                     | Powertrain Input Rail Sense. Monitors the input supply of the DC-DC converter. Connect a series 2k $\Omega$ resistor between input rail and INSNS pin.  |
| 14     | LXSNS                     | Switching Node Sense Input. Connect a series 2k $\Omega$ resistor between switching node and LXSNS pin.   |
| 15     | DH                        | High-Side MOSFET Gate Drive   |
| 16     | LX                        | Switching Node. Connect directly to the high-side of the output inductor.   |
| 17     | BST                       | Bootstrap Capacitor Connection. Connect a 0.22 $\mu$ F ceramic capacitor between BST and the switching node.  |
| 18     | GDRV                      | Gate-Driver Supply. Bypass GDRV to PGND with a 2.2 $\mu$ F ceramic capacitor.   |
| 19     | DL                        | Low-Side MOSFET Gate Drive  |
| 20     | PGND                      | Power Ground. Connect to SGND and DGND using short wide PCB traces.   |
| 21     | LBI                       | BabyBuck Switching Node 1. See the <i>BabyBuck Regulator</i> section for configurations.  |
| 22     | PWR                       | Power-Supply Input. Connect to a power-supply input. Bypass to ground with a 1 $\mu$ F ceramic capacitor.   |
| 23     | LBO                       | BabyBuck Switching Node 2. See the <i>BabyBuck Regulator</i> section for configurations.  |
| 24, 25 | 3P3                       | Internal 3.3V Regulator Output. 3P3 is the supply rail for the internal analog circuitry. Bypass 3P3 to SGND with a 4.7 $\mu$ F ceramic capacitor. This pin may not be used to power any circuitry external to the MAX15301.                          |
| 26     | OUTN                      | Output Voltage Differential Sense Negative Input. Connect to ground at the load.  |
| 27     | OUTP                      | Output Voltage Differential Sense Positive Input. Connect to the output at the load.  |
| 28, 29 | I.C.                      | Internally Connected. Connect directly to ground near the MAX15301.   |
| 30     | DCRP                      | Output Current Differential Sense Positive Input. Connect to the inductor or current-sense element positive side through an appropriate filter network.   |
| 31     | DCRN                      | Output Current Differential Sense Negative Input. Connect to the inductor or current-sense element negative side.   |
| 32     | PG                        | Open-Drain Power-Good Indicator. PG asserts high when soft-start is complete, the voltage has reached regulation, after a successful InTune calibration is completed.   |
| EP     | SGND                      | Exposed Pad and Analog Ground. The EP serves two purposes: it is both the analog ground of the device and a conduit for heat transfer. Connect to a large ground plane to maximize thermal performance. See the <i>PCB Layout Guidelines</i> section. |

The diagram illustrates the internal architecture and external connections of the MAX15301. The internal components include an IO block, a MUX, an AUX ADC, an NLSS COMPENSATOR, a DRIVER, a DPWM, an LX DETECT, an OSC/SYNC block, a THERMAL PROTECTION block, an HSSP, an MCU, RAM, FLASH, a PMBus, a FAULT PROCESSOR, a SOFT-START, and an FB ADC. The external connections are as follows:

- Top Left:** LXSENS, INSNS
- Left Side:** ADDR0, ADDR1, SET, CIO, SYNC, PG, TEMPX, EN, SCL, SDA, SALRT, DGND, EP
- Right Side:** 1.8V REG, IP8, 3P3, PWR, LBI, LBO, GDRV, BST, DH, LX, DL, PGND, DCRP, DCRN, OUTP, OUTN, SGND

The MAX15301 is an innovative, PMBus-compliant, mixed-signal power management IC with a built-in high-performance digital PWM controller for POL applications. The MAX15301 is based on Maxim's InTune automatically compensated digital PWM control loop. The MAX15301 has optimal partitioning of the digital power management and the digital power conversion domains to minimize startup times and reduce bias current. The MAX15301 supports over 80 standard and manufacturer-specific PMBus commands.

The MAX15301 features integrated power conversion to self-bias its digital, analog, and driver blocks from a single input supply ( $V_{PWR}$ ). The MAX15301 relies on mixed-signal design techniques to control the power system efficiently and precisely. It does not require any software to configure or initialize the device. In addition, functions can be monitored and configured through the SMBus interface using standard PMBus commands resulting in ease of design and flexibility.

The control loop is separated from the housekeeping, power monitoring, and fault management blocks. Control loop parameters are stored in an on-chip nonvolatile flash memory. An internal microcontroller enables monitoring operating conditions using the SMBus interface. The DPWM control loop is implemented using dedicated state machines, there is no DSP or MCU in the control loop. This partition allows for architecture that minimizes power consumption while optimizing performance.

The [Functional Diagram](#) shows the controller implementation using a digital state space compensator (model predictive) controller, a microcontroller unit (MCU), a digital pulse-width modulator (DPWM), a PLL-based master timing generator, and a PMBus serial communication port.

### State-Space Controller and DPWM

The MAX15301 uses a digital pulse-width modulation (DPWM) control scheme to regulate the output voltage. Traditional PWM regulators (both analog and digital) use classical control methods for DC-DC converters based on linear models of a discrete time nature and root locus, Bode and Nyquist plots. These linear time-invariant approximations work well for small signals. However, when large transients cause duty-cycle saturation, the performance of the closed loop can be degraded (larger overshoots) and the output transients will be “slower” (large settling times). Tighter regulation performance during these disturbances is becoming a requirement. The MAX15301 addresses the issue by using model-predictive-based feedback design to compensate the DPWM.

The MAX15301 automatically constructs a state-space model (state estimator) of the control plant ([Figure 1](#)). The internal model gives access to state control variables that are otherwise unavailable. The state control variables are used to set the proper control values. For a given input to output step-down ratio and PWM switching frequency the MAX15301 sets the compensation coefficients for that application. Upon output enable, or in response to a

PMBus command, the MAX15301 will perform the InTune calibration. During this calibration several powertrain parameter values are measured and the extracted parameters are used to create the internal model to optimize the bandwidth and transient response of the converter.

The state-space compensator block generates the duty-cycle command for the DPWM block. The DPWM block generates the required PWM outputs for the driver. The state-space controller block also contains a digital-to-analog converter that adjusts the gate-drive voltage. The gate-drive voltage can be set using a PMBus command (manufacturer specific) to a value between 5V and 8.5V to improve the power-supply efficiency.

### BabyBuck Regulator

The MAX15301 has an internal BabyBuck bias regulator circuit to generate both the gate-drive voltage supply and the internal digital supply to power the controller. The BabyBuck bias regulator is an internal two output switching regulator that uses a small (1008-size), low-cost inductor. If the user is not concerned with optimizing operating efficiency, the inductor can be omitted from the designs (connect the LBI pin to the PWR pin through a 100kΩ resistor). In this configuration, the bias regulator operates as a linear regulator (LDO). If an external gate-drive voltage is available, the LBI pin can be connected to  $V_{IN}$  through a 2kΩ resistor and the GDRV pin can be connected to the external source.

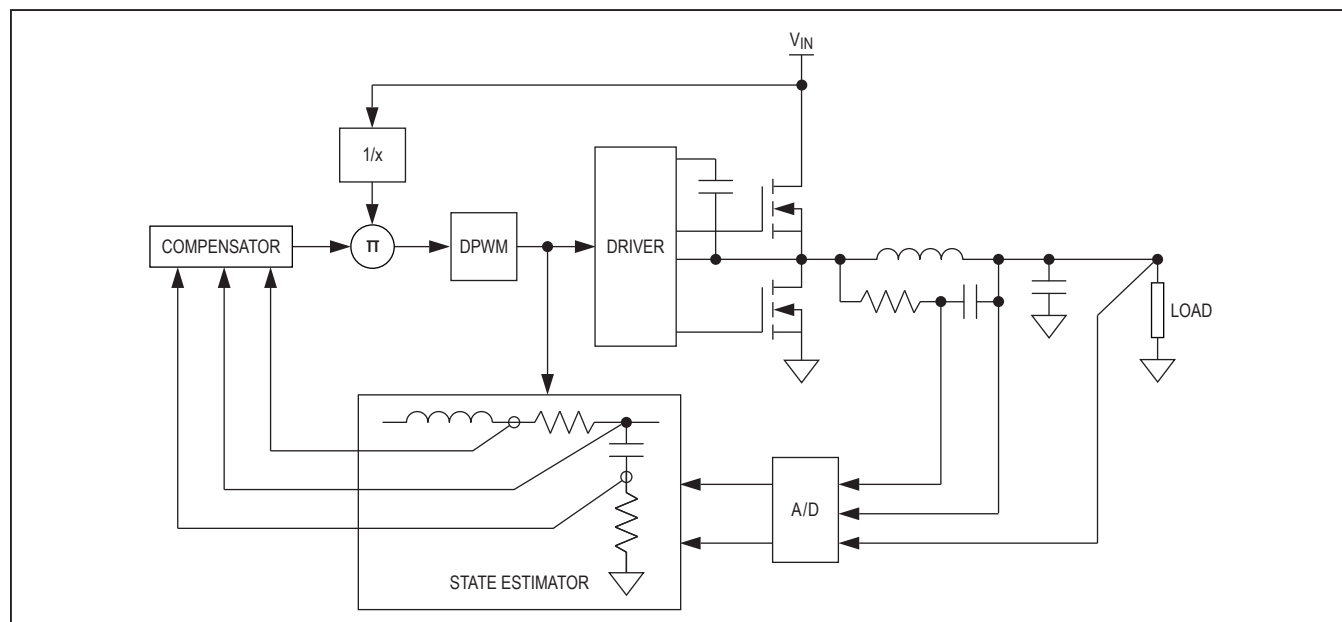


Figure 1. State-Space Controller Concept

External Temperature Sense

A temperature sensor input pin (TEMPX) automatically performs a temperature measurement using the base-emitter junction of a standard 2N3904 transistor. When this device is connected to the TEMPX pin, the MAX15301 uses the external temperature information for temperature fault and current measurement temperature compensation (tempco). If the external temperature measurement feature is not required, connect TEMPX to ground. In this case, the MAX15301 ignores the invalid external reading and uses the internal signal for temperature compensation and thermal fault protection.

The temperature measurements can be read using the PMBus commands READ\_TEMPERATURE\_1 and READ\_TEMPERATURE\_2 for internal and external temperature, respectively.

Regulation and Monitoring Functions

The MAX15301 improves the reliability of the system it powers with multiple circuits that protect the regulator and the load from unexpected system faults. The MAX15301 continuously monitors the input voltage, output voltage and current, internal and external temperatures. The MAX15301 can be configured to provide alerts for specific conditions of the monitored parameters. The thresholds and responses for these parameters have factory-default values but can also be configured through the PMBus interface. The status of the power supply can be queried any time by a PMBus master.

