Ideal Diode Controllers for Active Rectification of AC Voltage Ripple for Automotive Applications: LM7480-Q1 and LM7481-Q1

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ABSTRACT

Automotive electronic modules are required to work uninterrupted when AC ripple voltage is superimposed on the battery input line and AC ripple current flows into the modules. Reverse battery protection circuit contains components such as electrolytic capacitors, P-Channel MOSFETs or diodes. Reverse battery protection circuits using P-Channel MOSFETs does not rectify the AC ripple voltage due to lack of reverse current blocking and hence power dissipation in these components increases as the RMS value of the AC ripple current increases. It affects the overall system reliability and degrades the operating life time. Further, AC ripple frequency over laps with the audio frequency and can cause interference in modules such as Audio Amplifiers which are sensitive to AC ripple voltage on its supply. The AC ripple voltage must be rectified and filtered to achieve superior audio performance. This application report discusses the key benefits of using TI's Ideal Diode Controllers LM7480-Q1 and LM7481-Q1 for active rectification of the AC ripple voltage superimposed on the battery line.

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1 Introduction

In systems powered by internal combustion engines, alternator provides power to the automotive electrical system by charging the battery during normal runtime of the vehicle. Rectified alternator output voltage contains AC voltage ripple superimposed on the battery voltage during entire life time of the vehicle depending on the operating conditions. The alternator output voltage is regulated by a voltage regulator by controlling the rotor field current and alternator output contains residual AC voltage ripple superimposed on the DC battery line due to variation in engine speed, regulator duty cycle with field current switching ON/OFF and electrical load variations.

In fully electric systems or semi-hybrid systems, the entire electrical load is fed through DC-DC converters. Output voltage of DC-DC converter contains AC voltage ripple superimposed on the DC battery voltage up to 200 kHz.

Hence most of the automotive ECUs are verified for uninterrupted and stable operation with AC voltage ripple superimposed on the battery supply line by testing its reverse battery protection circuit according to different automotive test standards.

2 Automotive Test Standards

AC superimposed tests are specified in various automotive test standards such as ISO 16750-2, LV124, other OEM standards and are intended to verify stable operation of various electronic modules. Typically the input protection circuit or the reverse battery protection circuit is verified for normal operation without much degradation in the operating life time of the modules.

For ECU modules operating in an alternator powered vehicle, ISO 16750-2 and LV124 E-06 specifies AC ripple of 2-V Peak-Peak on a 13.5-V DC battery voltage, swept from 15 Hz to 30 kHz and the test waveform is shown in Figure 1. Other manufacturer specific requirements can vary and the frequency can go up to 100 kHz. Peak-Peak ripple amplitude varies from 2-V peak-peak to 6-V peak-peak, depending on the location of module with reference to Alternator and Battery. For ECU modules fed through a DC-DC converter, AC ripple frequency extends to 200 kHz.

![Figure 1. AC Super Imposed Test](image-url)
3 Rectification of AC Ripple Voltage

Conventional input protection circuits use either a Schottky diode or P-Channel MOSFET to provide reverse battery protection. Figure 2 shows two reverse battery protection circuits, first one using a Schottky diode and second one using P-Channel MOSFET.

Schottky diode rectifies the AC ripple superimposed on the battery voltage effectively, except the high power dissipation due to high forward voltage drop. At every AC cycle of the ripple voltage, the input voltage swings lower than the output, Schottky diode is reverse biased and block reverse current flow from output. Until the next positive cycle, load current is supplied by the output electrolytic capacitor and capacitor is charged during the next cycle by the battery.

However, reverse battery protection circuit using a P-Channel MOSFET shown in Figure 2 does not block reverse current and hence the AC ripple voltage is not rectified. Figure 3 shows the response of P-Channel MOSFET based reverse battery protection circuit. Since AC ripple is not rectified, output voltage follows input voltage and AC ripple current swings negative leading to increase in peak-peak ripple current of 10A and RMS ripple current. The RMS ripple current through the output electrolytic capacitors increases the power dissipation as the ripple current increase and its needs to be limited to minimize power dissipation reduce aging effect and improve overall reliability.
4 Active Rectification using Ideal Diode Controllers

The LM7480x-Q1 ideal diode controller features a dual-gate drives topology to control two external back to back N-Channel MOSFETs. One of the MOSFET is controlled to emulate an ideal diode and another MOSFET for power path ON/OFF control, inrush current limiting and over voltage protection.

Ideal Diode Controller LM748x-Q1 family of devices features a very low forward drop to minimize power dissipation in the N-Channel MOSFET during normal operation. Fast reverse current blocking response, fast DGATE turn on and dual gate drive enables LM7481-Q1 to rectify AC ripple voltage up to 200 KHz.

During each cycle when the input voltage swings below the output, DGATE is turned off within 1µs to block reverse current from flowing back into the battery. In the next ‘positive cycle’, when the input voltage swings above the output, ‘DGATE fast charge’ allows DGATE to turn ON quickly within 2 µs*, thereby reducing the power dissipation in the MOSFET. This enables LM748x-Q1 controller to do active rectification the AC voltage ripple.

Thus the key to uninterrupted cycle-cycle active rectification at 200 KHz is fast reverse recovery and fast forward turn ON.

Figure 4. Simplified Schematic of Ideal Diode Controller LM7480-Q1

A simplified schematic showing ideal diode used for active rectification is shown in Figure 4. For complete application circuit, refer to the LM7480-Q1 and LM7481-Q1 datasheet application section.

