Application Note

Buck Converter Design with LM5170-Q1 to Equalize Two-serial 12-V Batteries in Commercial Vehicles

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ABSTRACT

Commercial vehicles adopt two 12-V batteries in series to build 24-V battery, which enables system to use both 12-V electronics and 24-V electronics effectively. This application report introduces a buck converter design that not only equalizes the two 12-V battery voltages during operation but also achieves constant output current limit, both of which are important to maximize the battery life and improve the overall performance. The LM5170-Q1 multiphase bidirectional current controller is used as a controller in this design.

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1 Introduction

1.1 Commercial Vehicle Power System

Commercial vehicles usually adopt two 12-V automotive batteries in series to produce the needed 24-V supply rail. Figure 1-1 shows the typical architecture of commercial vehicle power system. Alternator charges the two 12-V batteries placed in series. The stacked 24-V voltage supports the 24-V electronics (or 24-V loads hereafter), while the bottom battery, namely Batt_B, supplies 12-V electronics in the vehicle. Such architecture allows the commercial vehicles to reuse the low cost 12-V electronics (or 12-V loads hereafter) developed for passenger cars, therefore reducing the overall electronic cost of the commercial vehicle.

In this architecture, the battery equalizer is necessary. Without the battery equalizer, Batt_B can be consumed faster than the top battery, namely Batt_T, which would become over-charged and Batt_B under-charged. The over-charge would degrade the lifetime of Batt_T, and the undercharge of Batt_B would lose sufficient supply voltage for the 12-V loads. Consequently, the overall system lifespan as well as performance will be adversely affected.

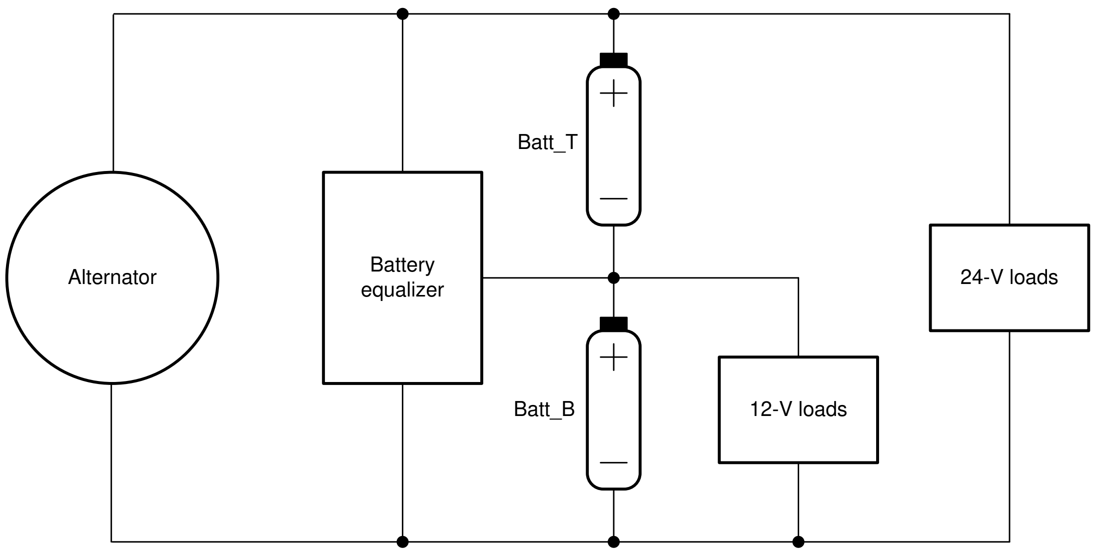

Figure 1-1. Power System of Commercial Vehicles

By introducing the battery equalizer, both Batt_T and Batt_B can stay well-balanced, resulting in maximal battery life time as well as improved system performance. In this report, a buck converter design based on the LM5170-Q1 controller is presented to implement the battery equalizer.

1.2 Operation of Battery Equalizer

Battery equalizer has two modes to support stable power for both 12-V and 24-V loads.

Constant voltage mode

Figure 1-2 shows constant voltage operation of battery equalizer. When 12-V loads are low-powered, namely Iload ≪ Imax, the 24-V load becomes the main load of the two batteries. The battery equalizer keeps Batt_B voltage to be right at 50% of the total voltage of the two series batteries, such that the two battery capacities get well-balanced.