Regulator Parameters

Key operating parameters in the MAX15301, such as output voltage, switching frequency, and current-sense resistance, can be configured using resistors. This provides flexibility for the user while ensuring that the device will have a well-defined “out-of-the-box” operational state. The pin configurations are only sampled when power is first applied (the MAX15301 ignores changes to resistor settings after power-up). From this initial operating state, it is possible for the user to change the parameters using PMBus commands. These changes can be stored in non-volatile memory, and the device will subsequently power up in the newly stored configuration state. However, it is recommended that the pin-strap or resistor settings always be applied with values chosen to provide a safe initial behavior prior to PMBus configuration.

Pin-strap settings are programmed by connecting a resistor from the appropriate MAX15301 pins to SGND. The MAX15301 reads the resistance at startup and sets com-

mand parameters per the tables in the following detail sections. Note that the external parts count can be reduced in some cases by floating or grounding the configuration pins.

Output Voltage Selection

The SET pin is used to establish the initial output voltage; it can be pin strapped high or low, or connected to SGND through a resistor, to select the output voltage as shown in Table 1. Note that the SET pin is read once at power-up and cannot be used to change the output voltage after that time.

If the desired output voltage is not included in Table 1, use a resistor to set the initial approximate output voltage, and then send VOUT\_COMMAND to set the exact desired output voltage.

The output voltage can be set to any voltage between 0.5V and 5.25V, including margining, provided the input voltage to the DC-DC converter ( $V_{PWR}$ ) is higher than the output voltage by an amount that conforms to the maximum duty cycle specification.

Table 1. Output Voltage Setting Using Pin-Resistor Setting

| RSET (kΩ)    | OUTPUT VOLTAGE (V) |
|--------------|--------------------|
| 0 to 4.3     | Track mode         |
| 5 to 5.2     | 0.6                |
| 6.1 to 6.3   | 0.7                |
| 7 to 7.3     | 0.75               |
| 8.1 to 8.4   | 0.8                |
| 9.4 to 9.7   | 0.85               |
| 10.8 to 11.2 | 0.9                |
| 12.5 to 12.9 | 0.95               |
| 14.5 to 14.9 | 1                  |
| 17.6 to 18   | 1.05               |
| 21.2 to 21.8 | 1.1                |
| 25.8 to 26.4 | 1.2                |
| 31.2 to 32   | 1.5                |
| 37.9 to 38.7 | 1.8                |
| 43.7 to 44.7 | 2.5                |
| 50.5 to 51.7 | 3.3                |
| 58.4 to 59.6 | 5                  |
| 67.4 to Open | 0                  |

**Table 2. Interleave Settings**

| SMBus ADDRESS | PHASE DELAY (°) |
|---------------|-----------------|
| xxxx000b      | 0               |
| xxxx001b      | 60              |
| xxxx010b      | 120             |
| xxxx011b      | 180             |
| xxxx100b      | 240             |
| xxxx101b      | 300             |
| xxxx110b      | 90              |
| xxxx111b      | 270             |

**Setting Switching Frequency**

The switching frequency can be adjusted from 300kHz to 1MHz with an external resistor from SYNC to SGND per [Table 3](#), or by sending the PMBus FREQUENCY\_SWITCH command.

As a guideline, lower frequencies can be used to improve efficiency, while higher frequencies can be selected to reduce the physical size and value of the external filter inductor and capacitors.

**External Synchronization**

The MAX15301 may be configured to synchronize with an external clock to eliminate beat noise on the input and output voltage lines or to minimize input voltage ripple. Synchronization is achieved by connecting a clock source to the SYNC pin. The incoming clock signal must be in the 300kHz to 1MHz range and must be stable (see the SYNC Frequency Drift Tolerance specification in the [Electrical Characteristics](#) table). The MAX15301 synchronizes to the rising edge of the clock after the IC is enabled. In the event of a loss of the external clock signal during normal operation after successful synchronization with the external clock, the MAX15301 automatically switches at the frequency programmed into the PMBus command's FREQUENCY\_SWITCH variable. If an external clock is present at power-on, the IC writes 300kHz into FREQUENCY\_SWITCH. If the clock is still present at enable, the IC overwrites FREQUENCY\_SWITCH with the actual clock frequency. If a clock is not present at power-on, the MAX15301 reads the pinstrap resistor value and writes the frequency into FREQUENCY\_SWITCH per [Table 5](#). If an external clock is applied to SYNC after power on but before enable, the IC overwrites FREQUENCY\_SWITCH with the external clock frequency at enable. If an external clock is not applied

**Table 3. Switching Frequency Resistor Settings (SYNC)**

| R <sub>SYNC</sub> (kΩ) | SWITCHING FREQUENCY (kHz) |
|------------------------|---------------------------|
| 0 to 4.3               | 575                       |
| 5 to 5.2               | 300                       |
| 6.1 to 6.3             | 350                       |
| 7 to 7.3               | 400                       |
| 8.1 to 8.4             | 450                       |
| 9.4 to 9.7             | 500                       |
| 10.8 to 11.2           | 550                       |
| 12.5 to 12.9           | 600                       |
| 14.5 to 14.9           | 650                       |
| 17.6 to 18             | 700                       |
| 21.2 to 21.8           | 750                       |
| 25.8 to 26.4           | 800                       |
| 31.2 to 32             | 850                       |
| 37.9 to 38.7           | 900                       |
| 43.7 to 44.7           | 950                       |
| 50.5 to 51.7           | 1000                      |
| 58.4 to Open           | 575                       |

prior to the IC being enabled, the IC keeps the originally programmed FREQUENCY\_SWITCH value. For proper synchronization, the external clock may be applied prior to applying power to the IC but must be applied prior to enabling the IC. The external clock frequency should not be changed after the IC is enabled.

The MAX15301 supports interleaving with an external sync input. Phase delay between the rising edge of the SYNC clock signal and the center of the PWM pulse is set to a default value determined by the 7-bit SMBus address as shown in [Table 2](#). The phase delay can also be changed by sending the PMBus INTERLEAVE command while the output is disabled.

**ILIM and SMBus Address Selection**

The ADDR0 and ADDR1 pins are used in combination to set both the current-sense resistance and the SMBus address as listed in [Table 4a](#) and [Table 4b](#). Note that SMBus specification recommends against using the shaded addresses.

**Table 4a. SMBus Address Set by ADDR0, ADDR1 Resistor Connections**

| DCR                     | R <sub>ADDR1</sub> (kΩ)    |                |                |                |                |
|-------------------------|----------------------------|----------------|----------------|----------------|----------------|
| 0.4mΩ →                 | 0 to 4.3                   | 5 to 5.2       | 6.1 to 6.3     | 7 to 7.3       | 8.1 to 8.4     |
| 0.8mΩ →                 | 9.4 to 9.7                 | 10.8 to 11.2   | 12.5 to 12.9   | 14.5 to 14.9   | 17.6 to 18     |
| 1.2mΩ →                 | 21.2 to 21.8               | 25.8 to 26.4   | 31.2 to 32     | 37.9 to 38.7   | 43.7 to 44.7   |
| 1.6mΩ →                 | 50.5 to 51.7               | 58.4 to 59.6   | 67.4 to 68.8   | 85.7 to 87.5   | 113.8 to 116.2 |
| 2.0mΩ →                 | 138.6 to 141.4             | 167.3 to 170.7 | 202.9 to 207.1 | 234.6 to 239.4 | 271.2 to Open  |
| R <sub>ADDR0</sub> (kΩ) | SMBus 7-BIT DEVICE ADDRESS |                |                |                |                |
| 0 to 4.3                | 0x0A                       | 0x22           | 0x3A           | 0x52           | 0x6A           |
| 5 to 5.2                | 0x0B                       | 0x23           | 0x3B           | 0x53           | 0x6B           |
| 6.1 to 6.3              | 0x0C                       | 0x24           | 0x3C           | 0x54           | 0x6C           |
| 7 to 7.3                | 0x0D                       | 0x25           | 0x3D           | 0x55           | 0x6D           |
| 8.1 to 8.4              | 0x0E                       | 0x26           | 0x3E           | 0x56           | 0x6E           |
| 9.4 to 9.7              | 0x0F                       | 0x27           | 0x3F           | 0x57           | 0x6F           |
| 10.8 to 11.2            | 0x10                       | 0x28           | 0x40           | 0x58           | 0x70           |
| 12.5 to 12.9            | 0x11                       | 0x29           | 0x41           | 0x59           | 0x71           |
| 14.5 to 14.9            | 0x12                       | 0x2A           | 0x42           | 0x5A           | 0x72           |
| 17.6 to 18              | 0x13                       | 0x2B           | 0x43           | 0x5B           | 0x73           |
| 21.2 to 21.8            | 0x14                       | 0x2C           | 0x44           | 0x5C           | 0x74           |
| 25.8 to 26.4            | 0x15                       | 0x2D           | 0x45           | 0x5D           | 0x75           |
| 31.2 to 32              | 0x16                       | 0x2E           | 0x46           | 0x5E           | 0x76           |
| 37.9 to 38.7            | 0x17                       | 0x2F           | 0x47           | 0x5F           | 0x77           |
| 43.7 to 44.7            | 0x18                       | 0x30           | 0x48           | 0x60           | 0x78           |
| 50.5 to 51.7            | 0x19                       | 0x31           | 0x49           | 0x61           | 0x79           |
| 58.4 to 59.6            | 0x1A                       | 0x32           | 0x4A           | 0x62           | 0x7A           |
| 67.4 to 68.8            | 0x1B                       | 0x33           | 0x4B           | 0x63           | 0x7B           |
| 85.7 to 87.5            | 0x1C                       | 0x34           | 0x4C           | 0x64           | 0x7C           |
| 113.8 to 116.2          | 0x1D                       | 0x35           | 0x4D           | 0x65           | 0x7D           |
| 138.6 to 141.4          | 0x1E                       | 0x36           | 0x4E           | 0x66           | 0x7E           |
| 167.3 to 170.7          | 0x1F                       | 0x37           | 0x4F           | 0x67           | 0x7F           |
| 202.9 to 207.1          | 0x20                       | 0x38           | 0x50           | 0x68           | 0x7F           |
| 234.6 to Open           | 0x21                       | 0x39           | 0x51           | 0x69           | 0x7F           |

**Note:** The SMBus specification recommends against using the shaded addresses.

**Table 4b. IOUT\_CAL\_GAIN Set by ADDR1 Resistor Connection**

| R <sub>ADDR1</sub> (kΩ) | IOUT_CAL_GAIN (mΩ) |
|-------------------------|--------------------|
| 0 to 8.4                | 0.4                |
| 9.4 to 18               | 0.8                |
| 21.2 to 44.7            | 1.2                |
| 50.5 to 116.2           | 1.6                |
| 138.6 to Open           | 2.0                |



### Internal Bias Regulators

The MAX15301 analog circuitry is powered by an internal 3.3V regulator (3P3). The MAX15301 also has an internal bias regulator to generate a 1.8V rail (1P8) to power internal digital circuitry. Bypass the 3P3 pin to SGND with a 4.7 $\mu$ F ceramic (X5R or better) capacitor. Bypass 1P8 to DGND with a 10 $\mu$ F ceramic (X5R or better) capacitor. These internal regulators are not designed to power external circuitry.

