Constant Current Constant Voltage (CCCV) Application for Power Adaptor with LLC Output Stage

Contents

Introduction

Renesas Inc. has a design guide describing a TDAIO-TPH-ON-240W-RD 240 W 24 V 10 A AC-DC power adaptor. The adaptor reference design illustrates a PFC + LLC implementation with peak efficiency of greater than 95%, a power density of 24 W/in^3 using 3 Renesas GaN TP65H150G4PS (650 V SuperGaN® FET) TO-220 with Renesas's latest Gen IV technology with OnSemi's NCP1654 CCM PFC controller and NCP1399AA LLC controller with output voltage 24 V / 10 A. If the heatsink height is re-designed to 20 mm, the design can achieve close to 30 W/in^3 power density. The design shows high-power density and efficiency.

The AC-DC power adaptor key specifications, features and key applications are listed below.

| Key Specs	Schematics
Input	90-264 Vac
Output Voltages	24V
Max Output Current	10 A
Max Output Power	240 W
Efficiency	~95% Full Power Efficiency @ 230V

Features

- Renesas SuperGaN TP65H150G4PS TO-220 x 3
- CCM PFC + LLC topology
- Board-end ~95% Efficiency (90 Vac)
- Flat Efficiency Across Universal (90 - 265 Vac) Input Voltage and Load
- Tight Switching Frequency Regulation forImproved Input EMI Filter Utilization
- Up to 180 kHz Switching Frequency Operation
- OTP, UVLO, OCP, and OSC Protections
- < 300 mW No Load Power Consumption
- Up to 240 W Output Power

Applications

- High-Power-Density AC/DC Battery Chargers (CCCV)
- High-Power-Density AC/DC CV Power Supplies
- High-Power-Density AC/DC LED Dimmable Drivers
- Gaming Devices
- Fast charging
- Laptops and IoT devices

The adaptor has two stages. The first stage is an AC-DC PFC stage. The second stage is an LLC Stage that provides galvanized isolation and output voltage regulation. The LLC stage schematic is re-produced below.
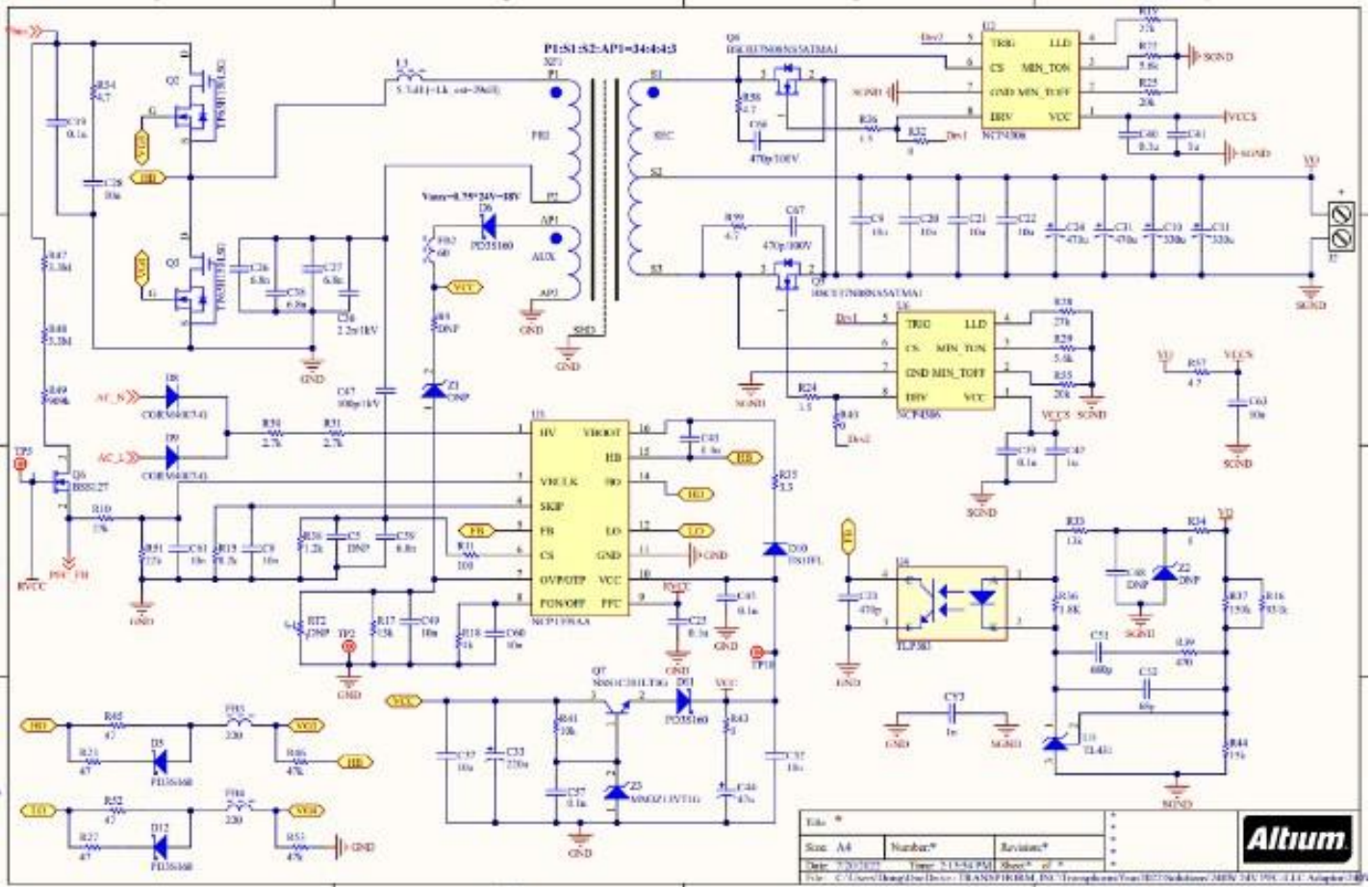
240W LLC Section Schematic

The LLC controller IC NCP1399AA operates the resonant circuit consisting of Q2/Q3, L3, XF1, and C26/C27/C36/C38 to transfer energy from PFC stage output DCBUS (across C19) to transformer XF1 secondary output. XF1 secondary output voltage is monitored and regulated by U5 TL431.