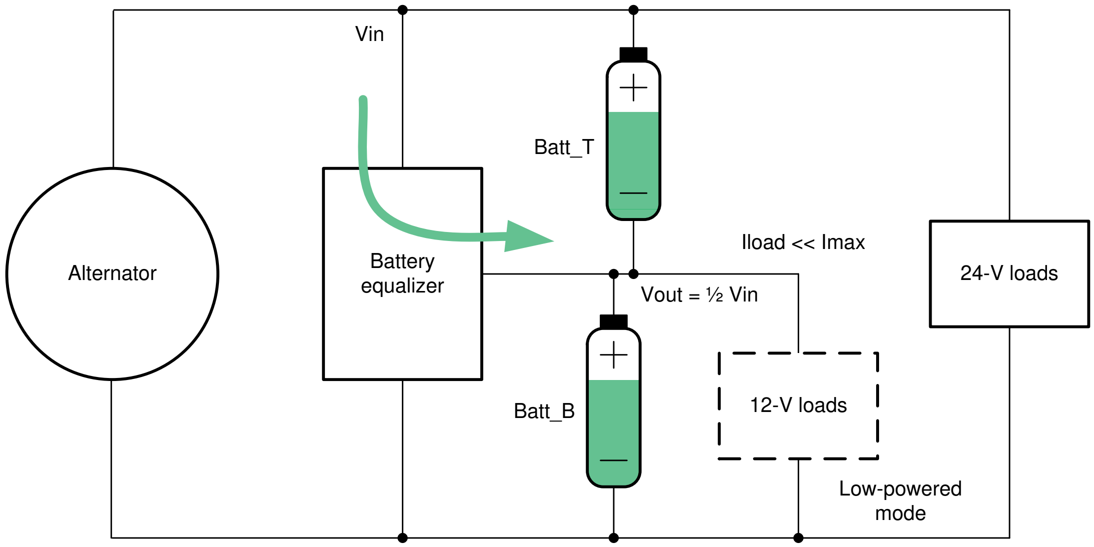

Figure 1-2. Constant Voltage Mode of Battery Equalizer

Constant current mode

Figure 1-3 shows constant current operation of battery equalizer. When 12 V loads consume high power, Batt_B is consumed faster than Batt_T. The battery equalizer will produce 12-V load current to prevent Batt_B from being discharged, therefore the two batteries remains the voltage balance. Obviously, the battery equalizer should provide Iout = Imax.

