High Efficiency Switching Mode Battery Charger

General Description

The RT9538 is a PWM switch mode battery charger controller to fast charge single or multiple Li-ion, NiMH and NiCd batteries, using constant current or constant voltage control. Maximum current can be easily adjusted by an external resistor. The constant voltage output can support up to 30V with 0.5% accuracy.

A third control loop limits the input current drawing from the adapter during charging. This allows simultaneous operation of the equipment and fast battery charging without over loading to the adapter.

The RT9538 can charge batteries from 2.5V to 25V with dropout voltage as low as 2V. A diode is not required in series with the battery because the charger automatically enters a 10μA sleep mode when the adapter is unplugged.

A logic output indicates Li-ion full charge when current drops to 20% of the full-scale adjusted charge current.

Marking Information

1C= : Product Code
YMDNN : Date Code

Features

- Fast Charging for Li-ion, NiMH and NiCd Batteries
- Adjustable Battery Voltages from 2.5V to 25V
- High Efficiency: Up to 95%
- Charging Current Adjusted by Resistor
- Precision 0.5% Charging Voltage Accuracy
- Provide 5% Charging Current Accuracy
- Input Current Limit Maximizes Charging Rate
- 475kHz Switching Frequency
- Flag Indicates Li-ion Charge Completion
- Auto Shutdown with Adapter Removal
- Only 10μA Battery Drain When Idle
- Available in an 16-Lead WQFN Package
- RoHS Compliant and Halogen Free

Applications

- Notebook Computers
- Portable Instruments
- Chargers for Li-ion, NiMH, NiCd and Lead Acid
- Rechargeable Batteries

Simplified Application Circuit
**Functional Pin Description**

<table>
<thead>
<tr>
<th>Pin No.</th>
<th>Pin Name</th>
<th>Pin Function</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>ACN</td>
<td>Negative Terminal to Sense Input Current. A 0.1μF ceramic capacitor is placed from ACN to ACP to provide differential-mode filtering the switching noise.</td>
</tr>
<tr>
<td>2</td>
<td>ACP</td>
<td>Positive Terminal to Sense Input Current.</td>
</tr>
<tr>
<td>3</td>
<td>ISET</td>
<td>Charge Current Setting and System Loop Compensation Pin. Connect a resistor from this pin to ground to set the charge current. A capacitor of at least 0.1μF to GND filters out the current ripple.</td>
</tr>
<tr>
<td>4</td>
<td>VC</td>
<td>Control Signal of the Inner Loop of the Current Mode PWM. It provides the loop compensation and soft-start.</td>
</tr>
<tr>
<td>5</td>
<td>VFB</td>
<td>Charge Voltage Analog Feedback Adjustment. Connect a resistor divider from output to VFB to GND to adjust the output voltage. The internal regulation limit is 2.5V.</td>
</tr>
<tr>
<td>6</td>
<td>BATT</td>
<td>Battery Voltage Sense Input. A 10μF or larger X5R ceramic capacitor is recommended for filtering charge current ripple and stability purpose.</td>
</tr>
<tr>
<td>7</td>
<td>SNSL</td>
<td>Negative Terminal for Sensing Charge Current. A 0.1μF ceramic capacitor is placed from SRN to SRP to provide differential-mode filtering.</td>
</tr>
<tr>
<td>8</td>
<td>SNSH</td>
<td>Positive Terminal for Sensing Charge Current.</td>
</tr>
<tr>
<td>9</td>
<td>STATUS</td>
<td>Flag to Indicate Charge Completion. It turns to logic high when the charge current drops below 20% of the setting charge current. A 0.1μF capacitor from STATUS to ground is needed to filter the sampled charge current ripple.</td>
</tr>
<tr>
<td>10</td>
<td>SW</td>
<td>Switch Node. This pin switches between ground and VIN with high dv/dt rates. Care needs to be taken in the PCB layout to keep this node from coupling to other sensitive nodes.</td>
</tr>
<tr>
<td>11</td>
<td>TG</td>
<td>Gate Driver Output for the External N-MOSFET.</td>
</tr>
<tr>
<td>12</td>
<td>BOOT</td>
<td>Bootstrap for High-Side Gate Driver. In normal operation, ( V_{BOOT} = V_{SW} + 5V ).</td>
</tr>
<tr>
<td>13</td>
<td>V5V</td>
<td>Output of Internal 5V LDO. Connect a 1μF ceramic capacitor from this pin to GND for stability.</td>
</tr>
</tbody>
</table>