The LLC controller IC NCP1399AA monitors the resonant circuit current magnitude, proportional to voltage across the resonant capacitors C26/C27/C36/C38, through the capacitor divider C47/C59 and R11 at pin 6. When resonant circuit current magnitude is detected too high, NCP1399AA stops operation for about 1 second before retrying. This protection feature of the controller IC has been utilized to implement the Over Current Protection (OCP) function for the adaptor. When the adaptor output is overloaded, the controller NCP1399AA forces the output to hiccup, hence limits its output power. TDAIO-TPH-ON-240W-RD resonant circuit component values and the feedback components are tuned to provide OCP at 13 A ~ 16 A output current level.

Although TDAIO-TPH-ON-240W-RD adaptor has an OCP protection feature, it hiccups but does not regulate output current to a constant level. When TDAIO-TPH-ON-240W-RD is used in battery charger application, additional constant current regulation stage needs to be inserted between the adaptor and battery. Li-Ion battery typically requires constant current charging with a voltage limit at its rated voltage. Charger needs to provide constant current and constant voltage function (CCCV). TDAIO-TPH-ON-240W-RD already has a constant voltage (CV) output function. We would like to understand how practical an LLC stage can provide a constant current (CC) output function additionally.

Li-Ion Battery Characteristics

Before moving to CCCV implementation for the adaptor LLC Stage, we would like to understand how Li-Ion battery behaves as a load to a charger. We took a size 18650 Li-Ion battery for some tests. The size 18650 battery rated voltage is 3.7 V. Before any tests, the battery positive terminal has been taped up for last few years (~5 to 6 years at least). We remove the tape and measure the battery terminal voltage. It is about 2 V.

Next, we connect some resistors (about 1 Ω) to discharge the battery to 0.3 V for about 30 minutes. The discharge resistor is removed. The battery is left no load for about one hour. Its terminal voltage recovers back to 1.78 V. We estimate Li-Ion battery operating voltage range is half rated voltage to rated voltage. For size 18650 battery, this range is 1.8 V ~ 3.7 V.

Next, we do a charge up test. Below is a picture of the charge up test along with a scope waveform picture of battery terminal voltage (purple) and current (blue). We limit the voltage to 3.7 V and current to 0.39 A. We observe that the battery terminal volage jumps from 1.78 V to 2.9 V in 1.5 minutes. The entire charging process takes about 4 hours before battery terminal voltage reaches its rated 3.7 V.
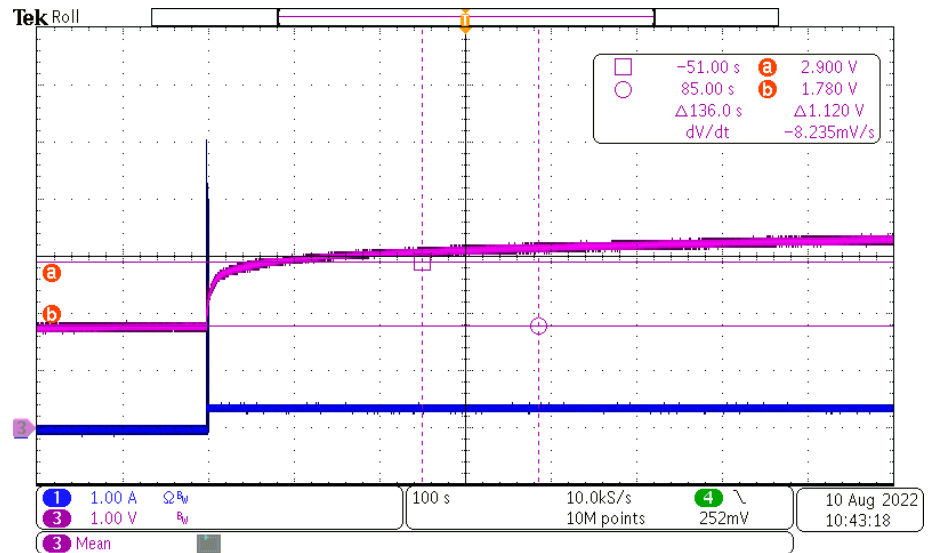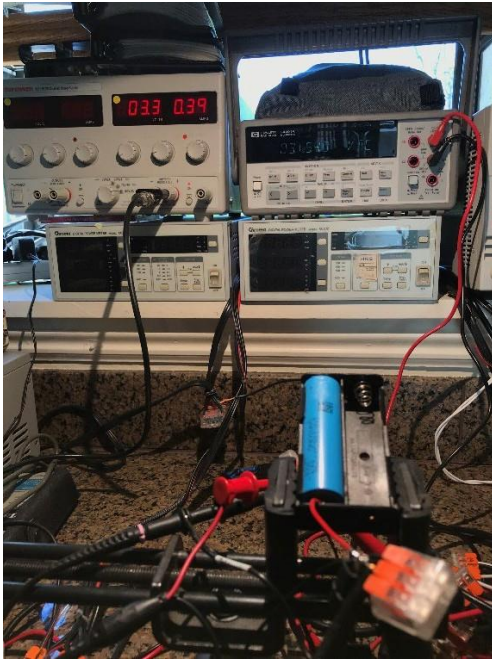
Constant Current Constant Voltage (CCCV)

A traditional CC/CV OpAmp IC circuit is used to implement this function to replace the TL431 regulator circuit on the XF1 secondary side (output side) of the TDAIO-TPH-ON-240W-RD adaptor.   An AP4310A IC is selected such that we can route arbitrarily chosen Vref value to the current regulation OpAmp.

A low resistance value high power current sense resistor is placed in series with the main output path for output current sensing while minimizing the loss. Since the sense resistor terminal voltage is at low value, requiring small signal processing at OpAmp circuit might be subject to common mode noise interference from the main adaptor power converter circuit. We choose to amplify this current sense signal before the OpAmp circuit. A good differential wide operating voltage OpAmp NCS20071 is chosen here.

Detail CCCV circuit and layout (top and bottom layers) are below.