### Input Voltage Feed-Forward

The MAX15301 uses input voltage feed-forward techniques to provide excellent line regulation. Connect the INSNS pin to the powertrain input voltage through a 2k $\Omega$  series resistor for input voltage feed-forward and telemetry. The voltage at INSNS is sampled every 4 $\mu$ s.

The MAX15301 does not enable DC-DC conversion if the voltage at INSNS is below the PMBus VIN\_UV\_FAULT\_LIMIT threshold (default 4V) or below the VIN\_ON, VIN\_OFF limits (default 6V rising and 5.5V falling, respectively.) The user can read back the measured input voltage value using the PMBus READ\_VIN command.

### Output On/Off Control

The MAX15301 features both a hardware enable input (EN pin) and a PMBus enable function. The factory default for the enable functions is that the MAX15301 can be enabled by either an assertion of the hardware EN pin

to a logic-high level or by issuing a PMBus enable command. The enable functionality can be changed using the PMBus ON\_OFF\_CONFIG PMBus command (see the PMBus specification for details).

The MAX15301 default configuration allows the output to be enabled either by driving the EN input to a logic-high level, or by sending the PMBus OPERATION command. The enable criteria can be changed using the PMBus ON\_OFF\_CONFIG command.

### Device Initialization

The MAX15301 includes power-on reset circuits that monitor the internal bias supplies and the external supply voltage. When all supplies are above their UVLO thresholds, the following self-test sequence occurs:

- 1) Run self test and CRC check on the memory.
- 2) Read resistor settings and set command values and program working memory accordingly.
- 3) Confirm absence of any faults that would prevent turn-on.
- 4) Begin wait for a valid output enable condition (hardware or PMBus command).

The power-up and initialization process takes approximately 25ms, depending upon the specific combination of pin-strap resistor values to be read. The MAX15301 will not enable output regulation until initialization is complete.

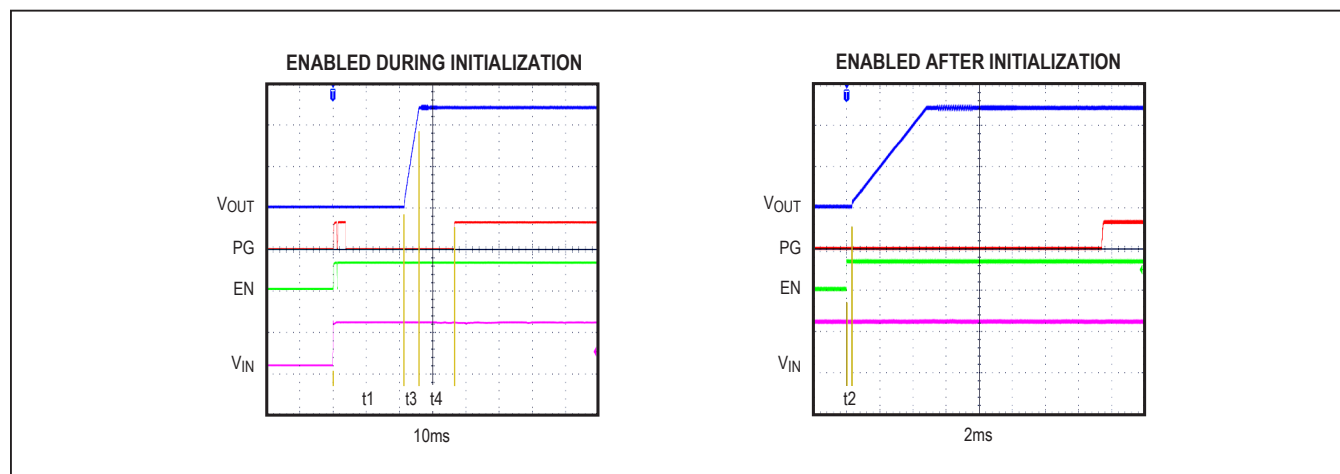


Figure 2. Startup Timing Diagrams

## Output Voltage Sequencing

In a system with multiple MAX15301 devices or other PMBus controlled ICs, output voltage sequencing can be achieved by configuring each power supply with different turn-on/turn-off delays and output rise/fall times. All power supplies are then commanded to turn on (or off) simultaneously using a combined EN signal, or by using the PMBus Group Command Protocol.

The MAX15301 supports soft-start and soft-stop functionality as shown in [Figure 3](#). The PMBus TON\_RISE and TOFF\_FALL commands determine the soft-start and soft-stop ramp times. The TON\_DELAY command sets the time from a valid enable condition to the beginning of the output voltage ramp. Similarly, the TOFF\_DELAY command sets the time between loss of valid enable condition and the beginning of the output ramp down to 0V. The default setting for TON\_DELAY is the minimum value of 1ms and the default setting for the TON\_RISE is 5ms.

The output voltage slew-rates for turn-on and turn-off are given by  $V_{OUT\_COMMAND} \div TON\_RISE$  and  $V_{OUT\_COMMAND} \div TOFF\_FALL$ , respectively. It is recommended to set TON\_RISE and TOFF\_FALL to at least 1ms to prevent excessive inrush currents due to high dV/dt. The output voltage ramp-up rises monotonically above 300mV regardless of input voltage, output voltage, or prebias voltage on the output. Note that the MAX15301 initiates the InTune calibration process after the soft-start ramp-up is complete.

## Startup with Prebias

The MAX15301 supports soft-start into a prebias output voltage condition. A prebias condition occurs when there is already a voltage at the output of the power supply before it has been enabled. This can be caused by pre-charged output capacitors, or a parasitic ESD diode in the load IC that pulls the output up to another system supply rail. When EN is asserted, the MAX15301 checks the

output for the presence of prebias voltage. If the prebias voltage is less than 200mV, startup is performed normally assuming no prebias. If the prebias is greater than 200mV but below the target set point for the output, the MAX15301 ramps up the output voltage from the prebias voltage to the regulation set point as shown in [Figure 4](#). If the prebias is above the VOUT\_OV\_FAULT\_LIMIT value, the MAX15301 does not attempt soft-start.

If prebias was detected at the time of enable, the MAX15301 saves the prebias voltage level in a register and terminates the output voltage ramp-down at the prebias voltage when disabled.

## Voltage Tracking

The MAX15301 supports voltage tracking of the output from a reference input. To select the tracking mode, connect the SET pin to SGND. The MAX15301's output tracks the V<sub>TRACK</sub> voltage with a preset ratio governed by an internal feedback divider (RDIV) and an external resistive voltage-divider (R1, R2) which is placed from the supply being tracked to SGND ([Figure 5](#)). The center tap of the external divider should be connected to the CIO input.

In tracking mode, V<sub>OUT</sub> is regulated to the lower of:

$$V_{OUT} = \frac{V_{TRACK}}{RDIV} \times \frac{R1}{R1+R2}$$

or the output set-point voltage V<sub>OUT(SET)</sub> as determined by the VOUT\_COMMAND. As seen in the above equation, if the resistor-divider ratio  $RR = R1/(R1 + R2)$  is chosen such that it is equal to the operational RDIV, the output voltage follows the tracking voltage coincidentally ([Figure 6a](#)). For all other cases, the V<sub>OUT</sub> follows a ratio-metric tracking ([Figure 6b](#)) depending on the ratio of RR and RDIV. The MAX15301 automatically selects RDIV based on the output set-point voltage as shown in [Table 5](#). For example, if V<sub>OUT(SET)</sub> is set to 1.6V by the VOUT\_

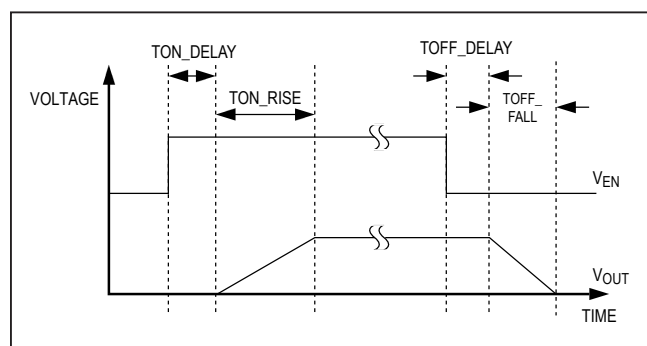


Figure 3. Turn-On/-Off Delays and Soft-Start/-Stop Times

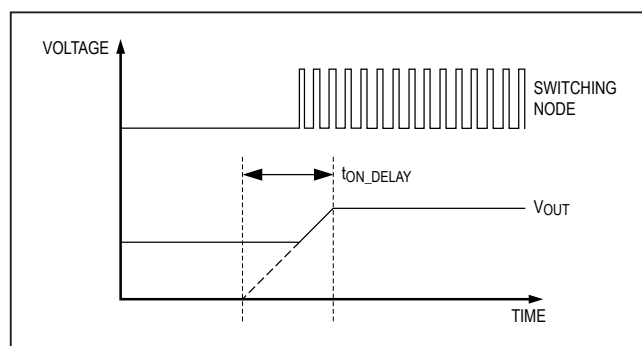


Figure 4. Startup into a Prebiased Output



COMMAND, RDIV is set to 0.54247. For a reliable voltage tracking, it is recommended that once the IC is powered up, the VOUT\_COMMAND should not be changed so as to cause a change to the operational RDIV (Table 5). If such a change in VOUT\_COMMAND is required, the user should save the new VOUT(SET) in the device memory (using STORE\_USER\_ALL\_COMMAND) and recycle the input power to set a new RDIV operational value. For simplicity, fix R1 at 10kΩ and use the following equation to determine R2:

$$R2 = 10k \times \left( \frac{V_{TRACK}}{R_{DIV} \times V_{OUT}} - 1 \right)$$

For the best voltage regulation, RR should be set such that the final VOUT tracking target voltage is slightly higher than the output set-point voltage determined by VOUT\_COMMAND. The output ramp tracks the VTRACK input as shown in Figure 6 until reaching the VOUT\_COMMAND value. If the application requires continuous ratiometric tracking,

VOUT\_COMMAND should be set higher than the desired VOUT tracking target or left at the 5.0V default value. In this case, there is a small regulation inaccuracy due to the tolerance of the external resistors.