**Note:**
- RoHS compliant and compatible with the current requirements of IPC/JEDEC J-STD-020.
- Suitable for use in SnPb or Pb-free soldering processes.
<table>
<thead>
<tr>
<th>Pin No.</th>
<th>Pin Name</th>
<th>Pin Function</th>
</tr>
</thead>
<tbody>
<tr>
<td>14</td>
<td>VIN</td>
<td>Input Power Supply. Connect a low ESR capacitor of 10(\mu)F or higher from this pin to ground for good bypass.</td>
</tr>
<tr>
<td>15</td>
<td>EN</td>
<td>Enable Control Input (Active High). It must be connected to a logic voltage or pulled up to VIN with a 100k(\Omega) resistor.</td>
</tr>
<tr>
<td>16</td>
<td>ACDRV</td>
<td>Gate Driver Output for Input P-MOSFET.</td>
</tr>
<tr>
<td>17</td>
<td>GND</td>
<td>Ground. The exposed pad must be soldered to a large PCB and connected to GND for maximum power dissipation.</td>
</tr>
</tbody>
</table>

**Function Block Diagram**
Operation

The RT9538 is a current-mode PWM step-down switching charger controller. The battery DC charge current is adjusted by a resistor R4 at the ISET pin and the ratio of sense resistor RS2 over RS1 in the typical application circuit. Amplifier CA converts the charge current through RS1 to a much lower sampled current $I_{CHG}$ ($I_{CHG} = I_{BATT} \times (RS1 / RS2)$) fed into the ISET pin. Amplifier EA compares the output of CA with 2.5V reference voltage and drives the PWM loop to force them to be equal. Note that $I_{CHG}$ has both AC and DC components. High DC accuracy is achieved with averaging filter R3 and C3 at the ISET pin. $I_{CHG}$ is mirrored to go through R4 and generates a ramp signal that is fed to the PWM control comparator, forming the current mode inner loop. An internal LDO generates a 5V to power high-side FET gate driver. For batteries like lithium that require both constant current and constant voltage charging, the 0.5% 2.5V reference and the voltage amplifier VA reduce the charge current when battery voltage reaches the normal charge voltage level. For NiMH and NiCd, VA can be used for over-voltage protection.

CL Amplifier

The amplifier CL monitors and limits the input current, normally from the AC adapter to a preset level (100mV/RS4). At input current limit, CL will supply the adjusted current at the ISET pin, thus reducing battery charging current.

Charge STATUS

When the charger is in voltage mode and the charge current level is reduced to 20%, the STATUS pin will turn to logic high. This charge completion signal can be used to start a timer for charge termination. A 0.1μF capacitor from STATUS to ground is needed to filter the sampled charging current ripple.

ACDRV Driver

The ACDRV pin drives an external P-MOSFET to avoid reverse current from battery to input supply. When input supply is removed, the RT9538 goes into a low current, 10µA maximum, sleep mode as VIN drops below the battery voltage.
### Absolute Maximum Ratings (Note 1)

- **VIN, EN, ACN, BATT, SW to GND**
  - $-0.3\text{V}$ to $36\text{V}$
- **ACDRV**
  - $(\text{ACN} - 6\text{V})$ to $(\text{ACN} + 0.3\text{V})$
- **ACP**
  - $(\text{ACN} - 0.3\text{V})$ to $(\text{ACN} + 0.6\text{V})$
- **ISET, VC, STATUS, VFB, V5V to GND**
  - $-0.3\text{V}$ to $6\text{V}$
- **SNSL**
  - $(\text{BATT} - 0.3\text{V})$ to $(\text{BATT} + 0.3\text{V})$
- **SNSH**
  - $(\text{SNSL} - 0.3\text{V})$ to $(\text{SNSL} + 0.3\text{V})$
- **BOOT**
  - $(\text{SW} - 0.3\text{V})$ to $(\text{SW} + 6\text{V})$
- **TG**
  - $(\text{SW} - 0.3\text{V})$ to $(\text{BOOT} + 0.3\text{V})$