5100-00001-1 Rev2
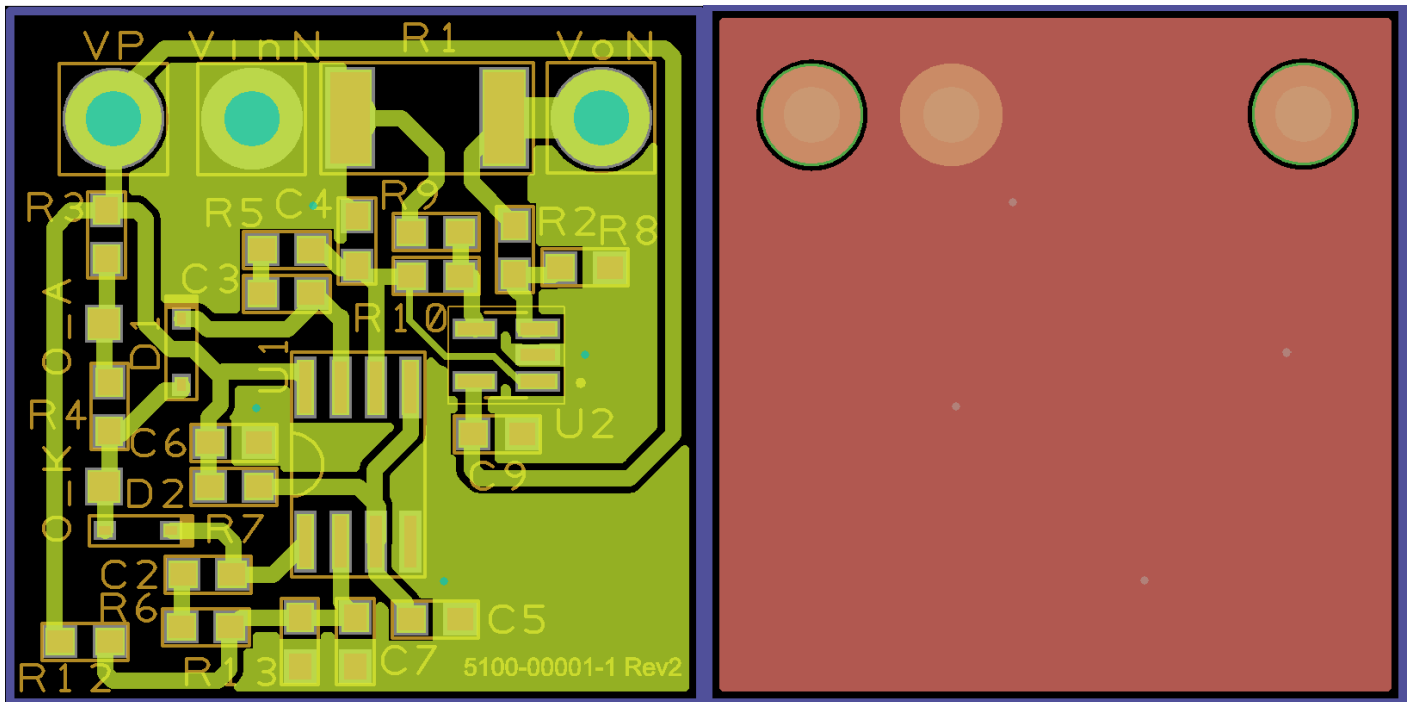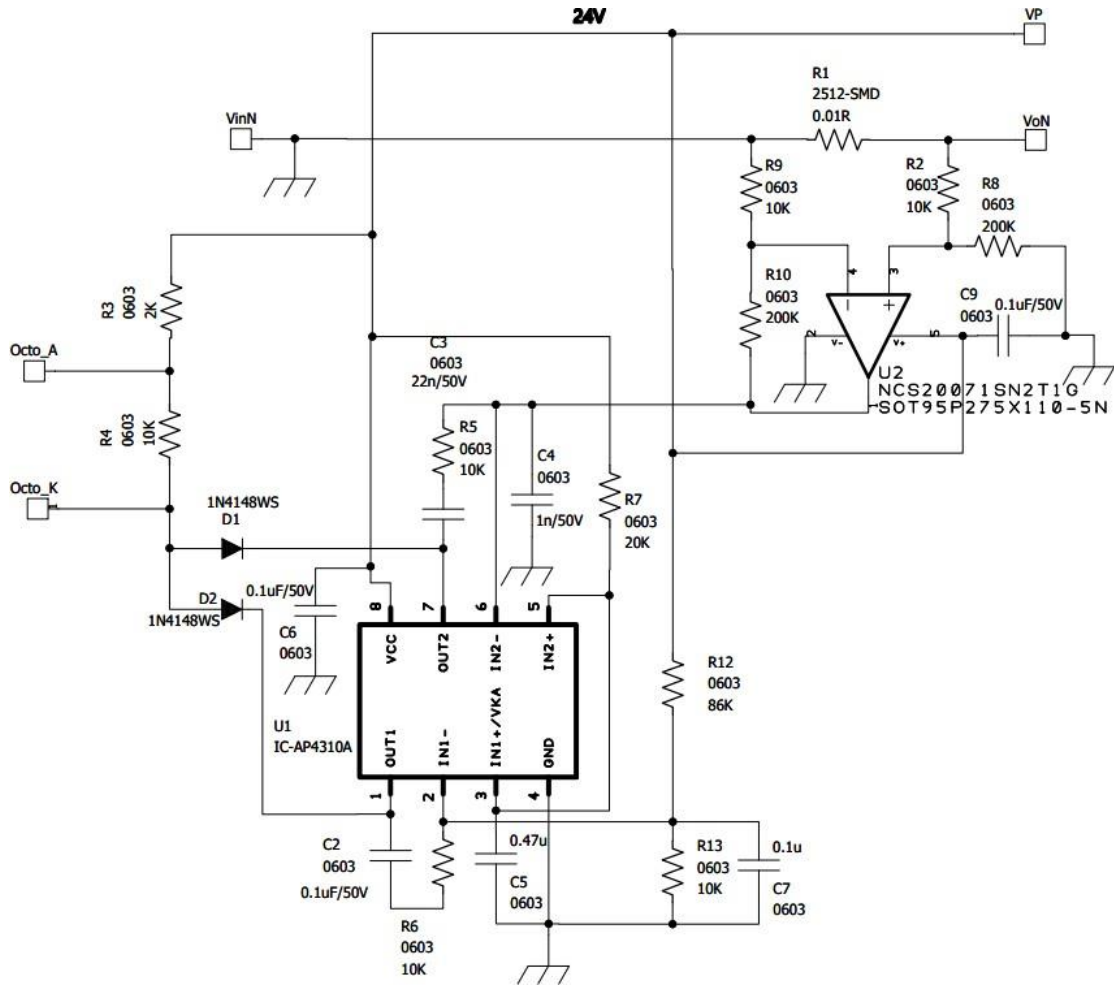
Below shows the CCCV daughter board being mounted on top of a TDAIO-TPH-ON-240W-RD adaptor output two terminals. The optocoupler IC U4 TLP383 two input pins are lifted off from the main adaptor PCB and re-connected to Octo-A (O_A on PCB) and Octo-K (O_K on PCB) pads on the CCCV daughter board. C59 on TDAIO-TPH-ON-240W-RD adaptor board has been increased to 10nF so that its OCP function does not come too soon to interfere with the newly added CC function. Both output Vo vs Io and entire adaptor efficiency data are collected as below plot as well. The tests are conducted with Vin = 110 V.