Table 5. Required Divider Ratio (RDIV) as a Function of VOUT

| VOUT_COMMAND (V) | RDIV    |
|------------------|---------|
| < 0.65           | 0.99547 |
| 0.65 to < 1.12   | 0.88222 |
| 1.12 to < 1.28   | 0.76897 |
| 1.28 to < 1.50   | 0.65572 |
| 1.50 to < 1.82   | 0.54247 |
| 1.82 to < 2.29   | 0.42922 |
| 2.29 to < 3.12   | 0.31597 |
| 3.12 to < 5.25   | 0.20272 |

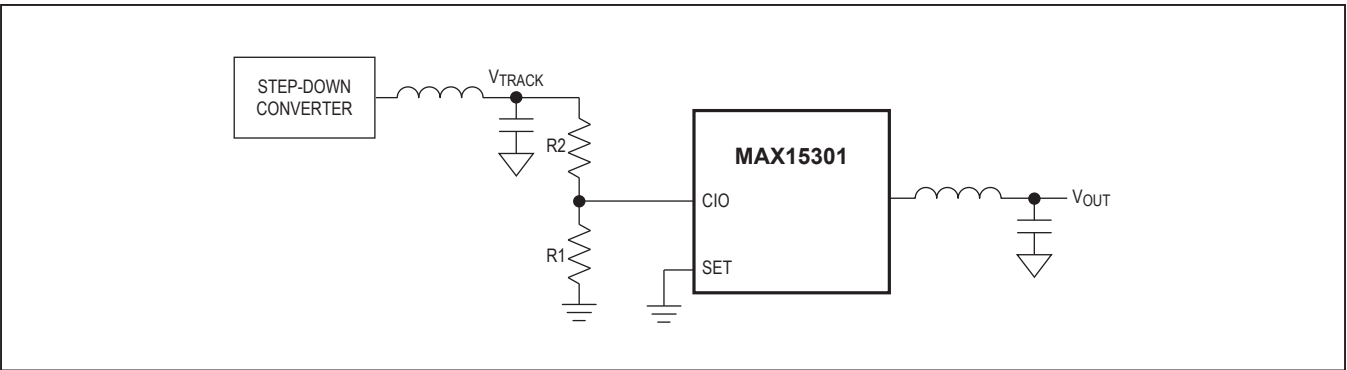


Figure 5. Tracking Mode Configuration

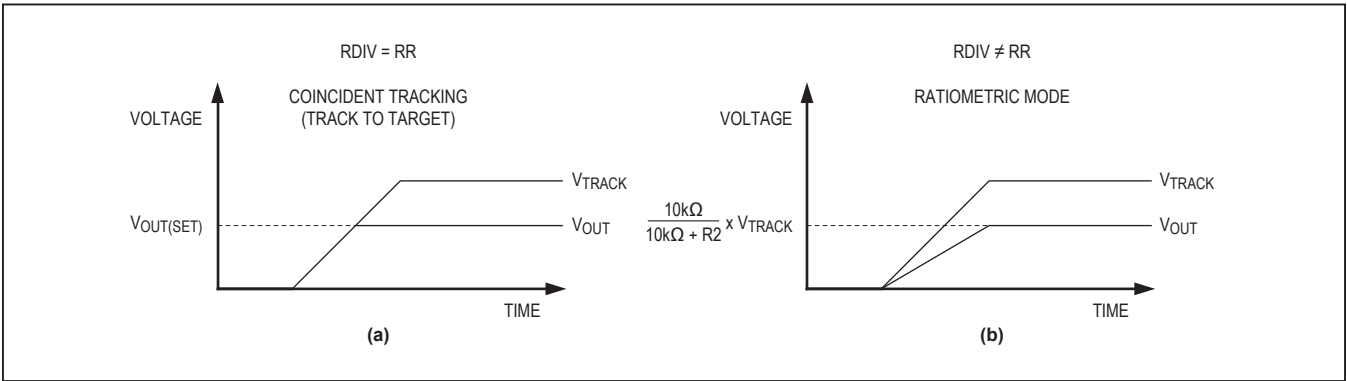


Figure 6. Tracking

### Output Voltage Margining

The MAX15301 supports voltage margining, which can be used to test the end equipment's design margin associated with power-supply variation. The margin setpoint commands `VOUT_MARGIN_HIGH` and `VOUT_MARGIN_LOW` are set to  $\pm 5\%$  of `VOUT_COMMAND` by default, but can be changed via the PMBus interface. Output voltage margining is controlled by the `OPERATION` command.

### Output Voltage Ranges and Fault Limits

The MAX15301 features output undervoltage and over-voltage protection. The PMBus `VOUT_OV_FAULT_LIMIT` is set to 115% of `VOUT_COMMAND` by default, and `VOUT_UV_FAULT_LIMIT` is set to 85%. These thresholds can be changed through PMBus and set anywhere between 0V and the lower of either the ADC full-scale value or `VOUT_MAX` (`VOUT_MAX` is 110% of `VOUT_COMMAND` by default).

The MAX15301 continuously monitors the output voltage. If the voltage exceeds the protection limits, the MAX15301 follows the actions prescribed by the `VOUT_OV_FAULT_RESPONSE` or `VOUT_UV_FAULT_RESPONSE` commands as appropriate. By default, an overvoltage fault results in an immediate shutdown with no retry attempts, whereas undervoltage faults are ignored. The fault response commands can be changed at any time, but changes to the fault-response commands only take effect when the output is disabled.

### Output-Overcurrent Protection

The MAX15301 monitors the voltage across the output inductor resistance (or other resistive sense element) to provide output current monitoring and overload protection. The voltage signal at the current-sense element is divided by the `IOUT_CAL_GAIN` value to yield output current in Amps. The value of `IOUT_CAL_GAIN` is initially set by the `ADDR1` resistance according to [Table 4b](#) and should be

set as close as possible to the inductor DCR (or the resistive sense element's resistance.) More accurate output current measurement can be achieved by calibrating the `IOUT_CAL_GAIN` value; contact Maxim for an application note describing the `READ_IOUT` calibration process.

The overcurrent fault threshold is set by the `IOUT_OC_FAULT_LIMIT` command; the default value is 25A. If an overcurrent condition is detected, the MAX15301 shuts down, delays for 700ms, and then attempts to restart the regulator. This process repeats indefinitely until the fault condition no longer persists. This fault response behavior can be changed using the PMBus `IOUT_OC_FAULT_RESPONSE` command.

### Fault Handling

The MAX15301 monitors input voltage, output voltage, output current, and both internal and external temperatures. The fault thresholds and responses are factory-set, but may be changed using PMBus commands. Fault detection can be individually enabled or disabled for the parameters through PMBus. The default limits are as indicated in [Table 6](#). The response to a fault condition can be changed through PMBus.

### Nonvolatile PMBus Memory

The MAX15301 includes three nonvolatile stores for PMBus configuration values. The first is the MAXIM store, which contains a read-only copy of all default command settings. The next is the read/write-accessible DEFAULT store, which is intended to contain an equipment manufacturer's preferred or suggested settings. Third is the read/write accessible USER store, which is intended to store the end-user's preferred settings.

When the device is enabled, a combination of the pin-configurable command values and the contents of the USER store are loaded into working memory. Any command values that have been edited and stored to the USER memory takes precedence over their corresponding pin-configured values.

Equipment manufacturers should ensure that the DEFAULT and USER stores are saved with duplicate copies of the manufacturer's preferred or suggested command values. In this manner, an end user can restore the DEFAULT memory and save to the USER store any time they wish to return the device to the manufacturer's original configuration.

Special security commands and features are included so that a manufacturer user can store and lock the regulator's configuration on a command-by-command basis. Contact Maxim for application notes describing these security features.

**Table 6. Fault Conditions**

| FAULT CONDITION        | DEFAULT THRESHOLD                | RANGE           |
|------------------------|----------------------------------|-----------------|
| $V_{IN}$ Overvoltage   | 14V                              | 0 to 14.7V      |
| $V_{IN}$ Undervoltage  | 4.2V                             | 0 to 14.7V      |
| $V_{OUT}$ Overvoltage  | <code>VOUT_COMMAND</code> x 115% | 0 to 5.5V       |
| $V_{OUT}$ Undervoltage | <code>VOUT_COMMAND</code> x 85%  | 0 to 5.5V       |
| $I_{OUT}$ Overcurrent  | 25A                              | 0 to 30A        |
| Overtemperature        | 115°C                            | -40°C to +150°C |

## Temperature Sensing

The MAX15301 supports remote temperature sensing in addition to sensing its own internal temperature. The MAX15301 uses a  $\Delta V_{BE}$  measurement internally and at the TEMPX input to compute temperature. This technique is widely employed because it requires no calibration of the sensor. Any PN junction can be used as a temperature sensor. The 2N3904, 2N2222 transistors and integrated thermal diodes found in microprocessors, FPGAs, and ASICs are commonly used temperature sensors. Connect a 100pF filter capacitor as shown in [Figure 7](#) to ensure accurate temperature measurements.

The device temperature and thermal fault thresholds are programmed through the PMBus interface. The default value for the thermal shutdown threshold is +115°C. The MAX15301 shuts down and PG pulls low when it crosses the temperature fault threshold.

## Power Good (PG)

PG, power good, is an open-drain output used to indicate when the MAX15301 is ready to provide regulated output voltage to the load. During startup and during a fault condition, PG is held low. PG is asserted high after the output has ramped to a voltage above the POWER\_GOOD\_ON (5Eh) threshold and a successful InTune calibration has completed. If the output regulation voltage falls below the POWER\_GOOD\_OFF (5Fh) threshold, PG will be deasserted.

## PMBus Digital Interface

The MAX15301 is a PMBus-compatible device that includes many of the standard PMBus commands. A PMBus 1.2-compliant device uses the System Management Bus (SMBus) version 2.0 for transport protocol and responds to the SMBus slave address. In this data sheet, the term SMBus is used to refer to the electrical characteristics of the PMBus communication using the

SMBus physical layer. The term PMBus is used to refer to the PMBus command protocol.

The MAX15301 employs six standard SMBus protocols (Write Byte, Read Byte, Write Word, Read Word, Write Block, and Read Block) to program output voltage and warning/faults thresholds, read monitored data, and provide access to all manufacturer-specific commands.

The MAX15301 also supports the group command. The group command is used to send commands to more than one PMBus device. It is not required that all the devices receive the same command. However, no more than one command can be sent to any one device in one group command packet. The group command must not be used with commands that require the receiving device to respond with data, such as the STATUS\_BYTE command. When the MAX15301 receives a command through this protocol, it begins execution immediately of the received command after detecting the STOP condition.

When the data word is transmitted, the lower order byte is sent first and the higher order byte is sent last. Within any byte, the most significant bit (MSB) is sent first and the least significant bit (LSB) is sent last.

Contact the factory for detailed PMBus command support.

## Supported PMBus Commands

The MAX15301 supports the standard PMBus commands given in [Table 7](#). Contact Maxim for an application note that describes all MAX15301 PMBus command functionality in detail.

A single pair of pullup resistors (one each for SCL and SDA) is required for each shared bus as shown in [Figure 8](#). Consult the SMBus 2.0 specifications as well as the guaranteed drive capability of SDA in the [Electrical Characteristics](#) table to determine the value of the pullup resistors.