- **Power Dissipation, $P_D @ T_A = 25^\circ\text{C}$**
  - WQFN-16L 4x4
  - $3.5\text{W}$

- **Package Thermal Resistance (Note 2)**
  - WQFN-16L 4x4, $\theta_{JA}$
  - $28.5^\circ\text{C/W}$
  - WQFN-16L 4x4, $\theta_{JC}$
  - $7^\circ\text{C/W}$

- **Junction Temperature**
  - $150^\circ\text{C}$

- **Lead Temperature (Soldering, 10 sec.)**
  - $260^\circ\text{C}$

- **Storage Temperature Range**
  - $-65^\circ\text{C}$ to $150^\circ\text{C}$

- **ESD Susceptibility (Note 3)**
  - HBM (Human Body Model)
  - $2\text{kV}$

### Recommended Operating Conditions (Note 4)

- **Supply Input Voltage, VIN**
  - $4.5\text{V}$ to $28\text{V}$

- **Junction Temperature Range**
  - $-40^\circ\text{C}$ to $125^\circ\text{C}$

- **Ambient Temperature Range**
  - $-40^\circ\text{C}$ to $85^\circ\text{C}$

### Electrical Characteristics

$(V_{IN} = V_{BATT} + 3\text{V}, V_{BATT}$ is the full charge voltage, pull-up EN to VIN with $100\text{k}\Omega$ resistor, $T_A = 25^\circ\text{C}$, unless otherwise specified)