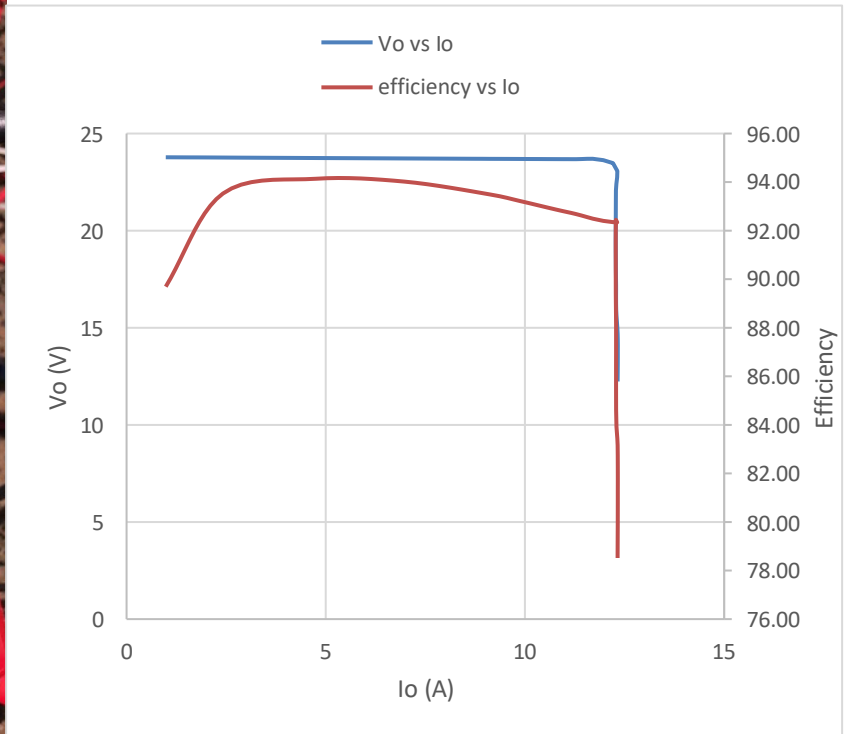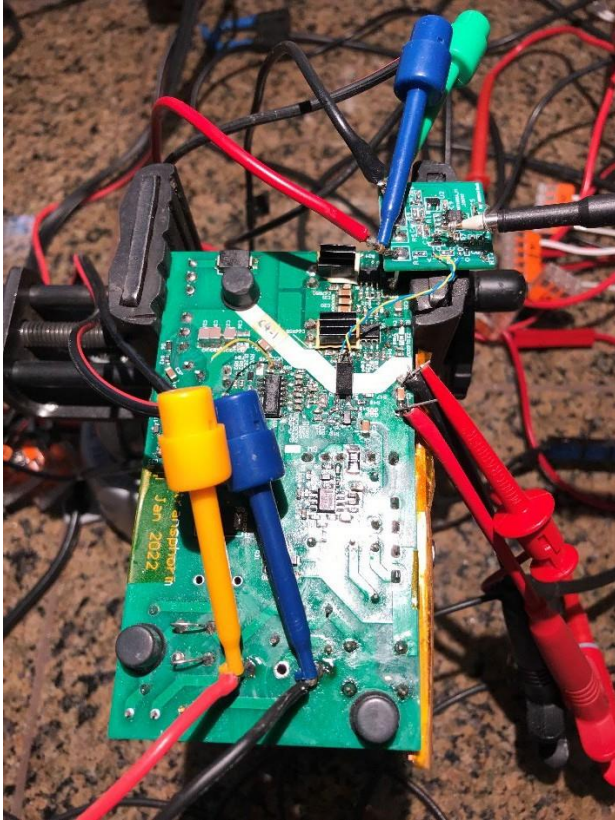
The test is conducted with an electronic load set in constant resistor mode. The collected data shows that the TDAIO-TPH-ON-240W-RD adaptor with an add-on CCCV daughter card can provide the CCCV function well. Before the output load current increases to 12.2 A, the set constant current (CC) level, the output voltage is maintained at 24V. Once output current increases to 12.2 A, output voltage is brought down such that the CCCV circuit can maintain the constant current (CC) level at 12.2 A.