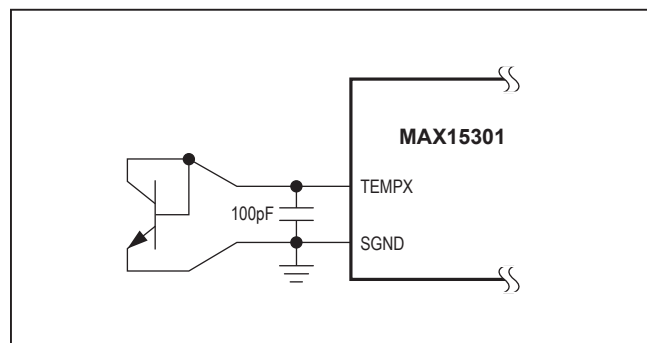


Figure 7. Temperature Sensing with a 2N3904 npn Transistor

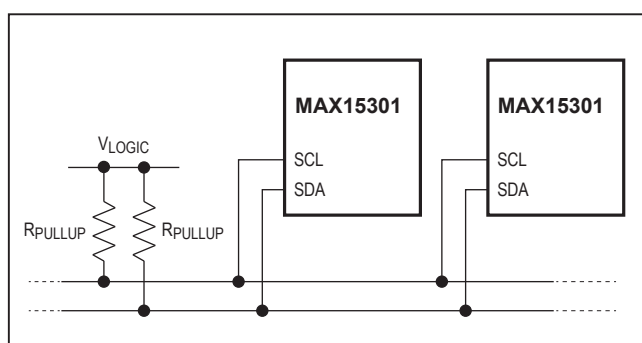


Figure 8. SMBus Multidevice Configuration

**Table 7. PMBus Command Summary**

| COMMAND CODE | COMMAND NAME           | SMBus TRANSFER TYPE | # OF DATA BYTES | MIN | MAX  | DEFAULT VALUE              | UNITS |
|--------------|------------------------|---------------------|-----------------|-----|------|----------------------------|-------|
| 0x01         | OPERATION              | R/W Byte            | 1               | —   | —    | 0x40                       | —     |
| 0x02         | ON_OFF_CONFIG          | R/W Byte            | 1               | —   | —    | 0x16                       | —     |
| 0x03         | CLEAR_FAULTS           | Send Byte           | 0               | —   | —    | —                          | —     |
| 0x10         | WRITE_PROTECT          | R/W Byte            | 1               | —   | —    | 0                          | —     |
| 0x11         | STORE_DEFAULT_ALL      | Send Byte           | 0               | —   | —    | —                          | —     |
| 0x12         | RESTORE_DEFAULT_ALL    | Write Byte          | 0               | —   | —    | —                          | —     |
| 0x15         | STORE_USER_ALL         | Send Byte           | 0               | —   | —    | —                          | —     |
| 0x16         | RESTORE_USER_ALL       | Write Byte          | 0               | —   | —    | —                          | —     |
| 0x19         | CAPABILITY             | Read Byte           | 1               | —   | —    | 0xA0                       | —     |
| 0x20         | VOUT_MODE              | Read Byte           | 1               | —   | —    | 0x14                       | —     |
| 0x21         | VOUT_COMMAND           | R/W Word            | 2               | 0.5 | 5.25 | SET pin resistor setting   | V     |
| 0x22         | VOUT_TRIM              | R/W Word            | 2               | —   | —    | 0                          | V     |
| 0x23         | VOUT_CAL_OFFSET        | R/W Word            | 2               | —   | —    | 0                          | V     |
| 0x24         | VOUT_MAX               | R/W Word            | 2               | —   | —    | VOUT_COMMAND + 10%         | V     |
| 0x25         | VOUT_MARGIN_HIGH       | R/W Word            | 2               | —   | —    | VOUT_COMMAND + 5%          | V     |
| 0x26         | VOUT_MARGIN_LOW        | R/W Word            | 2               | —   | —    | VOUT_COMMAND - 5%          | V     |
| 0x27         | VOUT_TRANSITION_RATE   | R/W Word            | 2               | —   | —    | 0.1                        | mV/μs |
| 0x28         | VOUT_DROOP             | R/W Word            | 2               | —   | —    | 0                          | mΩ    |
| 0x33         | FREQUENCY_SWITCH       | R/W Word            | 2               | 300 | 1000 | SYNC pin resistor setting  | kHz   |
| 0x35         | VIN_ON                 | R/W Word            | 2               | 4   | 12   | 6                          | V     |
| 0x36         | VIN_OFF                | R/W Word            | 2               | 4   | 12   | 5.5                        | V     |
| 0x37         | INTERLEAVE             | R/W Word            | 2               | —   | —    | See Table 2                | —     |
| 0x38         | IOUT_CAL_GAIN          | R/W Word            | 2               | —   | —    | ADDR1 pin resistor setting | mΩ    |
| 0x39         | IOUT_CAL_OFFSET        | R/W Word            | 2               | —   | —    | 0                          | A     |
| 0x40         | VOUT_OV_FAULT_LIMIT    | R/W Word            | 2               | —   | —    | VOUT_COMMAND + 15%         | V     |
| 0x41         | VOUT_OV_FAULT_RESPONSE | R/W Byte            | 1               | —   | —    | 0x80                       | —     |
| 0x44         | VOUT_UV_FAULT_LIMIT    | R/W Word            | 2               | —   | —    | VOUT_COMMAND - 15%         | V     |
| 0x45         | VOUT_UV_FAULT_RESPONSE | R/W Byte            | 1               | —   | —    | 0x00                       | —     |
| 0x46         | IOUT_OC_FAULT_LIMIT    | R/W Word            | 2               | —   | —    | 25                         | A     |
| 0x47         | IOUT_OC_FAULT_RESPONSE | R/W Byte            | 1               | —   | —    | 0xBF                       | —     |
| 0x4F         | OT_FAULT_LIMIT         | R/W Word            | 2               | —   | —    | 115                        | °C    |
| 0x50         | OT_FAULT_RESPONSE      | R/W Byte            | 1               | —   | —    | 0xC0                       | —     |
| 0x51         | OT_WARN_LIMIT          | R/W Word            | 2               | —   | —    | 95                         | °C    |

**Table 7. PMBus Command Summary (continued)**

| COMMAND CODE | COMMAND NAME          | SMBus TRANSFER TYPE | # OF DATA BYTES | MIN | MAX | DEFAULT VALUE       | UNITS |
|--------------|-----------------------|---------------------|-----------------|-----|-----|---------------------|-------|
| 0x55         | VIN_OV_FAULT_LIMIT    | R/W Word            | 2               | —   | —   | 14                  | V     |
| 0x56         | VIN_OV_FAULT_RESPONSE | R/W Byte            | 1               | —   | —   | 0xC0                | —     |
| 0x59         | VIN_UV_FAULT_LIMIT    | R/W Word            | 2               | —   | —   | 4.2                 | V     |
| 0x5A         | VIN_UV_FAULT_RESPONSE | R/W Byte            | 1               | —   | —   | 0xC0                | —     |
| 0x5E         | POWER_GOOD_ON         | R/W Word            | 2               | —   | —   | VOUT_COMMAND - 10%  | V     |
| 0x5F         | POWER_GOOD_OFF        | R/W Word            | 2               | —   | —   | VOUT_COMMAND - 15%  | V     |
| 0x60         | TON_DELAY             | R/W Word            | 2               | —   | —   | 5                   | ms    |
| 0x61         | TON_RISE              | R/W Word            | 2               | —   | —   | 5                   | ms    |
| 0x64         | TOFF_DELAY            | R/W Word            | 2               | —   | —   | 1                   | ms    |
| 0x65         | TOFF_FALL             | R/W Word            | 2               | —   | —   | 5                   | ms    |
| 0x78         | STATUS_BYTE           | Read Byte           | 1               | —   | —   | —                   | —     |
| 0x79         | STATUS_WORD           | Read Word           | 2               | —   | —   | —                   | —     |
| 0x7A         | STATUS_VOUT           | Read Byte           | 1               | —   | —   | —                   | —     |
| 0x7B         | STATUS_IOUT           | Read Byte           | 1               | —   | —   | —                   | —     |
| 0x7C         | STATUS_INPUT          | Read Byte           | 1               | —   | —   | —                   | —     |
| 0x7D         | STATUS_TEMPERATURE    | Read Byte           | 1               | —   | —   | —                   | —     |
| 0x7E         | STATUS_CML            | Read Byte           | 1               | —   | —   | —                   | —     |
| 0x88         | READ_VIN              | Read Word           | 2               | —   | —   | —                   | V     |
| 0x8B         | READ_VOUT             | Read Word           | 2               | —   | —   | —                   | V     |
| 0x8C         | READ_IOUT             | Read Word           | 2               | —   | —   | —                   | A     |
| 0x8D         | READ_TEMPERATURE_1    | Read Word           | 2               | —   | —   | —                   | °C    |
| 0x8E         | READ_TEMPERATURE_2    | Read Word           | 2               | —   | —   | —                   | °C    |
| 0x94         | READ_DUTY_CYCLE       | Read Word           | 2               | —   | —   | —                   | %     |
| 0x95         | READ_FREQUENCY        | Read Word           | 2               | —   | —   | —                   | kHz   |
| 0x98         | PMBUS_REVISION        | Read Byte           | 1               | —   | —   | —                   | —     |
| 0x99         | MFR_ID                | R/W Block           | 8               | —   | —   | null                | —     |
| 0x9A         | MFR_MODEL             | R/W Block           | 13              | —   | —   | null                | —     |
| 0x9B         | MFR_REVISION          | R/W Block           | 7               | —   | —   | null                | —     |
| 0x9C         | MFR_LOCATION          | R/W Block           | 8               | —   | —   | null                | —     |
| 0x9D         | MFR_DATE              | R/W Block           | 6               | —   | —   | null                | —     |
| 0x9E         | MFR_SERIAL            | R/W Block           | 13              | —   | —   | null                | —     |
| 0xAD         | IC_DEVICE_ID          | Read Block          | 8               | —   | —   | "MAX15301"          | —     |
| 0xAE         | IC_DEVICE_REV         | Read Word           | 8               | —   | —   | <firmware revision> | —     |

| COMMAND CODE | COMMAND NAME      | SMBus TRANSFER TYPE | # OF DATA BYTES | MIN | MAX | DEFAULT VALUE     | UNITS |
|--------------|-------------------|---------------------|-----------------|-----|-----|-------------------|-------|
| 0xD0         | ADAPTIVE_MODE     | Write Byte          | 2               | —   | —   | 0x024B            | —     |
| 0xD3         | FEEDBACK_EFFORT   | R/W Word            | 2               | —   | —   | 0.5               | —     |
| 0xD5         | LOOP_CONFIG       | R/W Word            | 2               | —   | —   | 0x0100            | —     |
| 0xDB         | COMP_MODEL        | R/W Block           | 6               | —   | —   | 0.03167, 0.5, 0.5 | —     |
| 0xE0         | MANUF_CONF        | R/W Block           | 32              | —   | —   | 0                 | —     |
| 0xE1         | MANUF_LOCK        | R/W Byte            | 2               | —   | —   | 0                 | —     |
| 0xE2         | MANUF_PASSWD      | R/W Word            | 2               | —   | —   | —                 | —     |
| 0xE3         | USER_CONF         | R/W Block           | 32              | —   | —   | 0                 | —     |
| 0xE4         | USER_LOCK         | R/W Byte            | 2               | —   | —   | 0                 | —     |
| 0xE5         | USER_PASSWD       | R/W Word            | 2               | —   | —   | 0                 | —     |
| 0xE6         | SECURITY_LEVEL    | Read Byte           | 1               | —   | —   | 0                 | —     |
| 0xE7         | DEADTIME_GCTRL    | R/W Block           | 19              | —   | —   | —                 | —     |
| 0xE8         | ZETAP             | R/W Word            | 2               | —   | —   | 1.5               | —     |
| 0xEA         | RESTORE_MAXIM_ALL | R/W Byte            | 0               | —   | —   | —                 | —     |
| 0xF8         | EXT_TEMP_CAL      | R/W Block           | 4               | —   | —   | 1.004363, 0       | —     |