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Symbol</th>
<th>Test Conditions</th>
<th>Min</th>
<th>Typ</th>
<th>Max</th>
<th>Unit</th>
</tr>
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<tbody>
<tr>
<td>Overall</td>
<td></td>
<td></td>
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<tr>
<td>Supply Quiescent Current</td>
<td>$I_Q$</td>
<td>No Charge Current</td>
<td>0.5</td>
<td>1.3</td>
<td>2</td>
<td>mA</td>
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<tr>
<td>Supply Shutdown Current</td>
<td>$I_{SD}$</td>
<td>$V_{EN} = 0$</td>
<td>--</td>
<td>--</td>
<td>12</td>
<td>$\mu\text{A}$</td>
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<tr>
<td>Reverse Current from Battery</td>
<td>$I_{REV}$</td>
<td>$V_{IN}$ Floating, Sleep Mode</td>
<td>--</td>
<td>--</td>
<td>10</td>
<td>$\mu\text{A}$</td>
</tr>
<tr>
<td>VIN Under-Voltage Falling Threshold</td>
<td>$V_{U\text{VLO}}$</td>
<td>Check ACDRV</td>
<td>3.6</td>
<td>3.8</td>
<td>4.2</td>
<td>V</td>
</tr>
<tr>
<td>VIN Under-Voltage Hysteresis</td>
<td>$V_{U\text{VLO}}$</td>
<td>$HYS$</td>
<td>--</td>
<td>300</td>
<td>--</td>
<td>mV</td>
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<tr>
<td>Reference</td>
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<tr>
<td>Reference Voltage</td>
<td>$V_{FB}$</td>
<td></td>
<td>2.488</td>
<td>2.5</td>
<td>2.512</td>
<td>V</td>
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<tr>
<td>FB Leakage Current</td>
<td>$I_{FB}$</td>
<td></td>
<td>--</td>
<td>--</td>
<td>0.1</td>
<td>$\mu\text{A}$</td>
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<tr>
<td>Parameter</td>
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<td>Typ</td>
<td>Max</td>
<td>Unit</td>
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<tr>
<td><strong>Charge Current</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>Full-Scale Charge Current</td>
<td>VICHG</td>
<td>Measure the Voltage Drop Across RS1</td>
<td>95</td>
<td>100</td>
<td>105</td>
<td>mV</td>
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<tr>
<td>Sense Voltage</td>
<td></td>
<td></td>
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<tr>
<td>ISET Output Current</td>
<td>ISET</td>
<td></td>
<td>0.5</td>
<td>--</td>
<td>--</td>
<td>mA</td>
</tr>
<tr>
<td>Termination Current Set Factor</td>
<td>VTM</td>
<td>1/5-Scale Charge Current when STATUS from Low to High</td>
<td>15</td>
<td>20</td>
<td>25</td>
<td>%</td>
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<tr>
<td>SNSH Bias Current</td>
<td>ISNSH</td>
<td></td>
<td>--36</td>
<td>--12</td>
<td>--6</td>
<td>µA</td>
</tr>
<tr>
<td>SNSL Bias Current</td>
<td>ISNSH</td>
<td>No Charge Current</td>
<td>--36</td>
<td>--12</td>
<td>--6</td>
<td>µA</td>
</tr>
<tr>
<td><strong>Battery Voltage</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>VIN Minimum Voltage with Respect to BATT</td>
<td>ΔVIN</td>
<td>(Note 5)</td>
<td>--</td>
<td>2</td>
<td>--</td>
<td>V</td>
</tr>
<tr>
<td>BATT Bias Current</td>
<td>IBATT</td>
<td></td>
<td>--30</td>
<td>--15</td>
<td>--5</td>
<td>µA</td>
</tr>
<tr>
<td>VC Pin Current</td>
<td>IVC</td>
<td>VVC = 0V</td>
<td>--25</td>
<td>--15</td>
<td>--8</td>
<td>µA</td>
</tr>
<tr>
<td><strong>Input Current Limit</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Input Current Limit Sense Voltage</td>
<td>VILMT</td>
<td>Measure the Voltage Drop Across RS4</td>
<td>90</td>
<td>100</td>
<td>110</td>
<td>mV</td>
</tr>
<tr>
<td>ACN Input Current</td>
<td>IACN</td>
<td>VACP = VACN = 0.1V</td>
<td>8</td>
<td>16</td>
<td>34</td>
<td>µA</td>
</tr>
<tr>
<td>ACP Input Current</td>
<td>IACP</td>
<td>VACP = VACN = 0.1V</td>
<td>25</td>
<td>50</td>
<td>100</td>
<td>µA</td>
</tr>
<tr>
<td>ACDRV ON Voltage</td>
<td>VACON</td>
<td>Measure the Voltage (VACN – VACDRV)</td>
<td>4</td>
<td>5.4</td>
<td>6</td>
<td>V</td>
</tr>
<tr>
<td>ACDRV OFF Voltage</td>
<td>VACOFF</td>
<td>Measure the Voltage (VACN – VACDRV), VEN = 0V</td>
<td>0</td>
<td>--</td>
<td>0.1</td>
<td>V</td>
</tr>
<tr>
<td>ACDRV Pull-Down Current</td>
<td>IACPDP</td>
<td>VACN – VACDRV = 3.8V</td>
<td>5</td>
<td>10</td>
<td>30</td>
<td>µA</td>
</tr>
<tr>
<td>ACDRV Pull-Up Current</td>
<td>IACPUP</td>
<td>VACN – VACDRV = 0.5V, VEN = 0V</td>
<td>--10</td>
<td>--5</td>
<td>--2</td>
<td>µA</td>
</tr>
<tr>
<td><strong>Switch Characteristics</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Switching Frequency</td>
<td>fOSC</td>
<td></td>
<td>425</td>
<td>475</td>
<td>525</td>
<td>kHz</td>
</tr>
<tr>
<td>TG Rising Time</td>
<td>TR</td>
<td>VBOOT – VSW = 5V, 1nF Load at TG Pin</td>
<td>--</td>
<td>25</td>
<td>75</td>
<td>ns</td>
</tr>
<tr>
<td>TG Falling Time</td>
<td>TF</td>
<td>VBOOT – VSW = 5V, 1nF Load at TG Pin</td>
<td>--</td>
<td>25</td>
<td>75</td>
<td>ns</td>
</tr>
<tr>
<td>Maximum Duty</td>
<td></td>
<td>(Note 5)</td>
<td>95</td>
<td>--</td>
<td>--</td>
<td>%</td>
</tr>
<tr>
<td>TG ON Voltage</td>
<td>VTS</td>
<td>VTS – VSW (Note 5)</td>
<td>--</td>
<td>5</td>
<td>--</td>
<td>V</td>
</tr>
<tr>
<td><strong>Regulator and Logic Characteristics</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>LDO Output Voltage</td>
<td>VLODO</td>
<td>40mA Load at V5V, VVC = 0V</td>
<td>4</td>
<td>5.2</td>
<td>6</td>
<td>V</td>
</tr>
<tr>
<td>STATUS High Voltage</td>
<td></td>
<td>STATUS Cap = 0.1µF</td>
<td>--</td>
<td>5</td>
<td>--</td>
<td>V</td>
</tr>
<tr>
<td>EN Input Voltage</td>
<td>VENH</td>
<td>Logic-High</td>
<td>2.5</td>
<td>--</td>
<td>--</td>
<td>V</td>
</tr>
<tr>
<td>EN Input Voltage</td>
<td>VENL</td>
<td>Logic-Low</td>
<td>--</td>
<td>--</td>
<td>0.6</td>
<td></td>
</tr>
<tr>
<td>EN Input Current</td>
<td>IEN</td>
<td>0V ≤ VEN ≤ 5V</td>
<td>--</td>
<td>--</td>
<td>10</td>
<td>µA</td>
</tr>
</tbody>
</table>
Note 1. Stresses beyond those listed “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 may affect device reliability.