We conducted the test until the output terminal reaches ~ 12 V and noticed that the entire system efficiency comes down to 78.5%. At this operating point, Pin = 192 W, Po = 150.8 W. The adaptor power loss is 192 W - 150.8 W = 41.4 W. This loss is too high to be practical.

By examining the system efficiency curve above, we find that if we keep TDAIO-TPH-ON-240W-RD output voltage within 20% of its rated 24 V value, system efficiency can be maintained above 90%. It is important to keep

the efficiency at 90% for the adaptor such that we do not need to increase components and overall solution size. Our earlier test on Li-Ion battery shows that the battery terminal voltage can be charged to within 20% of its rated voltage from empty within 1.5 minutes. There is enough thermal mass in the adaptor to withstand twice the normal loss for 1.5 minutes duration. This indicates that LLC + CCCV control is good to implement as a Li-Ion battery charger. User would need to monitor the resonant circuit component temperatures closely, and to shut down in case if there is any prolonged operation outside 20% of battery rated voltage.

A safer solution is to use the LLC as the CV output only, and to follow with a buck converter for CC operation to the battery. This is the traditional approach of AC-DC constant voltage adaptor + Buck battery charger. Although it is more costly, this method would be able to handle longer time operation if battery voltage does not come back up fast enough to within 20% of its rated voltage.

Analysis of TDAIO-TPH-ON-240W-RD LLC section

What is the reason that TDAIO-TPH-ON-240W-RD efficiency drops so quickly during constant current operation? Resonant frequency

f0 = $\frac{1}{2\pi\sqrt{CrLr}} = 154kHz$ where Lr and Cr are the resonant inductance and capacitance

Ln = $\frac{Lm}{Lr}$ = 9.38 where Lm is the magnetizing inductance of the transformer XF1.

For constant current operation,

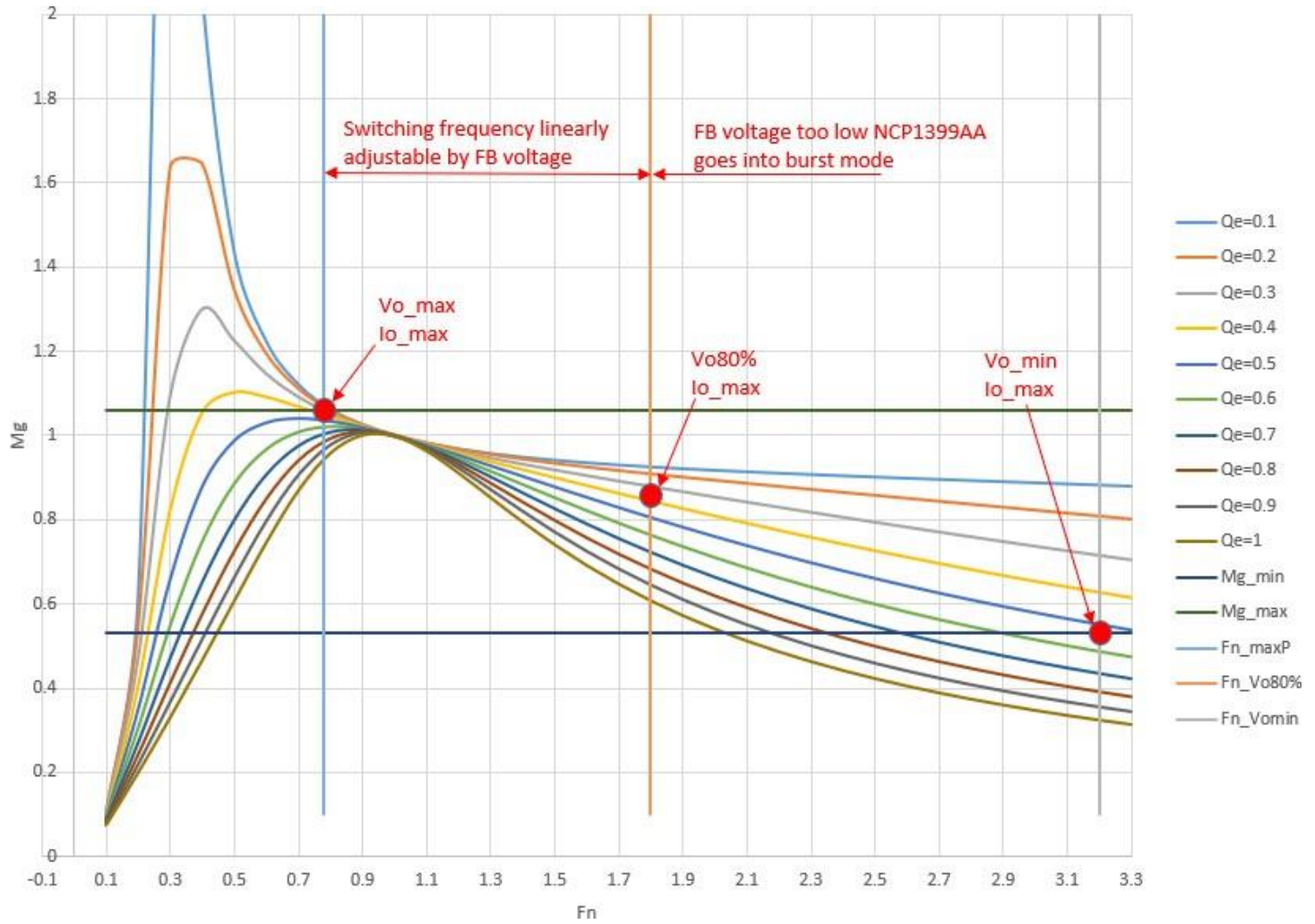Vo_max = 24 V, Io_max = 12.2 A, the quality factor Qe_min = 0.27.

At half battery voltage,

Vo_min = 12 V, Io_max = 12.2 A, the quality factor Qe_max = 0.54.

At 80% Vo_max,

Vo_80% = 19.2V and Io_max, the quality factor Qe_Vo_80% = 0.34.

Below is the gain vs normalized frequency plot of TDAIO-TPH-ON-240W-RD.