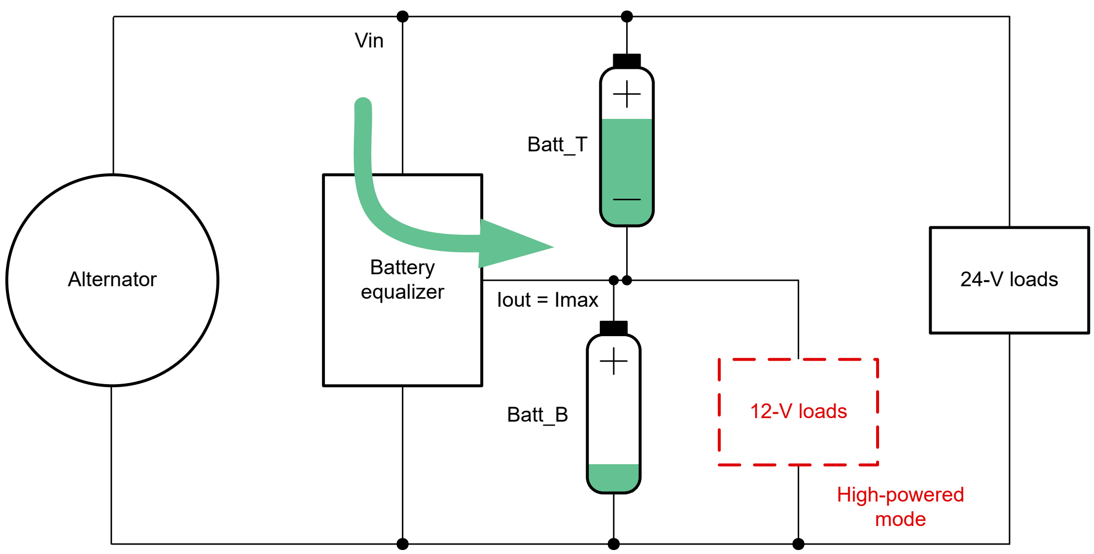

Figure 1-3. Constant Current Mode of Battery Equalizer

2 Designing Buck Converter with LM5170-Q1

2.1 V_{HV} to V_{LV} Buck Converter with 13-A Maximum Output Current

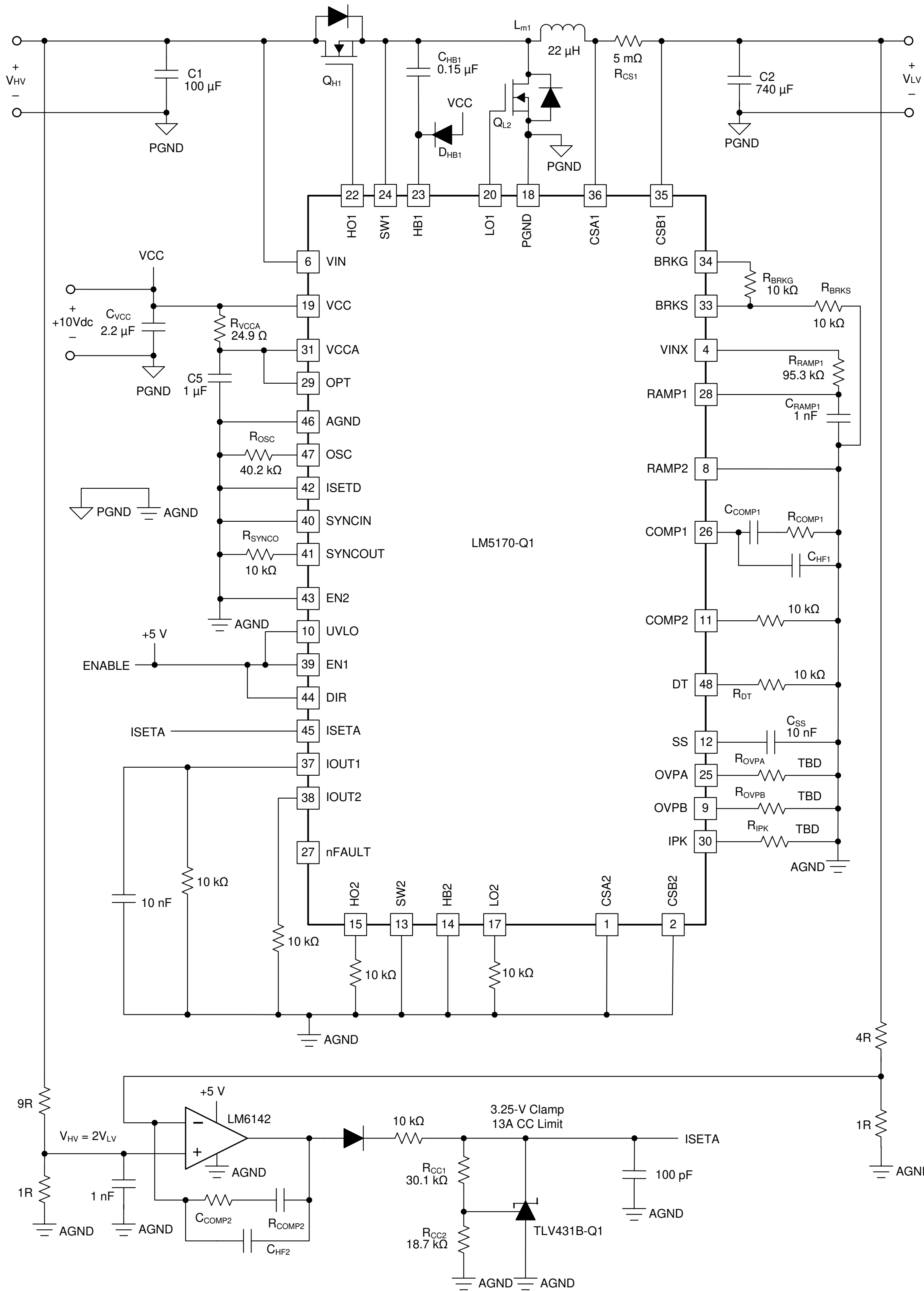

Figure 2-1. Schematic of Buck Converter for Battery Equalizer

Figure 2-1 shows schematic of the buck converter with LM5170-Q1. V_{HV} is the input voltage connected to the 24 V port, which is also the 24-V rail, V_{LV} and is the output voltage connected to the 12-V port, which is also the 12-V rail. Synchronous buck converter is implemented with Q_{H1} and Q_{L2} MOSFET while LM5170-Q1 channel-2 is disabled. R_{CS1} is the shunt resistor to sense inductor current of buck converter. The current sense signal is used for inner current loop regulation. The output voltage of the equalizer is regulated by an external Op-amp LM6142. The designs of the inner current loop and external voltage loop to achieve constant current operation and voltage equalization are detailed in the following section.

2.2 Inner Current Loop Design

As shown in Figure 2-2, LM5170-Q1 provides COMP pin where type II compensation network can be designed externally. It's important to select right R_{COMP1}, C_{COMP1}, and C_{HF1} based on system transfer function. The poles and zeros of current loop system are determined by

$$F_{P\_PLANT} = \frac{R_{CS} + R_S}{2\pi \times L_m} \quad (1)$$

$$F_{P\_COMP} = \frac{1}{2\pi \times R_{COMP1} \times C_{HF1}} \quad (2)$$

$$F_{Z\_COMP} = \frac{1}{2\pi \times R_{COMP1} \times C_{COMP1}} \quad (3)$$

where R_S is the entire resistance on the LV port to the loads, and 50 mΩ assumed in this case.

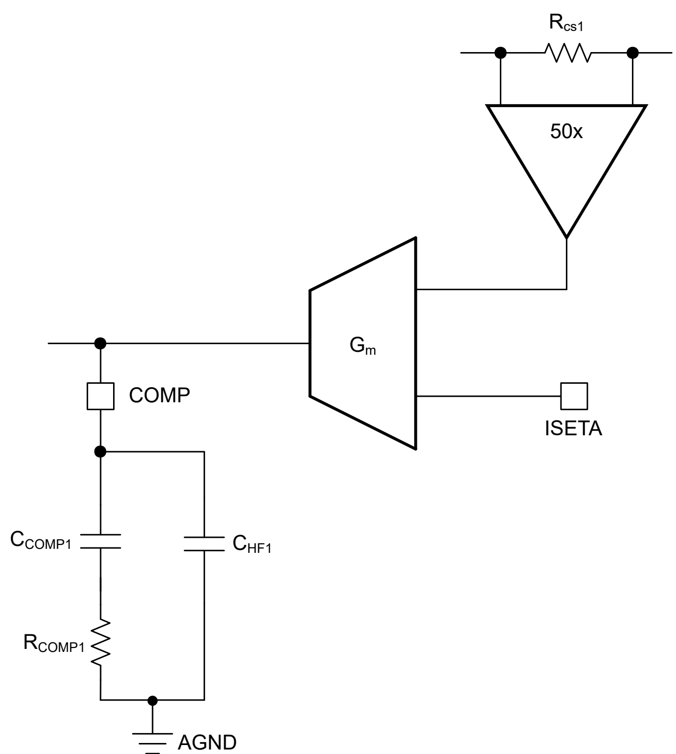

Figure 2-2. Inner Current Loop Control in LM5170-Q1

The compensation network's components are selected based on following guidance. F_{SW} is switching frequency of LM5170-Q1 and F_{CO_CUR} is the current loop crossover frequency.