Note 2. θJA is measured at T_A = 25°C on a high effective thermal conductivity four-layer test board per JEDEC 51-7. θJC is measured at the exposed pad of the package.

Note 3. Devices are ESD sensitive. Handling precaution is recommended.

Note 4. The device is not guaranteed to function outside its operating conditions.

Note 5. Design guarantee.
Note:

(1). For application with removable battery, a TVS with appropriate rating is required as shown above.

(2). $V_{IN} = 15V$ to $30V$, 3-cell, $I_{adapter\_limit} = 2.5A$, $I_{charge} = 2A$
Typical Operating Characteristics

Efficiency vs. Supply Voltage

- 5 Cell: V_{BATT} = 20V
- 4 Cell: V_{BATT} = 16V
- 3 Cell: V_{BATT} = 12V
- 2 Cell: V_{BATT} = 8V
- 1 Cell: V_{BATT} = 4V

IBATT = 1A

Supply Voltage (V) vs. Efficiency (%)

Charge Current vs. Supply Voltage

- 1 Cell: VIN = 12V, V_{BATT} = 4V
- 2 Cell: VIN = 24V, V_{BATT} = 8V
- 3 Cell: VIN = 24V, V_{BATT} = 12V
- 4 Cell: VIN = 24V, V_{BATT} = 16V
- 5 Cell: VIN = 24V, V_{BATT} = 20V

Supply Voltage (V) vs. Charge Current (A)

Supply Current vs. Temperature

- 1 Cell: VIN = 12V, V_{BATT} = 4V
- 2 Cell: VIN = 24V, V_{BATT} = 8V
- 3 Cell: VIN = 24V, V_{BATT} = 12V
- 4 Cell: VIN = 24V, V_{BATT} = 16V
- 5 Cell: VIN = 24V, V_{BATT} = 20V

Shutdown Current vs. Temperature

V5V Voltage vs. Temperature
Applications Information

Input and Output Capacitors

In the typical application circuit, the input capacitor (C2) is assumed to absorb all input switching ripple current in the converter, so it must have adequate ripple current rating. Typically, at high charging currents, the converter will operate in continuous conduction mode. In this case, the RMS current IRMSIN of the input capacitor C2 can be estimated by the equation:

\[ IRMSIN = \frac{I_{BATT}}{\sqrt{D - D^2}} \]

Where \( I_{BATT} \) is the battery charge current and D is the duty cycle. In worst case, the \( IRMSIN \) ripple current will be equal to one half of output charging current at 50% duty cycle. For example, \( I_{BATT} = 2A \), the maximum \( IRMSIN \) current will be 1A. A low-ESR ceramic capacitor such as X7R or X5R is preferred for the input-decoupling capacitor and should be placed to the Drain of the high-side MOSFET and Source of the low-side MOSFET as close as possible.