Two horizontal lines (green and blue) correspond to maximum and minimum gains for 24 V and 12 V output voltages. The 3 red dots correspond to operating points at Vo_max (24 V), Vo_80% (19.2 V), and Vo_min (12 V). Operation between Vo_max and Vo_80% can achieve > 90% efficiency. Resonant loop current is observed to be continuous. Operations between Vo_80% and Vo_min have efficiency drop quickly and resonant loop current is in pulse mode (discontinuous). A scope picture is below with CH1 (blue) Io, CH2 (light blue) Vbus, CH3 (purple) CC regulator output (AP4310A pin 7), CH4 (green) LLC resonant loop current. The resonant loop current is not stable at pulse mode. The pulse resonant loop current magnitude is much higher than the continuous current. This might be the primary reason why efficiency drops quickly. It is believed that NCP1399AA controller linear frequency range is only up to ~1.8 Fn (~ 280 kHz). Beyond this switching frequency the FB pin voltage might drop too low to force the loop into pulse mode operation.
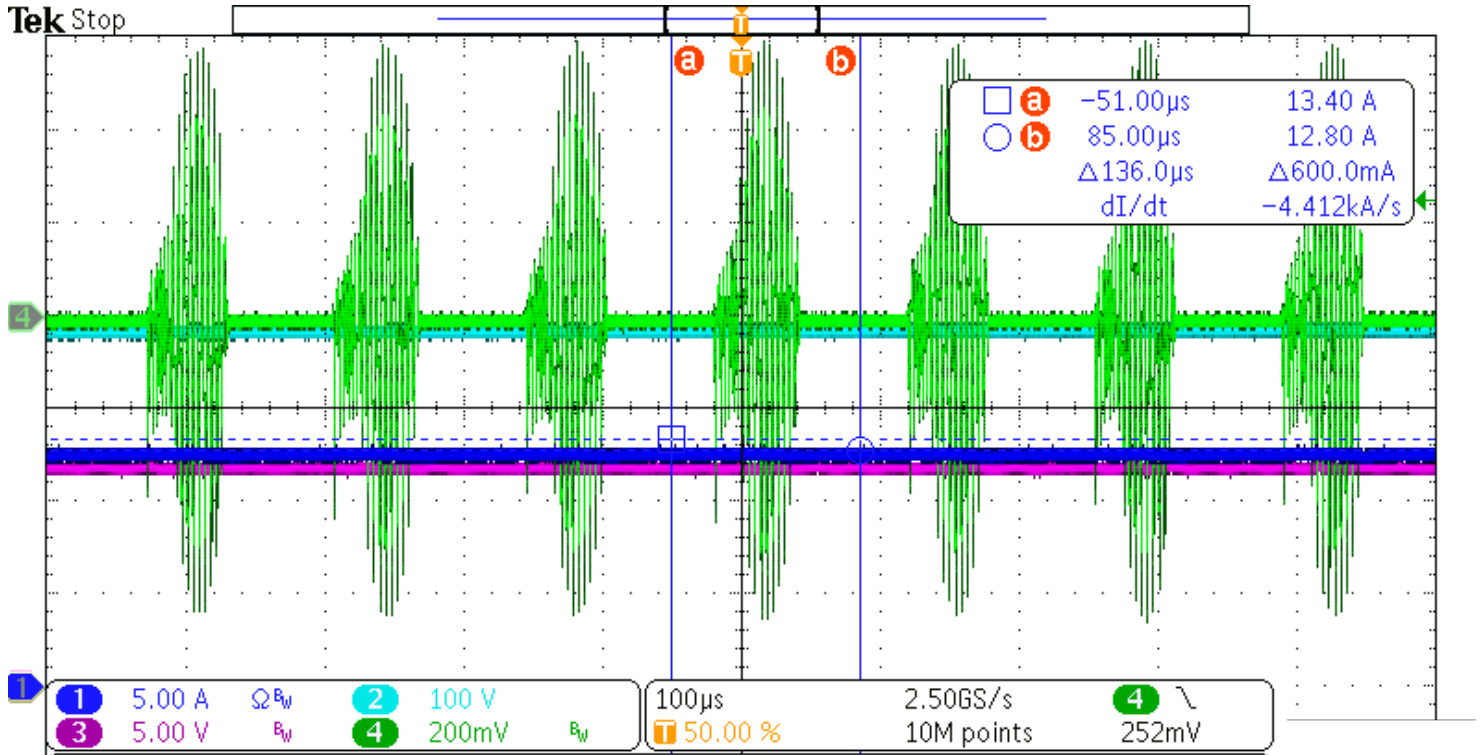
Transformer XF1 turn ratio is 34:4:4:3. When output is 24 V, auxiliary winding receives 24 V x ¾ = 18 V. When output is reduced to 12V in constant current operation, auxiliary winding only produces 12 V x ¾ = 8 V. With the deduction of multiple diode voltage drops, NCP1399AA Vcc would only receive 6.4 V. This gate voltage level may not be able to drive Q2 and Q3 fully on and might contribute to extra efficiency loss.

Re-Design TDAIO-TPH-ON-240W-RD LLC section for CC/CV operation

It is interesting to see the TDAIO-TPH-ON-240W-RD adaptor efficiency drop so fast along with output voltage in the constant current region. If the resonant loop components are re-designed to limit the operations within the linear region, it is possible to achieve some efficiency improvement. TDAIO-TPH-ON-240W-RD CV output is at 24 V. Half of this voltage is 12 V. It is uncommon for an end application battery pack to have such voltage requirement. The re-design would generate a new LLC stage that gives CV at 76 V and CC range between 38 V ~ 76 V. For convenience, the CC current is set to 4.2 A. Peak output power can reach ~ 320 W.

To achieve such a wide output voltage range, we want to limit the LLC switching frequency range into where NCP1399AA can accommodate. Below is a gain vs frequency plot with resonant loop Lr ~= 90 µH, Lm ~= 130 µH and Cr ~= 10 nF. Frequency range to cover output voltage range has been reduced to 1/5 of TDAIO-TPH-ON-240W-RD. Comparison to TDAIO-TPH-ON-240W-RD standard resonant loop components, Lr value is higher