## Design Procedure

### Switching Frequency Selection

The first step in selecting a buck controller's output filter is to select the desired switching frequency ( $f_{SW}$ ) for the PWM. The MAX15301 will switch at frequencies in the range of  $300\text{kHz} \leq f_{SW} \leq 1\text{MHz}$ . Select a low frequency for higher efficiency. Use a higher frequency to reduce the size of the external filter components and to improve transient response. Also consider system frequency requirements when choosing  $f_{SW}$ , such that the harmonics of the switching frequencies do not interfere with the system operation. The switching frequency for the MAX15301 is set by the SYNC pin connection per [Table 3](#). The switching frequency can be changed via the `FREQUENCY_SWITCH` PMBus command at anytime the controller is disabled. The selection of 600kHz provides a good balance of efficiency, small size, and good transient response.

### Inductor Selection

Three key inductor parameters must be specified to select an inductor for operation with the MAX15301: inductance

value ( $L$ ), inductor saturation current ( $I_{SAT}$ ), and maximum DC resistance (DCR).

- 1) Inductor value selection: For automatic compensation using InTune technology, the inductor is selected such that the peak-to-peak inductor ripple current (LIR) is 20% to 40% of the maximum operating current ( $I_{OUTMAX}$ ). Using a low LIR ratio (higher inductor value) will result in higher DC resistance in the inductor and will reduce efficiency. Using a high value of LIR will increase the RMS current which will also decrease efficiency. Maxim recommends 30% for a peak-to-peak ripple to maximum operating current ratio ( $LIR = 0.3$ ).

The nominal inductor value can now be calculated using LIR,  $f_{SW}$ ,  $V_{IN}$ ,  $V_{OUT}$ , and  $I_{OUTMAX}$  (the maximum DC load current) using the following equation:

$$L = \frac{V_{OUT}(V_{IN} - V_{OUT})}{V_{IN} f_{SW} I_{OUT} LIR}$$

$$0.2 \leq LIR \leq 0.4$$



The exact inductor value in this range is not critical and can be adjusted to make trade-offs among size, cost, and efficiency. A higher inductance can increase efficiency by reducing the RMS current. Lower inductor values minimize size and cost. Lower inductor values may also improve transient response but reduce efficiency due to higher peak currents.

- 2) The selected inductor's saturation current rating ( $I_{SAT}$ ) must exceed the user-defined current limit.  $I_{SAT}$  should generally be selected such that it is greater than  $I_{LIM} + LIR/2 + 10\%$  to provide adequate margin in the event of a large load transient. It is important to select an inductor that has a high enough  $I_{SAT}$  to satisfy this requirement though this parameter typically forces a certain dimension of inductor to be used.
- 3) Finally, the user should select an inductor with minimal DCR (DC series resistance) to reduce overall losses in efficiency.

### Output Capacitor Selection

The MAX15301 has been optimized to operate with low-ESR output capacitors. High-ESR capacitors can be added, but would provide little benefit to system performance. The output capacitor requirement is dependent upon two considerations:

- 1) Low output ripple voltage
- 2) Load current transient envelope

Low ripple voltage is easily achieved with an all-ceramic output capacitor. When all-ceramic output capacitors are used, load current transient envelope is the primary concern for capacitor selection. Designs with little load transients can use fewer capacitors and designs with more dynamic load content will require more load capacitors to reduce output "sag" and "soar."

To achieve low ripple voltage, the output capacitor bank must have a small ESR value. To calculate the maximum allowable ESR, start with the maximum desired output ripple voltage (typically 0.5% to 1% of  $V_{OUT}$ ) and calculate the maximum ESR using the LIR value from above.

$$ESR = \frac{V_{RIPPLE}}{I_{OUTMAX} \times LIR}$$

An ESR on the order of  $1m\Omega$  is typically required. The use of two or more  $100\mu F$  ceramic capacitors in parallel is typically sufficient to achieve a good ripple voltage.

To meet load current transient envelope requirements, the MAX15301 compensates for output filters with natural (resonant) frequencies  $f_{LC}$  such that the following is met:

$$25 \leq \frac{f_{SW}}{f_{LC}} \leq 70$$

where:

$$f_{LC} \doteq 1 / (2\pi\sqrt{LC})$$

Therefore:

$$\frac{1}{L} \left( \frac{25}{2\pi f_{SW}} \right)^2 \leq C \leq \frac{1}{L} \left( \frac{70}{2\pi f_{SW}} \right)^2$$

Most 600kHz PoL designs (10A to 25A) are satisfied using between  $200\mu F$  to  $1000\mu F$  of ceramic output capacitance and no additional electrolytic capacitors. The InTune adaptive compensation permits a very large range of output decoupling capacitances. Output capacitances resulting in  $f_{SW}/f_{LC}$  ratios greater than 60 are acceptable. This capability is important in module applications where the output capacitance may be unknown or not well controlled.

In general, smaller output voltage deviation is achieved by using greater capacitance.

### Input Capacitor Selection

The input filter capacitor reduces peak current drawn from the power source and reduces noise and voltage ripple on the input caused by the switching circuitry. The value of the input capacitor is selected to limit the ripple voltage ( $\delta V$ ) as follows:

$$C_{IN} \geq \frac{I_{OUT} \times \frac{V_{OUT}}{V_{IN}} \times \left( 1 - \frac{V_{OUT}}{V_{IN}} \right)}{f_{SW} \times \Delta V}$$

where  $\Delta V$  is the input ripple voltage. This calculation assumes there is measurable inductance back to the original  $V_{IN}$  source thus this calculation provides low source impedance at the input of the DC-DC converter. The capacitance requirement is greatest when the duty cycle is 50% and decreases as duty cycle increases (i.e. input voltage increases).

The input capacitor must meet the ripple current requirement ( $I_{RMS}$ ) imposed by the switching currents as defined by the following equation:

$$I_{RMS} = I_{LOAD(MAX)} \frac{\sqrt{V_{OUT}(V_{IN} - V_{OUT})}}{V_{IN}}$$

$I_{RMS}$  attains a maximum value when the input voltage equals twice the output voltage ( $V_{IN} = 2V_{OUT}$ ),

so  $I_{RMS(MAX)} = I_{LOAD(MAX)}/2$ . For most applications, nontantalum capacitors (ceramic, aluminum, polymer, or OS-CON) are preferred at the inputs due to the robustness of non-tantalum capacitors to accommodate high inrush currents of systems being powered from very low impedance sources. Additionally, two (or more) smaller-value low-ESR capacitors should be connected in parallel to reduce high-frequency noise.

### MOSFET Selection

The following guidelines address the challenge of selecting the appropriate MOSFETs for high-current application. The high-side MOSFET ( $Q_H$ ) must be able to dissipate the resistive losses plus the switching losses at both  $V_{IN(MIN)}$  and  $V_{IN(MAX)}$ . Calculate both these sums. Ideally, the losses at  $V_{IN(MIN)}$  should be roughly equal to losses at  $V_{IN(MAX)}$ , with lower losses in between. If the losses at  $V_{IN(MIN)}$  are significantly higher than the losses at  $V_{IN(MAX)}$ , consider increasing the size of  $Q_H$  (reducing  $R_{DS(ON)}$  but increasing  $C_{GATE}$ ). Conversely, if the losses at  $V_{IN(MAX)}$  are significantly higher than the losses at  $V_{IN(MIN)}$ , consider reducing the size of  $Q_H$  (increasing  $R_{DS(ON)}$  but reducing  $C_{GATE}$ ). If input voltage does not vary over a wide range, the minimum power dissipation occurs where the resistive losses equal the switching losses. Choose a low-side MOSFET that has the lowest possible on-resistance ( $R_{DS(ON)}$ ), comes in a moderate-sized package, and is reasonably priced. Ensure that the DL gate driver can supply sufficient current to support the gate charge and the current injected into the parasitic gate-to-drain capacitor caused by the high-side MOSFET turning on; otherwise, cross-conduction problems can occur.

### MOSFET Power Dissipation

Worst-case conduction losses occur at the duty cycle extremes. For the high-side MOSFET ( $Q_H$ ), the worst-case conduction losses occur at the minimum input voltage:

$$P_{Q_H-COND} = \frac{V_{OUT}}{V_{IN(MIN)}} \times I_{OUT}^2 \times R_{DS(ON)}$$

Generally, a small high-side MOSFET is desired to reduce switching losses at high input voltages. However, the  $R_{DS(ON)}$  required to stay within package-power dissipation often limits how small the MOSFETs can be. Again, the optimum occurs when the switching losses equal the conduction ( $R_{DS(ON)}$ ) losses.

Calculating the power dissipation in high-side MOSFETs ( $NH$ ) due to switching losses is difficult since it must allow for difficult quantifying factors that influence the turn-on and turn-off times. These factors include the internal gate resistance, gate charge, threshold voltage, source inductance, and PCB layout characteristics.

The following switching-loss calculation provides only a very rough estimate and is no substitute for prototype evaluation, preferably including verification using a thermocouple mounted on  $Q_H$ :

$$P_{Q_H-SW} = \left( \frac{1}{2} \times \frac{V_{IN(MAX)} I_{LOAD} f_{SW} Q_G}{I_{SWH-SOURCE}} \right) + \left( \frac{1}{2} \times \frac{V_{IN(MAX)} I_{LOAD} f_{SW} Q_{G(SW)}}{I_{SWH-SINK}} \right) + \left( \frac{C_{OSS} V_{IN(MAX)}^2 f_{SW}}{2} \right)$$

where  $C_{OSS}$  is the  $Q_H$  MOSFET's output capacitance,  $Q_{G(SW)}$  is the charge needed to turn on the high-side MOSFET,  $I_{DH-SOURCE}$  is the peak gate-drive source current (2A typ), and  $I_{DH-SINK}$  is the peak gate-drive sink current (4A typ).