1. F_{CO_CUR} is set to 1/10 ~ 1/5 of F_{SW}
2. The total inner current loop gain is set to unity at F_{CO_CUR}
3. The zero F_{Z_COMP} is placed at approximately close to the power plant pole F_{P_PLANT}
4. The pole F_{P_COMP} is placed at approximately one or two decades higher than F_{Z_COMP}, but lower than F_{SW}

Select R_{COMP1} = 1.15 kΩ, C_{COMP1} = 330 nF, and C_{HF1} = 3.3 nF which can meet in the following equations.

$$F_{SW} = \frac{40\ k\Omega \times 100\ kHz}{R_{OSC}} = \frac{40\ k\Omega \times 100\ kHz}{40.2\ k\Omega} = 99.5\ kHz \quad (4)$$

$$F_{CO\_CUR} = \frac{1}{5} \times F_{SW} = 19.9\ kHz \quad (5)$$

$$F_{P\_PLANT} = \frac{5\ m\Omega + 50\ m\Omega}{22\ uH} = 398\ Hz \quad (6)$$

$$F_{Z\_COMP} = \frac{1}{2\pi \times 1.15\ k\Omega \times 330\ nF} = 419\ Hz \quad (7)$$

$$F_{P\_COMP} = \frac{1}{2\pi \times 1.15\ k\Omega \times 3.3\ nF} = 41.9\ kHz \quad (8)$$

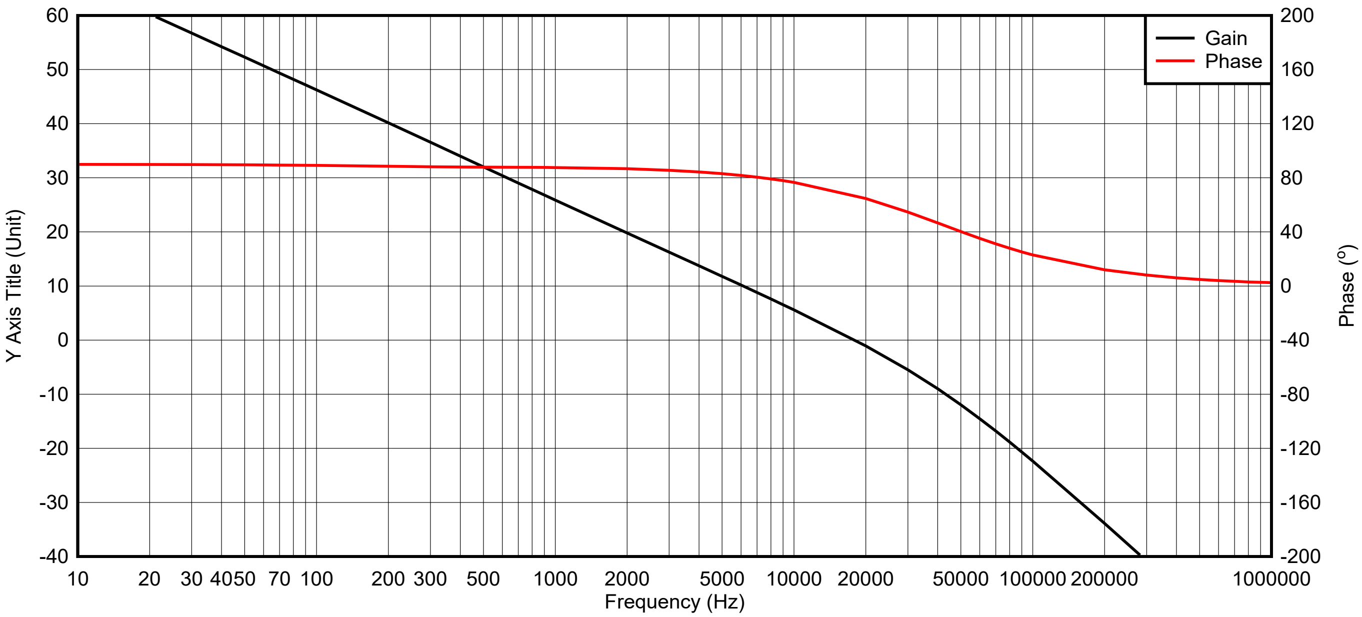

Figure 2-3. Bode Plot of Inner Current Loop

Figure 2-3 shows bode plot of inner current loop. Type II compensation network boosts the phase in mid-frequency range. In this example, the current loop crossover frequency is at about 20 kHz, and the phase margin is approximately 58 degree, which is higher than the needed minimal 45 degree of a stable system. F_{P_COMP} is placed at 41.9 kHz which is lower than the switching frequency (99.5 kHz). This helps to minimize output ripple caused by MOSFET switching.

2.3 Outer Voltage Loop Design

To implement outer voltage loop, an external Op-Amp (Texas Instruments LM6142) is used. The Op-Amp keeps constant ratio between V_{HV} and V_{LV}. The non-inverting input of the Op-Amp is connected to the 9R:1R resistor divider on the V_{HV} rail, and the inverting input is fed by the 4R:1R resistor divider on the V_{LV} rail. Therefore, the Op-Amp's non-inverting input voltage is at 1R/10R × V_{HV}, and the inverting input at 1R/5R × V_{LV}. In the closed loop operation, V_{HV} = 2 × V_{LV}, namely the two battery voltages are balanced.