The voltage rating of the capacitor must be higher than the normal input voltage level. 22\( \mu F \) capacitance is suggested for typical of 2A charging current.

The output capacitor (\( C_{BATT} \)) is also assumed to absorb output switching current ripple. The general formula for capacitor current \( IRMSCB \) is:

\[ IRMSCB = \frac{V_{BATT} \times \left(1 - \frac{V_{BATT}}{V_{VIN}}\right)}{2 \times \sqrt{3} \times L1 \times f_{OSC}} \]

For example, \( V_{VIN} = 19V, V_{BATT} = 8.4V, L1 = 10\mu H \), and \( f_{OSC} = 475kHz \), \( IRMSCB = 0.15A \).

EMI considerations usually make it desirable to minimize ripple current in the battery leads. Beads or inductors may be added to increase battery impedance at the 475kHz switching frequency. Switching ripple current splits between the battery and the output capacitor depending on the ESR of the output capacitor and the battery impedance. If the ESR of \( C_{OUT} \) is 0.2\( \Omega \) and the battery impedance is raised to 4\( \Omega \) with a bead or inductor, only 5% of the ripple current will flow in the battery.

Inductor

The inductor value will be changed for more or less current ripple. The higher the inductance, the lower the current ripple will be. As the physical size is kept the same, typically, higher inductance will result in higher series resistance and lower saturation current. A good tradeoff is to choose the inductor so that the current ripple is approximately 30% to 50% of the full-scale charge current. The inductor value is calculated as:

\[ L1 = \frac{V_{BATT} \times (V_{VIN} - V_{BATT})}{V_{VIN} \times f_{OSC} \times \Delta I_L} \]

Where \( \Delta I_L \) is the inductor current ripple. For example, \( V_{VIN} = 19V \), choose the inductor current ripple to be 40% of the full-scale charge current in the typical application circuit for 2A, 2-cell battery charger, \( \Delta I_L = 0.8A \), \( V_{BATT} = 8.4V \), calculate L1 to be 12.3\( \mu H \). So choose L1 to be 15\( \mu H \) which is close to 12.3\( \mu H \).

Soft-Start and Under-Voltage Lockout

The soft-start is controlled by the voltage rising time at VC pin. There is external soft-start in the RT9538. With a 0.47\( \mu F \) capacitor, time to reach full charge current is about 25ms and it is assumed that input voltage to the charger will reach full value in less than 25ms. The capacitor can be increased if longer input start-up time is needed.

For the RT9538, it provides Under-Voltage Lockout (UVLO) protection. If LDO output voltage is lower than 3.8V, high-side power FET M2 and input power FET M1 will be cut off. This will protect the adapter from entering a quasi “latch” state where the adapter output stays in a current limited state at reduced output voltage.

Adapter Current Limiting

An important feature of RT9538 is the ability to automatically adjust charge current to a level which avoids overloading the wall adapter. This allows the product to operate, and at the same time batteries are being charged without complex load management algorithms. Additionally, batteries will automatically be charged at the maximum possible rate of which the adapter is capable.
This is accomplished by sensing total adapter output current and adjusting charge current downward if a preset adapter current limit is exceeded. Amplifier CL in typical application circuit senses the voltage across RS4, connected between the ACP and ACN pins. When this voltage exceeds 100mV, the amplifier will override adjusted charge current to limit adapter current to 100mV/RS4. A low pass filter formed by 56Ω and 33nF is required to eliminate switching noise.