Switching losses in the high-side MOSFET can become an insidious heat problem when the maximum input voltage is applied due to the squared term in the switching-loss equation above. If the high-side MOSFET chosen for adequate  $R_{DS(ON)}$  at low input voltages becomes extraordinarily hot when biased from  $V_{IN(MAX)}$ , consider choosing another MOSFET with lower parasitic capacitance.

For the low-side MOSFET ( $Q_L$ ), the worst-case power dissipation always occurs at the maximum input voltage and is due primarily to conduction losses. Switching losses in the low-side FET are minimal because it is turned on and off when the body diode is conducting and hence under zero-voltage conditions.

$$P_{Q_L-COND} = \left( 1 - \frac{V_{OUT}}{V_{IN(MAX)}} \right) \times I_{OUT}^2 \times R_{DS(ON)}$$

The worst case for MOSFET power dissipation occurs under heavy load conditions that are greater than  $I_{OUT(MAX)}$ , but are not quite high enough to exceed the current limit and cause the fault latch to trip. The MOSFETs must have a good-sized heatsink to handle the overload power dissipation. The heatsink can be a large copper field on the PCB or an externally mounted device.

### Avoiding dV/dt Turn-On of the Low-Side MOSFET

At high input voltages, fast turn-on of the high-side MOSFET can momentarily turn on the low-side MOSFET due to the high dV/dt appearing at the drain of the low-side MOSFET. The high dV/dt causes a current flow through



the Miller capacitance ( $C_{RSS}$ ) and the input capacitance ( $C_{ISS}$ ) of the low-side MOSFET. Improper selection of the low-side MOSFET that results in a high ratio of  $C_{RSS}/C_{ISS}$  makes the problem more severe. To avoid this problem, minimize the ratio of  $C_{RSS}/C_{ISS}$  when selecting the low-side MOSFET. Adding a  $1\Omega$  to  $4.7\Omega$  resistor in series with the high-side MOSFET gate can slow the high-side MOSFET turn-on. Similarly, adding a small capacitor from the gate to the source of the high-side MOSFET has the same effect. However, both methods work at the expense of increased switching losses (lower efficiency).

### Boost Capacitor

The MAX15301 uses a bootstrap circuit to generate the necessary gate-to-source voltage to turn on the high-side MOSFET. The selected n-channel high-side MOSFET determines the appropriate boost capacitance value ( $C_{BST}$  in the [Typical Operating Circuit](#)) according to the following equation:

$$C_{BST} = \frac{Q_G}{\Delta V_{BST}}$$

where  $Q_G$  is the total gate charge of the high-side MOSFET and  $\Delta V_{BST}$  is the voltage variation allowed on the high-side MOSFET driver after turn-on. Choose  $\Delta V_{BST}$  such that the available gate-drive voltage is not significantly degraded (e.g.  $\Delta V_{BST} = 100\text{mV}$  to  $300\text{mV}$ ) when determining  $C_{BST}$ .

For most applications, a  $0.22\mu\text{F}$  low-ESR ceramic capacitor will suffice.

### Current Sense

The MAX15301 uses lossless DCR current sensing to reduce the overall power dissipation and improve efficiency. Lossless sensing is configured by connecting a series RC circuit across the inductor as shown in [Figure 9](#). Select the resistor and capacitor such that their time constant is equal to that of the inductor and its DCR:

$$R_L C_L = \frac{L}{DCR}$$

Use the typical inductance and DCR values provided by the inductor manufacturer. Use high accuracy and low tempco C0G ceramic capacitors for  $C_L$ . The maximum sense voltage produced using lossless sensing is:

$$V_{DCRP} - V_{DCRN} = DCR \times I_{OUT(MAX)}$$

Carefully observe the PCB layout guidelines provided in the datasheet to ensure the noise and DC errors do

not corrupt the differential current-sense signals seen by DCRP and DCRN. Place the RC network close to the inductor and Kelvin sense the voltage across the capacitor.

### Current Limit

The MAX15301 provides current-fault protection utilizing inductor DCR current sense. A resistor connected to the ADDR1 input can be used to set the current-sense calibration resistance in the MAX15301 as shown in Table 4b. For coarse adjustment of the overcurrent protection using external pin resistances only, select the RADDR1 value that best satisfies the following relationship:

$$I_{OUT\_CAL\_GAIN} \geq DCR \times I_{OUT(MAX)} / 25A$$

Optionally, for best precision, set  $I_{OUT\_CAL\_GAIN}$  to match the actual inductor DCR and adjust the overcurrent fault threshold  $I_{OUT\_OC\_FAULT\_LIMIT}$  directly using PMBus commands.

### Output Voltage Remote Sensing

The MAX15301 uses two dedicated inputs (OUTP and OUTN) for the output differential voltage sensing to reduce the common-mode noise sensitivity. This sensing circuitry is part of the feedback loop. The output voltage is connected to the MAX15301 directly through these two inputs without the need for an external resistive divider. The PCB traces to the OUTP and OUTN pins should be routed as a differential pair to the desired regulation sense point to minimize noise induced in the sensed signal.

### BabyBuck Component Selection

The MAX15301 features an internal DC-DC switching regulator to power internal circuitry and provide the gate-drive voltage for the external MOSFETs. Competing parts

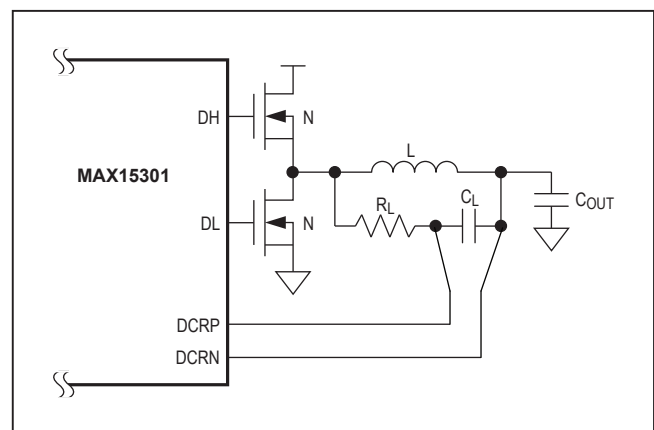


Figure 9. Lossless DCR Current Sensing

with internal driver circuits use linear regulators to provide these voltages which leads to significant efficiency loss when operating from an input voltage above ~6V. The patent-pending BabyBuck circuit improves overall efficiency in a typical application by more than 1% at full load and more than 10% in lightly loaded conditions.

The BabyBuck uses a tiny (1008-size) low current inductor connected across LBI and LBO (Figure 10). A

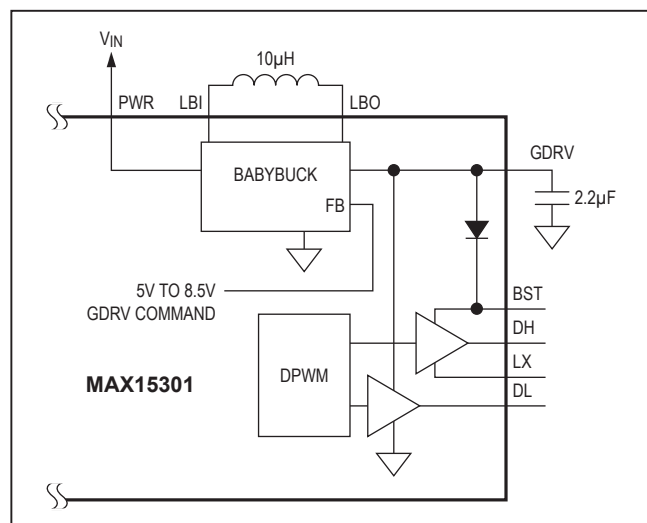


Figure 10. Gate Drivers Powered by Switching Regulator

10µH inductor with a saturation rating of at least 200mA and a 2.2µF ceramic capacitor at GDRV pin is recommended.

In addition to the efficiency improvement from using a DC-DC regulator to power the MOSFETs, the BabyBuck can vary the gate-drive voltage to improve the efficiency over different load current conditions. The variable gate-drive function can be disabled and the gate-drive voltage levels can be modified using PMBus commands.

For applications where efficiency is not critical, the inductor can be omitted and the BabyBuck automatically operates as a linear regulator (Figure 11). In this configuration, bypass GDRV to PGND with a 2.2µF ceramic capacitor and connect LBI to PWR through a 100kΩ resistor. The linear regulator can be bypassed altogether with an external power source. An external 5V to 9V supply can also be applied directly to the GDRV pin to power the gate drivers (Figure 12). Pull LBI up to PWR with a 2kΩ resistor and leave LBO unconnected to allow external gate drive supply.

## Design Examples

See Table 8 for the component values in the [Typical Operating Circuit](#). For additional examples and detailed layout information, refer to the MAX15301 evaluation kit.