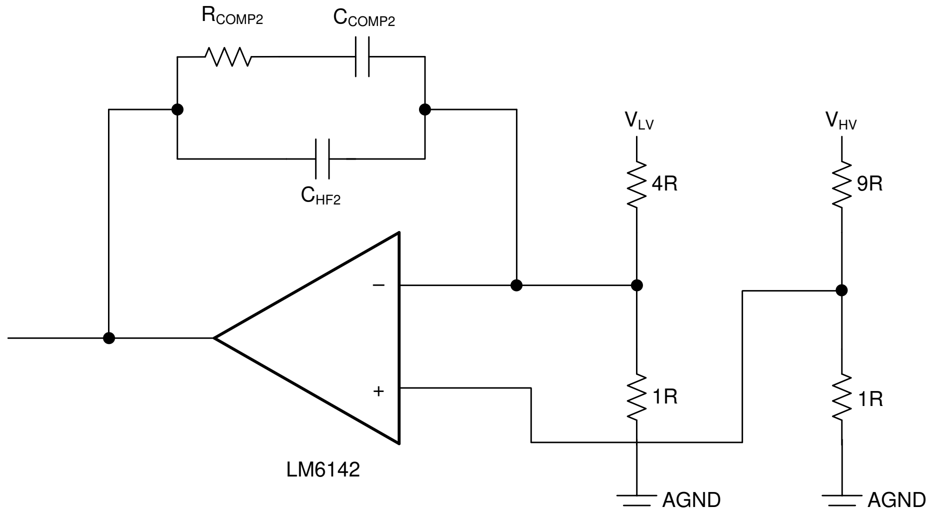

Figure 2-4. Outer Voltage Loop Control in LM5170-Q1

A Type II compensation network is used to stabilize the outer voltage loop. Figure 2-4 shows configuration of type II compensation network consisting of R_{COMP2}, C_{COMP2} , and C_{HF2}. The introduced poles and zero of compensation network are determined by

$$F_{P\_PLANT} = \frac{1}{2\pi \times R_L \times C_o} \quad (9)$$

$$F_{P\_COMP} = \frac{1}{2\pi \times R_{COMP2} \times C_{HF2}} \quad (10)$$

$$F_{Z\_COMP} = \frac{1}{2\pi \times R_{COMP2} \times C_{COMP2}} \quad (11)$$

where R_L is load equivalent resistance and C_o is output capacitance.

To tailor the total voltage loop gain to cross over at F_{CO_VOL}, select components of the compensation network according to the following guidelines, then fine tune the network for optimal loop performance.

1. The F_{CO_VOL} is set to 1/5 or 1/10 of F_{CO_CUR}
2. The total outer voltage loop gain is set to unity at F_{CO_VOL}
3. The zero F_{Z_COMP} is placed at the power stage power F_{P_PLANT}
4. The pole F_{P_COMP} is placed at approximately one or two decades higher than F_{Z_COMP}, but lower than F_{SW}

Select R_{COMP2} = 270 kΩ, C_{COMP2} = 2.7 nF, and C_{HF2} = 13 pF which can meet the following equations.

$$F_{CO\_VOL} = \frac{1}{5} \times F_{CO\_CUR} = 3.98\ \text{kHz} \quad (12)$$

$$F_{P\_PLANT} = \frac{1}{2\pi \times 0.92\Omega \times 740\text{uF}} = 234\ \text{Hz} \quad (13)$$

$$F_{Z\_COMP} = \frac{1}{2\pi \times 270\ \text{k}\Omega \times 2.7\ \text{nF}} = 218\ \text{Hz} \quad (14)$$

$$F_{P\_COMP} = \frac{1}{2\pi \times 270\ \text{k}\Omega \times 13\ \text{pF}} = 45.34\ \text{kHz} \quad (15)$$

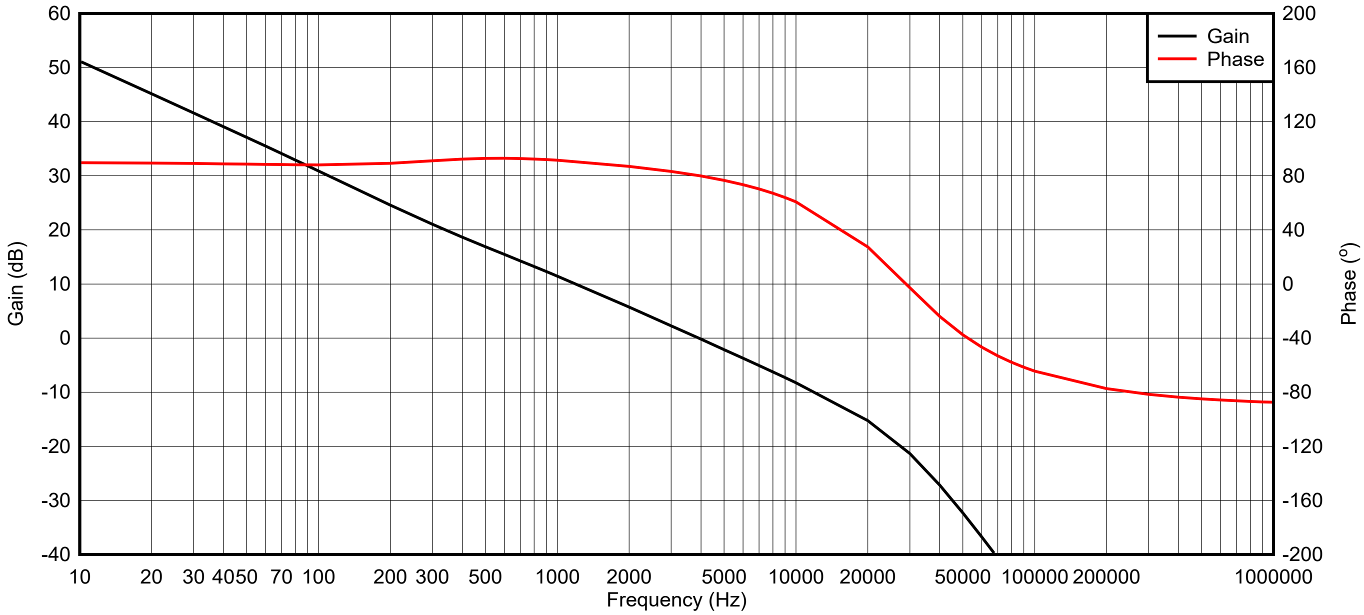

Figure 2-5. Bode Plot of Outer Voltage Loop

Figure 2-5 shows bode plot of outer voltage loop. Phase in mid-frequency range is boosted by type II compensation network. In this example, the crossover frequency is at about 4 kHz, and the phase margin is approximately 75 degree, which is greatly higher than the needed minimal 45 degree of a stable system. F_{P_COMP} is placed at 45.34 kHz which is lower than switching frequency (99.5 kHz) to minimize output ripple caused by MOSFET switching.