**Full-Scale Charge Current Programming**

The basic formula for full-scale charge current is (see Block Diagram):

\[ I_{BATT} = \left( \frac{V_{REF}}{R4} \right) \times \left( \frac{R2}{R1} \right); V_{REF} = V_{FB} = 2.5V \text{ (typ.)} \]

where \( R4 \) is the total resistance from ISET pin to ground.

For the sense amplifier CA biasing purpose, \( RS3 \) should have the same value as \( RS2 \) with 1% accuracy. For example, 2A full-scale charging current is needed. For low power dissipation on \( RS1 \) and enough signal to drive the amplifier CA, let \( RS1 = 100mV / 2A = 50m\Omega \). This limits \( RS1 \) power to 0.2W. Let \( R4 = 10k\Omega \), then:

\[ RS2 = RS3 = \frac{I_{BATT} \times R4 \times RS1}{V_{REF}} = \frac{2A \times 10k \times 0.05}{2.5V} = 400\Omega \]

Note that for charge current accuracy and noise immunity, 100mV full scale level across the sense resistor \( RS1 \) is required. Consequently, both \( RS2 \) and \( RS3 \) should be 400Ω. Select 399Ω for real application.

It is critical to have a good Kelvin connection on the current sense resistor \( RS1 \) to minimize stray resistive and inductive pickup. \( RS1 \) should have low parasitic inductance (typical 3nH or less). The layout path from \( RS2 \) and \( RS3 \) to \( RS1 \) should be kept away from the fast switching SW node. A 10pF ceramic capacitor can be used across SNSSH and SNSL should be kept away from the fast switching SW node.

**Battery Voltage Regulation**

The RT9538 uses a high-accuracy voltage bandgap and regulator for the high charging-voltage accuracy. The charge voltage is programmed via a resistor divider from the battery to ground, with the midpoint tied to the VFB pin. The voltage at the VFB pin is regulated to 2.5V, giving the following equation for the regulation voltage:

\[ V_{BATT} = 2.5 \times \left( 1 + \frac{RF2}{RF1} \right) \]

where \( RF2 \) is connected from VFB pin to the battery and \( RF1 \) is connected from VFB pin to GND.

**Charging**

The 2A Battery Charger (typical application circuit) charges lithium-ion batteries at a constant 2A until battery voltage reaches the setting value. The charger will then automatically go into a constant voltage mode with current decreasing to near zero over time as the battery reaches full charge.

**Charging Completion**

Some battery manufacturers recommend termination of constant voltage float mode after charge current has dropped below a specified level (typically around 20% of the full-scale charge current) and a further time-out period of 30 minutes to 90 minutes has elapsed. Check with manufacturers for details. The RT9538 provides a signal at the STATUS pin when charging is in voltage mode and charge current is reduced to 20% of full-scale charge current, assuming full-scale charge current is programmed to have 100mV across the current sense resistor \( V_{RS1} \).

The charge current sample \( I_{CHG} \) is compared with the output current \( I_{VA} \) of voltage amplifier VA. When the charge current drops to 20% of full-scale charge current, \( I_{CHG} \) will be equal to 20% of \( I_{VA} \) and the STATUS pin voltage will go logic high and can be used to start an external timer. When this feature is used, a capacitor of at least 0.1μF is required at the STATUS pin to filter out the switching noise. If this feature is not used, the capacitor is not needed.

**Dropout Operation**

The RT9538 can charge the battery even when VIN goes as low as 2V above the combined voltages of the battery and the drops on the sense resistor as well as parasitic wiring. This low VIN sometimes forces 100% duty cycle and TG stays on for many switching cycles. While TG stays on, the voltage \( V_{BOOT} \) across the capacitor C8 drops down slowly because the current sink at BOOT pin. C8 needs to be recharged before \( V_{BOOT} \) drops too low to keep the high-side switch on.
A unique design allows the RT9538 to operate under these conditions. If the SW pin voltage keeps larger than 1.3V for 32 oscillation periods, high-side power FET will be turned off and an internal FET will be turned on to pull the SW pin down. This function refreshes VBOOT voltage to a higher value.