indicating higher DCR loss, Lm lower indicating higher magnetizing current magnitude also higher loss. We are expecting efficiency is expected to drop to accommodate the wide output voltage range. The Cr value is lower and C59 value is needed to increase for proper OCP limit set point. 47 nF is selected for C59.
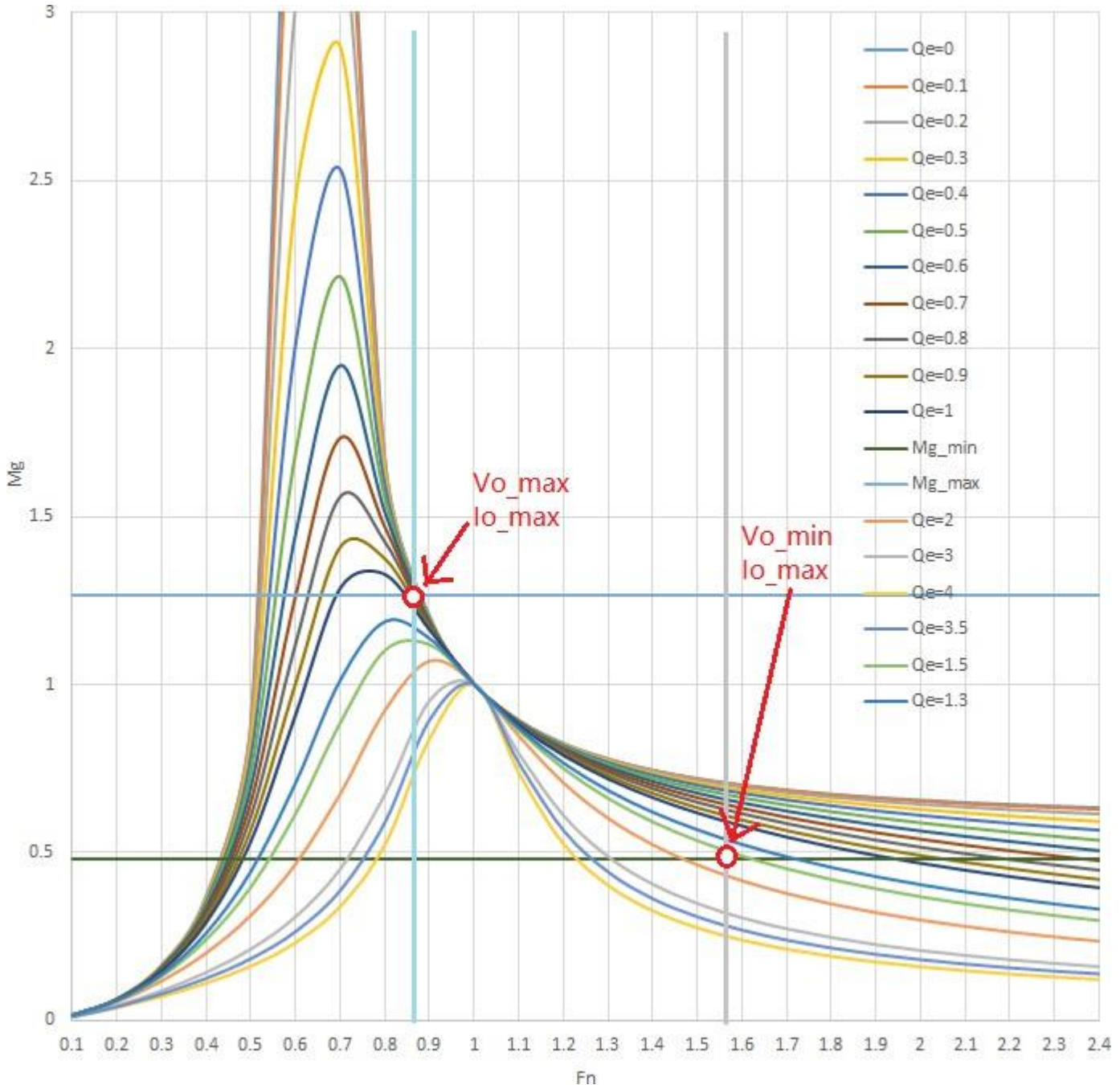

The LLC output voltage range 38 V ~ 76 V is much higher than 24 V of TDAIO-TPH-ON-240W-RD adaptor. The output components will need to be changed to accommodate higher voltage limit. As illustrated in the schematic below for the LLC output side, the sync FETs are changed to 200 V rating. The sync FET controller has been changed to MP6924 to save some space and better support. S1~S4 are LLC transformer output secondary

winding terminals. AS1 AS2 are from a secondary side auxiliary winding providing energy for a regulated 12 V supply to supply all secondary ICs and potential customer processor for additional battery management purpose. This 12 V power supply is additional to TDAIO-TPH-ON-240W-RD and it is expected to lower efficiency as well. The AP4310A and NCS20071 are the CC/CV controllers outputting to an optocoupler at terminals O_A and O_K. Optocoupler provides feedback to NCP1399AA on LLC primary side.