2.4 Implementation of Current Limit

The ISETA pin is analog current programming pin of LM5170-Q1. Figure 2-6 shows the inductor DC current is proportional to the ISETA voltage. V_{CS_dc} is the current sense voltage produced by the shunt resistor R_{CS1}. It has linear relationship with ISETA voltage by Equation 16.

$$V_{CS\_dc} = 0.02 \times V_{ISETA} \tag{16}$$

Or by Equation 17.

$$V_{CS\_dc} = I_{RCS1} \times R_{CS1} \tag{17}$$

Or by Equation 18.

$$I_{CS\_dc} = \frac{0.02 \times V_{ISETA}}{R_{CS1}} \tag{18}$$

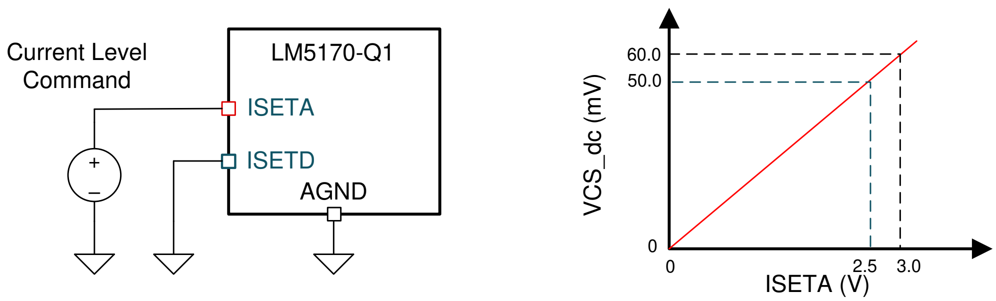

Figure 2-6. ISETA vs VCS_dc Graph of LM5170-Q1

To achieve the DC current limit, the ISETA voltage should be clamped. The DC current limit should be determined by maximum allowable load current of 12-V loads in the system. In this example, the maximum load current of the 12-V loads is about 13 A, therefore, VISETA should be clamped at 3.25 V approximately when 5-mΩ shunt resistor is used.

Figure 2-1 includes a simple VISETA clamp circuit consisting of TLV431B-Q1 and two resistor R_{CC1} and R_{CC2}. The resistor divider ratio sets the clamp voltage level. Note that R_{CC1} and R_{CC2} resistance can increase power consumption unnecessarily. In this example, R_{CC1} = 30.1 kΩ and R_{CC2} = 18.7 kΩ are used to limit the total power dissipation below 0.22 mW.

3 Experimental verification

The buck converter operation is verified by Texas Instruments LM5170EVM-BIDR evaluation module, as shown in Figure 3-1. The board is modified according to Figure 2-1 to implement the battery equalizer.

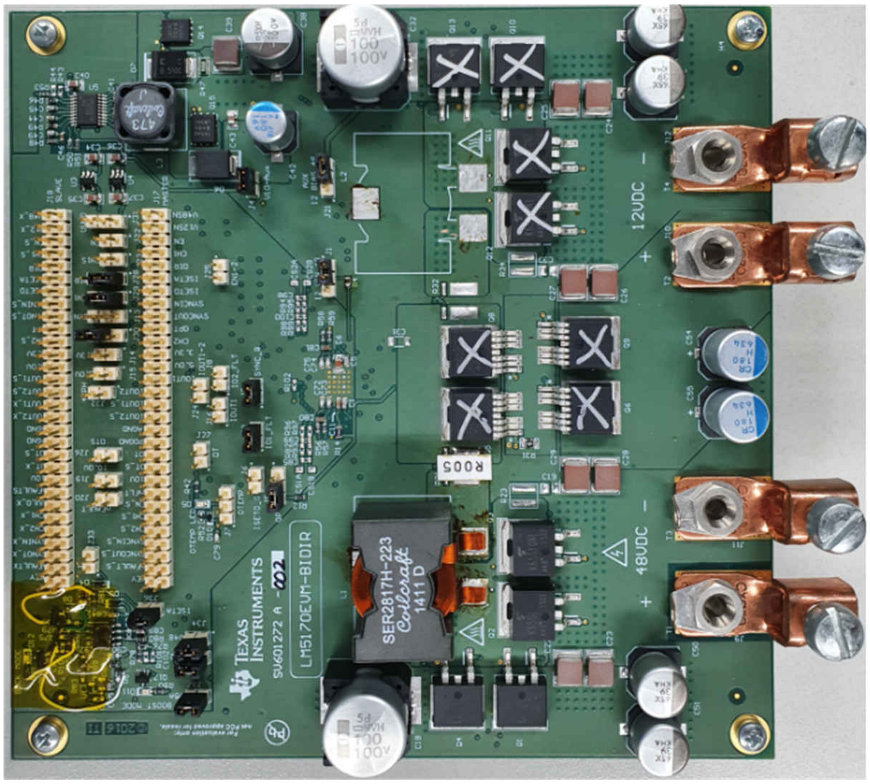

Figure 3-1. Test Board (Texas Instruments LM5170EVM-BIDIR Modified)

Figure 3-2 shows the measured buck converter efficiency versus output current.