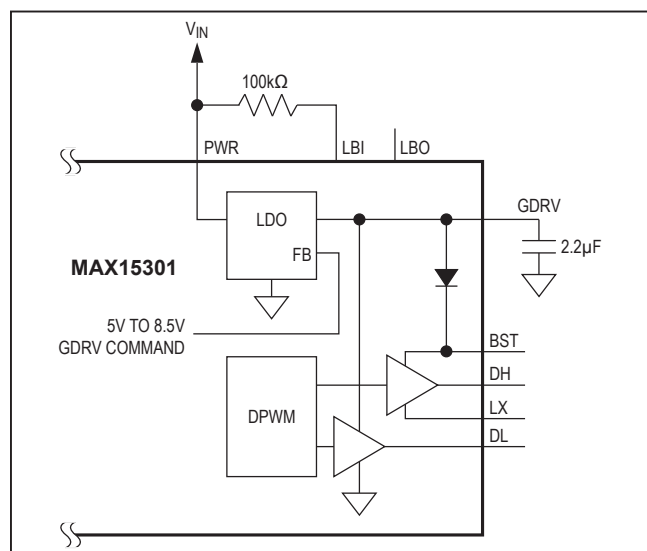


Figure 11. Gate Drivers Powered by Linear Regulator

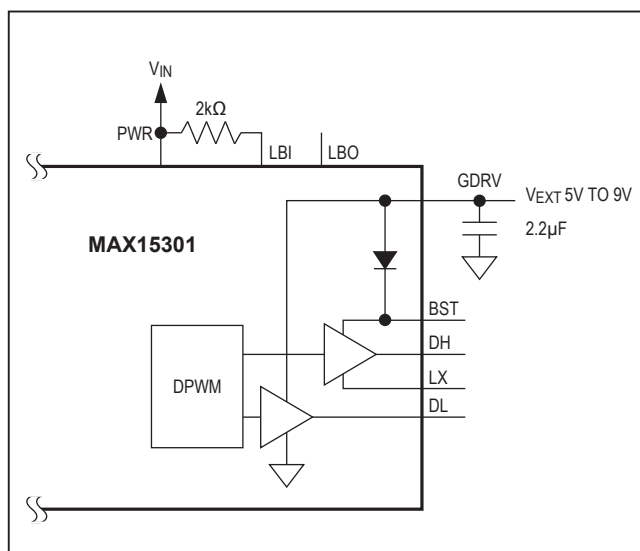


Figure 12. Gate Drivers Powered Externally

**Table 8. Typical Component Values**

| COMPONENT           | APPLICATION 1                              | APPLICATION 2                                  | APPLICATION 3                              |
|---------------------|--|--|--|
| Input Supply        | 12V  | 9V   | 12V  |
| Output Voltage      | 1.2V                                       | 0.9V   | 1.0V                                       |
| R <sub>SET</sub>    | 26.1kΩ                                     | 11.0kΩ   | 14.7kΩ                                     |
| Output Current      | 25A  | 8A   | 35A  |
| R <sub>ADDR1</sub>  | 0Ω to 8.4kΩ                                | 21.2kΩ to 44.7kΩ                               | 0Ω to 8.4kΩ                                |
| R <sub>ADDR0</sub>  | User defined<br>(see Table 4a)             | User defined<br>(see Table 4a)                 | User defined<br>(see Table 4a)             |
| Switching Frequency | 600kHz                                     | 450kHz   | 850kHz                                     |
| R <sub>SYNC</sub>   | 12.7kΩ                                     | 8.25kΩ   | 31.6kΩ                                     |
| Inductor L1         | Würth 744308033, 330nH,<br>370μΩ           | Coilcraft XAL7030-601ME_,<br>600nH, 3mΩ        | Coilcraft SLC1049-125                      |
| Inductor L2         | TDK NLCV25T-100K-PF, 10μH                  | TDK NLCV25T-100K-PF, 10μH                      | TDK NLCV25T-100K-PF, 10μH                  |
| R <sub>FILTER</sub> | 665Ω                                       | 9.09kΩ   | 2.10kΩ                                     |
| C <sub>FILTER</sub> | 1μF  | 0.22μF   | 0.22μF                                     |
| High-Side MOSFET    | Infineon BSC032NE2LS,<br>3.2mΩ (5mm x 6mm) | Infineon BSZ060NE2LS,<br>6.5mΩ (3.3mm x 3.3mm) | Infineon BSC032NE2LS,<br>3.2mΩ (5mm x 6mm) |
| Low-Side MOSFET     | Infineon BSC010NE2LS,<br>1.0mΩ (5mm x 6mm) | Infineon BSZ018NE2LS,<br>1.8mΩ (3.3mm x 3.3mm) | Infineon BSC010NE2LS,<br>1.0mΩ (5mm x 6mm) |
| Output Capacitance  | 6 x 100μF, X5R, 1206, 6.3V                 | 2 x 100μF, X5R, 1206, 6.3V                     | 10 x 100μF, X5R, 1206, 6.3V                |
| Input Capacitance   | 3 x 47μF, X5R, 1210, 16V                   | 1 x 47μF, X5R, 1210, 16V                       | 4 x 47μF, X5R, 1210, 16V                   |

## Applications Information

### PCB Layout Guidelines

Careful PCB layout is critical to achieve clean and stable operation. The switching power stage requires particular attention. Follow these guidelines for best thermal performance and signal integrity:

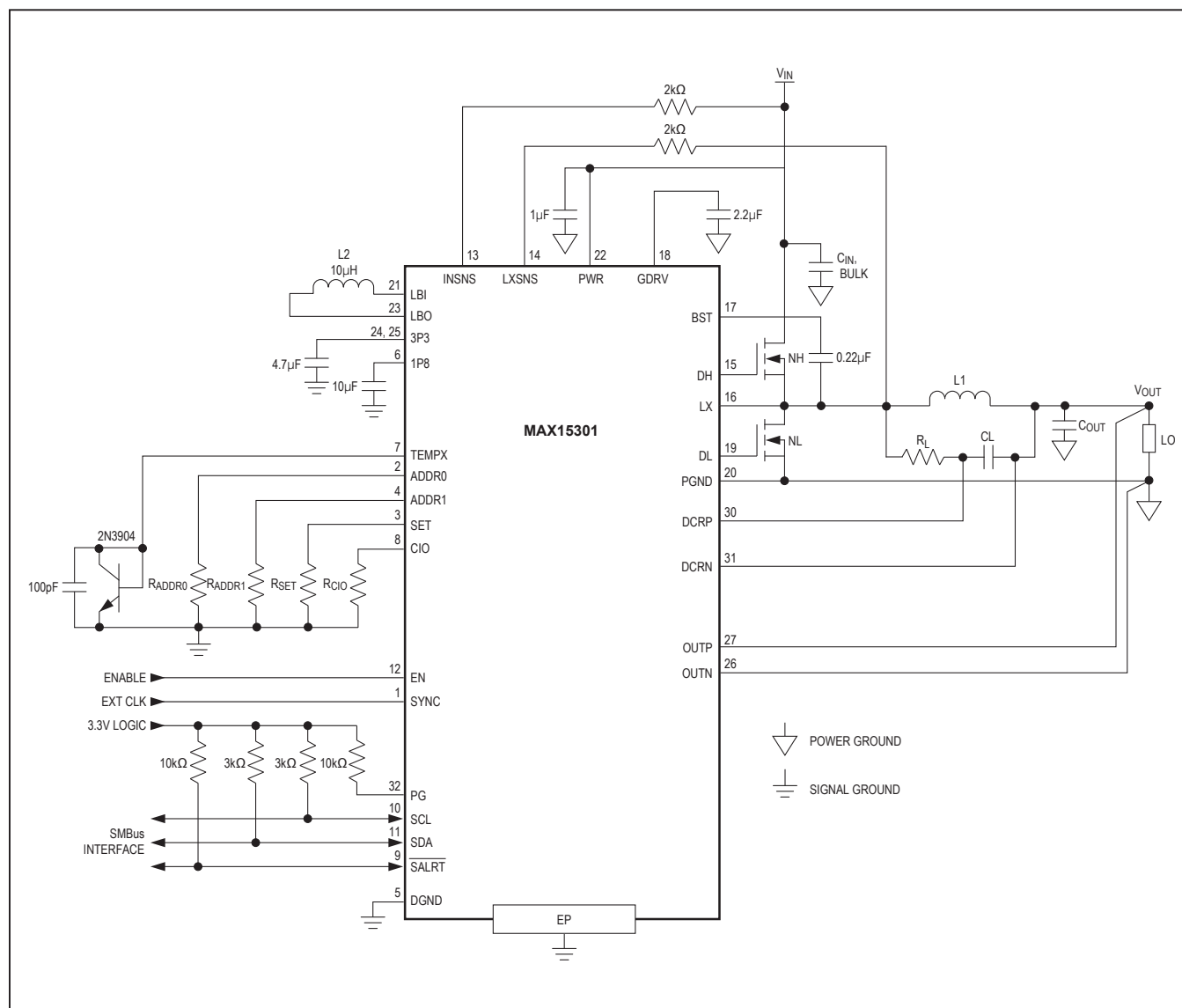
- 1) When using a resistor to set a command value, connect its return terminal to SGND.
- 2) Connect the power ground plane (connected to PGND), digital return (connected to DGND), and analog ground plane (SGND) at one point near the device.
- 3) Bypass GDRV to PGND, 3P3 to SGND, and 1P8 to DGND with ceramic decoupling capacitors. Place the capacitors as close as possible to the pins.
- 4) Minimize the length of the high-current loop from the input capacitor, the high-side switching MOSFET, and the low-side MOSFET back to the input-capacitor negative terminal.
- 5) Provide enough copper area at and around the switching MOSFETs and inductors to aid in thermal dissipation. Maintain a good balance between the LX copper area for thermal performance and electromagnetic radiation.
- 6) Route high-speed switching nodes (BST, LX, DH, and DL) away from sensitive sense inputs (OUTP, OUTN, DCRP, and DCRN).
- 7) Route the DCRP, DCRN and OUTP, OUTN traces as differential pairs.
- 8) Connect PGND of the MAX15301 as close as possible to the source of the low-side MOSFET.

### Thermal Layout

The MAX15301 is available in a small 5mm x 5mm TQFN package with exposed pad to remove heat from the internal semiconductor junctions. The exposed pad must be soldered to the copper on the PCB directly underneath

the device package reducing the  $\theta_{JA}$  down to approximately 40°C/W. The MAX15301 will shut down if its temperature increases beyond +115°C. (This threshold can be changed using a PMBus command). An evaluation kit is available that demonstrates the recommended layout practices for the MAX15301.

### Typical Operating Circuit



## Ordering Information

| PART            | TEMP RANGE     | PIN-PACKAGE | FIRMWARE |
|-----------------|----------------|-------------|----------|
| MAX15301AA01+CK | -40°C to +85°C | 32 TQFN-EP* | 4018     |

+Denotes lead(Pb)-free/RoHS-compliant package.

\*EP = Exposed paddle.

## Chip Information

PROCESS: BICMOS

## Package Information

For the latest package outline information and land patterns (footprints), go to [www.maximintegrated.com/packages](http://www.maximintegrated.com/packages). Note that a "+", "#", or "-" in the package code indicates RoHS status only. Package drawings may show a different suffix character, but the drawing pertains to the package regardless of RoHS status.

| PACKAGE TYPE | PACKAGE CODE | OUTLINE NO.             | LAND PATTERN NO.        |
|--------------|--------------|-------------------------|-------------------------|
| 32 TQFN-EP   | T3255M+51    | <a href="#">21-0140</a> | <a href="#">90-0013</a> |

## Revision History

| REVISION<br>NUMBER | REVISION<br>DATE | DESCRIPTION  | PAGES<br>CHANGED                        |
|--------------------|------------------|--|---|
| 0                  | 4/12             | Initial release  | —                                       |
| 1                  | 11/12            | Updated data sheet to reflect performance and operation of current silicon   | 1–35                                    |
| 2                  | 3/13             | Removed the current sharing function to be compliant with latest firmware; in the <i>Electrical Characteristics</i> table: changed the Power-Good Threshold parameter from 90%V <sub>OUT</sub> (typ) to 95%V <sub>OUT</sub> (typ), changed V <sub>GDRV</sub> from 4.2V(min) and 9.0V(max) to 5.2V(min) and 8.5V(max), and updated the PMBus/I <sup>2</sup> C parameters; updated Figures 1, 8, and 9, Tables 9 and 10, the <i>External Synchronization</i> section, and the <i>Typical Operating Circuit</i> | 1–5, 7, 10, 11,<br>12, 14,<br>16–24, 31 |
| 3                  | 11/13            | Rewrote and updated specifications to reflect production firmware (version 4018) functionality and features  | All                                     |

For pricing, delivery, and ordering information, please contact Maxim Direct at 1-888-629-4642, or visit Maxim Integrated's website at [www.maximintegrated.com](http://www.maximintegrated.com).

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