It is important to use 0.1 μF to hold VBOOT up for a sufficient amount of time. The P-MOSFET M1 is optional and can be replaced with a diode if VIN is at least 2.5V higher than VBATT. The gate control pin ACDRV turns on M1 when V5V gets up above the under-voltage lockout level and is clamped internally to 5V below VACN. In sleep mode when VIN is removed, ACDRV will clamp M1 VSG to less than 0.1V.

**Shutdown**
When adapter power is removed, VIN will drift down. As soon as VIN goes down to 0.1V above VBATT, the RT9538 will go into sleep mode drawing only ~10 μA from the battery. There are two ways to stop switching: pulling the EN pin low or pulling the VC pin low. Pulling the EN pin low will shut down the whole chip. Pulling the VC pin low will only stop switching and LDO stays work. Make sure there is a pull-up resistor on the EN pin even if the EN pin is not used; otherwise, internal pull-down current will keep the EN pin low to shut down mode when power turns on.

**Charger Protection**
If the VIN connector of typical application circuit can be instantaneously shorted to ground, the P-MOSFET M1 must be quickly turned off; otherwise, high reverse surge current might damage M1. An internal transient enhancement circuit is designed to quickly charge the ACDRV pin voltage to the ACN pin voltage.

Note that the RT9538 will operate even when VBATT is grounded. If VBATT of typical application circuit charger gets shorted to ground very quickly from a high battery voltage, slow loop response may allow charge current to build up and damage the high-side N-MOSFET M2. A small diode from the EN pin to VBATT will shut down switching and protect the charger.

**Thermal Considerations**
For continuous operation, do not exceed absolute maximum junction temperature. The maximum power dissipation depends on the thermal resistance of the IC package, PCB layout, rate of surrounding airflow, and difference between junction and ambient temperature. The maximum power dissipation can be calculated by the following formula:

\[ P_{D(MAX)} = \frac{T_{J(MAX)} - T_A}{\theta_{JA}} \]

where \( T_{J(MAX)} \) is the maximum junction temperature, \( T_A \) is the ambient temperature, and \( \theta_{JA} \) is the junction to ambient thermal resistance.

For recommended operating condition specifications, the maximum junction temperature is 125°C. The junction to ambient thermal resistance, \( \theta_{JA} \), is layout dependent. For WQFN-16L 4x4 package, the thermal resistance, \( \theta_{JA} \), is 28.5°C/W on a standard JEDEC 51-7 four-layer thermal test board. The maximum power dissipation at \( T_A = 25°C \) can be calculated by the following formula:

\[ P_{D(MAX)} = \frac{(125°C - 25°C)}{(28.5°C/W)} = 3.5W \]

The maximum power dissipation depends on the operating ambient temperature for fixed \( T_{J(MAX)} \) and thermal resistance, \( \theta_{JA} \). The derating curve in Figure 1 allows the designer to see the effect of rising ambient temperature on the maximum power dissipation.

![Figure 1. Derating Curve of Maximum Power Dissipation](image)
Layout Considerations

Switch rise and fall times are under 20ns for maximum efficiency. To prevent radiation, the power MOSFETs, the SW pin, the rectifier Schottky diode D1 and input bypass capacitor leads should be kept as short as possible. A ground plane should be used under the switching circuitry to prevent inter-plane coupling and to act as a thermal spreading path. Note that the rectifier Schottky diode D1 is probably the most heat dissipating device in the charging system.

The voltage drop on a 2A Schottky diode can be 0.5V. With 50% duty cycle, the power dissipation can go as high as 0.5W. Expanded traces should be used for the diode leads for low thermal resistance. Another large heat dissipating device is probably the inductor. The fast switching high current ground path including the MOSFETs, D1 and input bypass capacitor C2 should be kept very short. Another smaller input bypass (1μF ceramic or larger paralleled with Cn) should be placed to VIN pin and GND pin as close as possible.

Figure 2. PCB Layout Guide
### Outline Dimension

**W-Type 16L QFN 4x4 Package**

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Dimensions In Millimeters</th>
<th>Dimensions In Inches</th>
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</tr>
</tbody>
</table>

Note: The configuration of the Pin #1 identifier is optional, but must be located within the zone indicated.

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