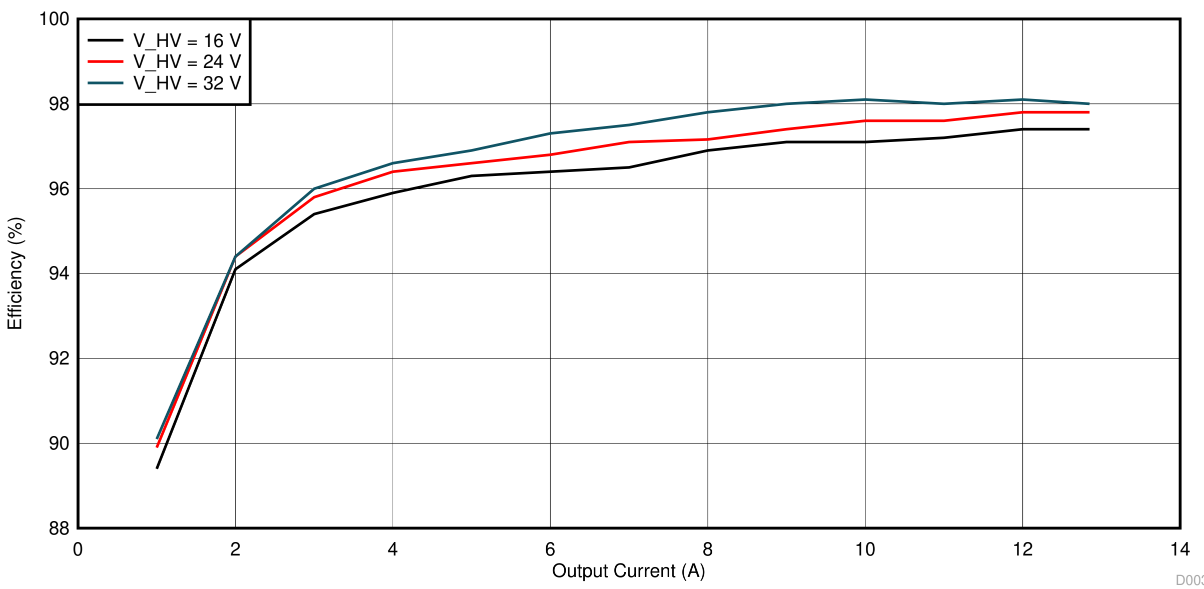

Figure 3-2. Buck Converter Efficiency

During constant voltage mode of battery equalizer, buck converter should keep constant ratio between input voltage and output voltage. Figure 3-3 shows transition of V_{LV} depending on V_{HV} (V_{HV} = 2 × V_{LV}).

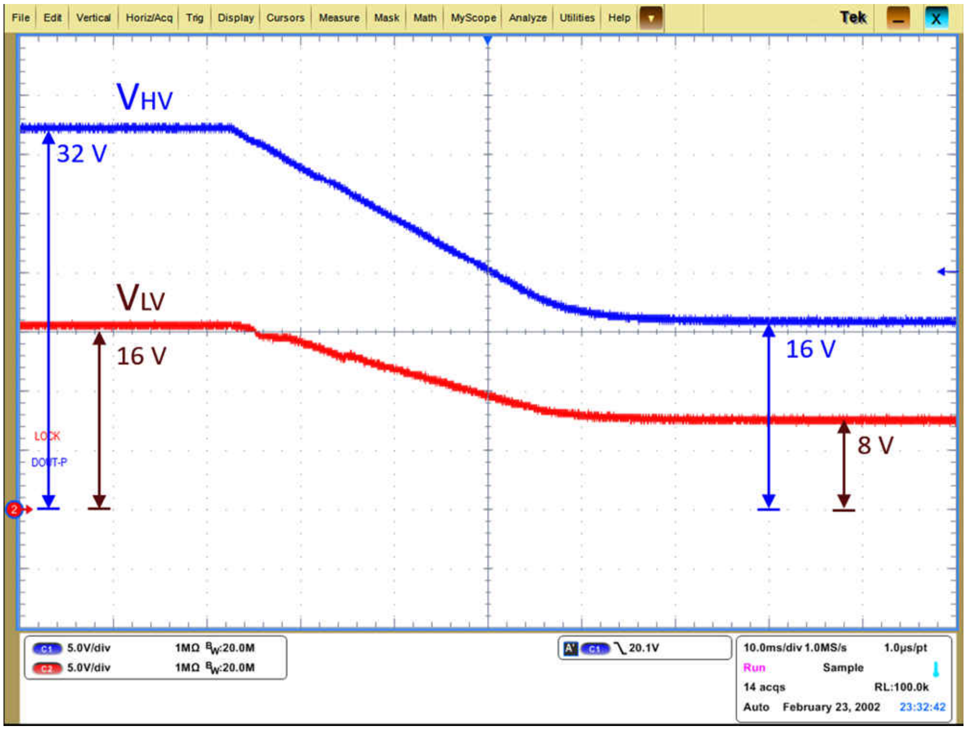

Figure 3-3. Input Voltage and Output Voltage Waveform in Constant Voltage Mode

During constant current mode of battery equalizer, the buck converter keeps the maximum output current. As shown in Figure 3-4, the output current (I_{out}) is maintained at 13 A (I_{max}) approximately. LM5170-Q1 IOUT pin is used to measure output current.