Active rectification of 2-V peak-peak 5 kHz and 30 kHz AC voltage ripple by LM7480-Q1 is captured in Figure 5 and Figure 6 respectively. During the positive cycle MOSFET is turned ON, output capacitor charges and output follows input until the current through the MOSFET reverses. As soon as reverse current is detected, LM748x-Q1 turns off the MOSFET within 1 µs, thereby blocking the reverse current completely. In the negative cycle, output capacitor discharges at a constant rate determined by the load current and amount of output capacitance.
Fast reverse current blocking minimizes the peak reverse current and completely block reverse current during the negative cycle. Thus AC ripple current RMS value is reduced by half which in-turn reduces the power dissipation in the output electrolytic capacitor ESR by half. Very low forward voltage drop and reduced RMS ripple current reduces the power dissipation in the MOSFET as well.

Figure 5. LM7480-Q1 - Active Rectification of 2-V Peak-Peak 5 kHz AC Ripple
5 Charge Pump and MOSFET Gate Capacitance

During the active rectification of AC voltage ripple, DGATE drive turns the MOSFET ON and OFF every cycle continuously and this result in increased loading on the charge pump depending on the MOSFET gate capacitance and frequency of the AC Voltage ripple. The charge pump loading is determined by

\[ I_{CP} = Q_{GM} \times F_{AC} \]  

(1)

\( Q_{GM} \) is the gate capacitance at \( V_{GS} \) 6 V, de-rated for miller charge and \( F_{AC} \) is the frequency of the AC voltage ripple.

MOSFET manufacturers usually specify the gate charge characteristics in three region: Gate-Source charge \( Q_{GS} \) determines the MOSFET turn ON, Gate-Drain charge \( Q_{GD} \) depends on the Drain-Source Voltage and \( Q_{G(total)} \) the total gate charge. Due to the orientation of the MOSFET in an ideal diode application, maximum \( V_{DS} \) cannot be more than the maximum forward diode voltage and hence the gate charge \( Q_{GS} \) needs to be derated accordingly. Figure 7 shows derated Gate charge \( Q_{GM} \) at 6-V \( V_{GS} \) in dotted lines.
Figure 7. Gate Charge Derating for Active Rectification

For continuous cycle-cycle active rectification of AC superimposed ripple, higher charge pump capacity is required as the frequency increases. Table 1 shows comparison of charge pump current for LM7480-Q1, LM7481-Q1 and LM74700-Q1 along with maximum gate charge $Q_{GM}$ for continuous active rectification of AC ripple.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>LM74700-Q1</th>
<th>LM7480-Q1</th>
<th>LM7481-Q1</th>
</tr>
</thead>
<tbody>
<tr>
<td>Charge Pump Current at VCAP-VS = 6V</td>
<td>300 µA</td>
<td>600 µA</td>
<td>3000 µA</td>
</tr>
<tr>
<td>Maximum Gate Charge $Q_{GM}$ at AC ripple frequency $F_{AC}$</td>
<td>30 kHz</td>
<td>10nC</td>
<td>20nC</td>
</tr>
<tr>
<td></td>
<td>100 kHz</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>200 kHz</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

LM7481-Q1 with higher charge pump current than LM7480-Q1 and LM74700-Q1 is recommended for higher power ECU applications and applications having AC ripple frequency 100 kHz or 200 kHz requirements. Figure 8 shows the AC super imposed test run at 100 kHz on LM7481-Q1 driving MOSFET BUK9J2R8-40H. At 100 kHz maximum gate charge is 30nC and MOSFET BUK9J2R8-40H having 20nC gate charge $Q_{GM}$ meets the requirements of maximum gate charge. Figure 9 shows the 200 kHz AC super imposed test on LM7481-Q1 driving MOSFET BUK7Y3R5-40H with 12nC gate charge $Q_{GM}$. This meets the maximum gate charge $Q_{GM}$ of 15nC at 200 kHz. Due its fast gate drive and fast reverse recovery response, LM7481-Q1 is able to drive the MOSFETs ON/OFF continuously at 100 kHz and 200 kHz.
Figure 8. LM7481-Q1 Active Rectification at 100 kHz – BUK9J2R8-40H

Figure 9. LM7481-Q1 Active Rectification at 200 kHz – BUK7Y3R5-40H
6 Summary

Rectification of the AC ripple by reverse battery protection circuit with Schottky Diode involves power dissipation due to high forward voltage drop along with the AC ripple current. Reverse battery protection solution using P-Channel MOSFETs lack reverse current blocking and does not rectify the AC ripple leading to increased power dissipation in MOFET and electrolytic capacitors.

Key performance features such as very low forward voltage drop, fast gate drive, fast reverse recovery response and higher charge pump enables LM748x-Q1 family of ideal diode controllers to achieve active rectification of AC voltage ripple. Efficient active rectification results in low forward voltage drop and reduced RMS ripple current leading to lower power dissipation in MOSFET and output capacitors.

7 References

- Texas Instruments, LM7480x-Q1 Ideal Diode Controller with Load Dump Protection Data Sheet
- Texas Instruments, LM74810-Q1 Ideal Diode Controller with Active Rectification and Load Dump Protection Data Sheet
- Texas Instruments, LM74700-Q1 Low Iq Reverse Battery Protection Ideal Diode Controller Data Sheet
- Texas Instruments, Basics of Ideal Diodes Application Report
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