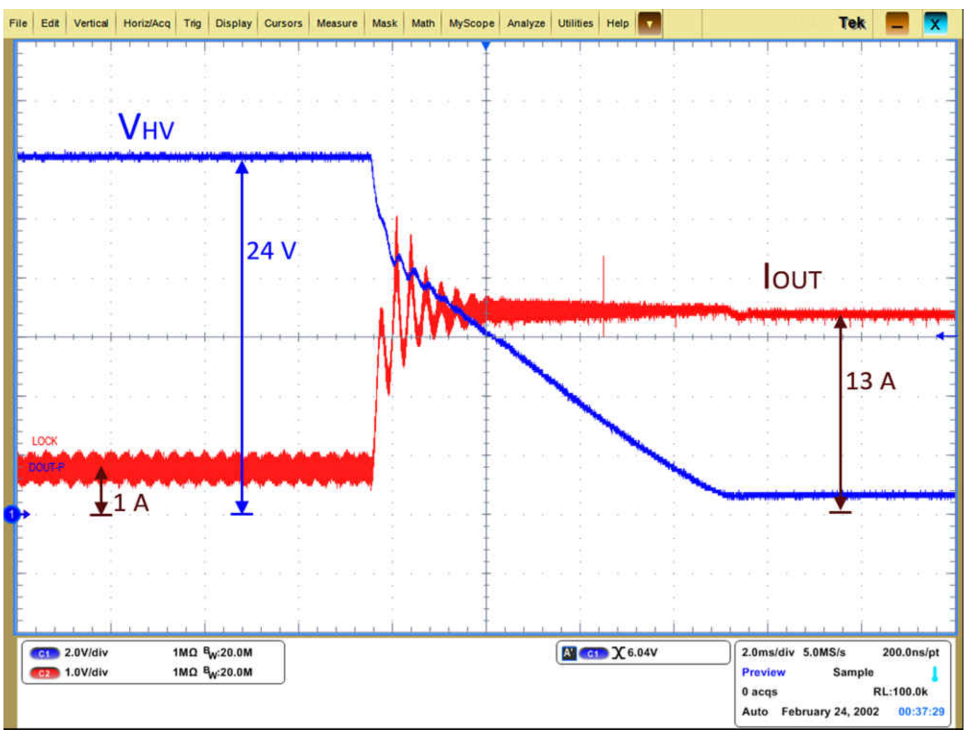

Figure 3-4. Input Voltage and Output Current Waveform in Constant Current Mode

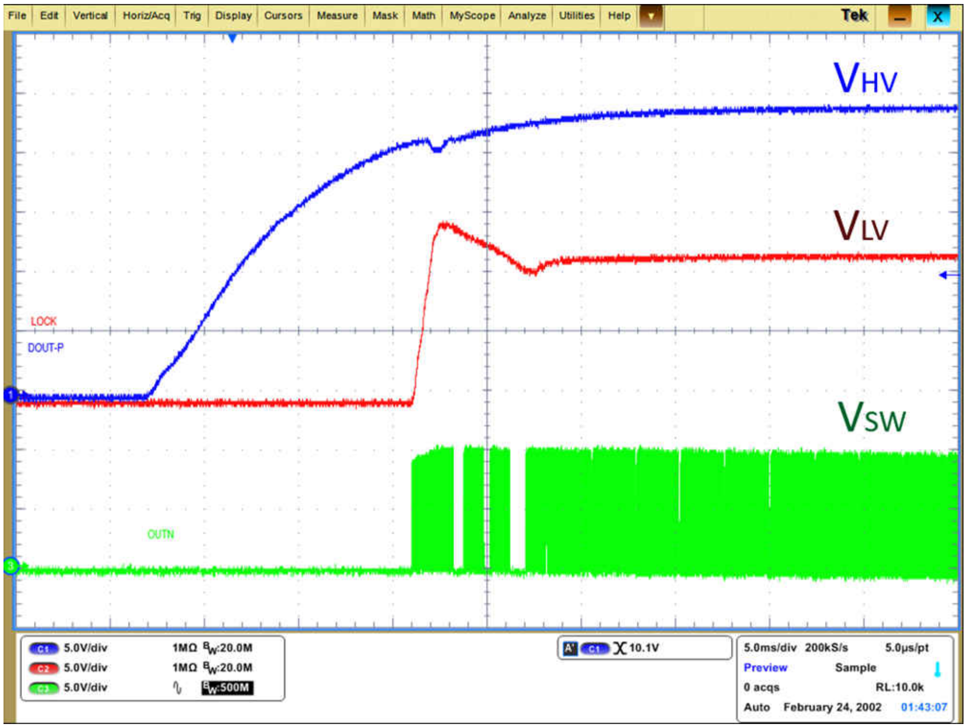

Figure 3-5. Start-up Sequence of Buck Converter

4 Conclusion

Texas Instruments LM5170-Q1 current controller is used to design buck converter for battery equalizer system. Battery equalizer helps to balance two 12-V batteries in commercial vehicles and allows commercial vehicle manufacturers to utilize both 12-V and 24-V loads more effectively. The presented solution with LM5170-Q1 can achieve well-balanced battery voltages, enhancing the batteries lifespan and overall system performance. The design is straightforward and can easily be modified for different commercial vehicles with different combination of electronics. The closed loop designs are presented, too, which can be followed by the readers in their own designs.

5 References

1. *Development of Battery Equalizer for Commercial Vehicle, The Korean Institute of Power Electronics,* Deok-kwan Choi, Jong-Cheol, Ho-sik Kim, Jae-kyu Park, Hyundai MOBIS, Hyundai-Kia Motors.
2. Texas Instruments, *Demystifying Type II and Type III Compensators Using Op-Amp and OTA for DC/DC Converters* application report.