For a stable constant voltage operation, C7 is removed. To achieve stable constant current at rated 4.2 A operation with constant resistor load, the CC controller loop has been tuned to quite slow with R5 bypassed, C4 0.1 μF, and R11 100 kΩ. R1 is changed to 0.03 Ω for ~ 4.2 A rating.
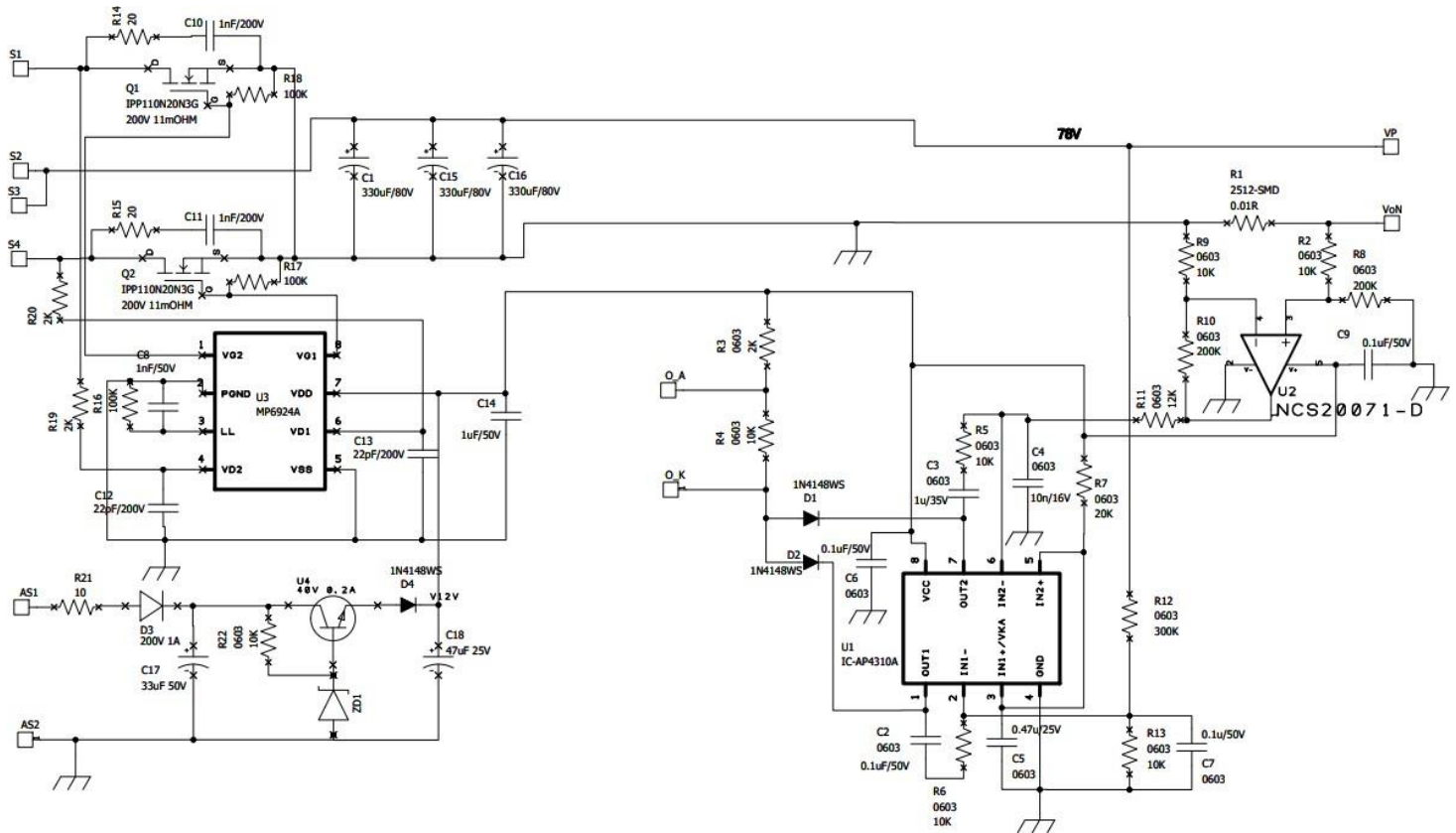
These are the PCB top and bottom layers.
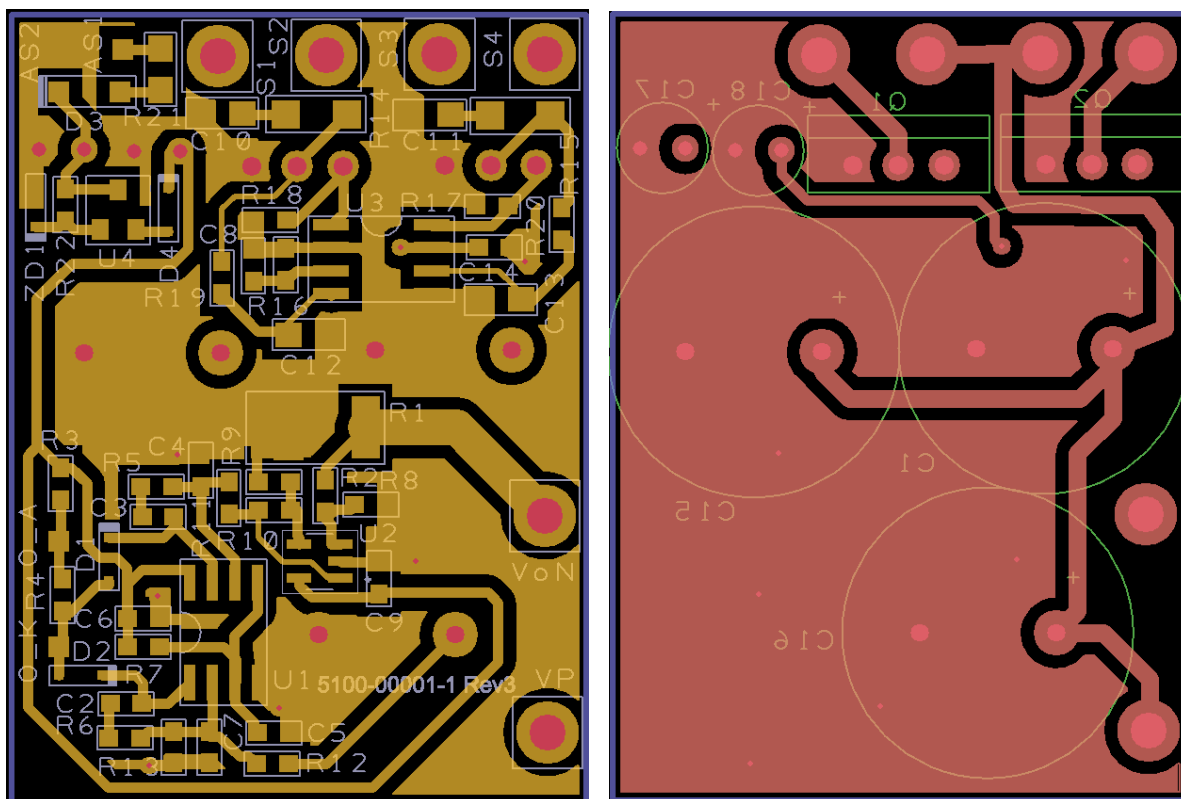
Beside the resonant loop component values changes on LLC primary side, transformer XF1 adds a secondary size auxiliary winding with turn ratio 24:4:8:8:4 with magnetizing inductance of 130 µH. D6 has changed to a 200 V 1 A diode. C37 and C33 voltage rating must be able to handle > ~ 40 V. Below picture shows the resulting prototype under bench test.
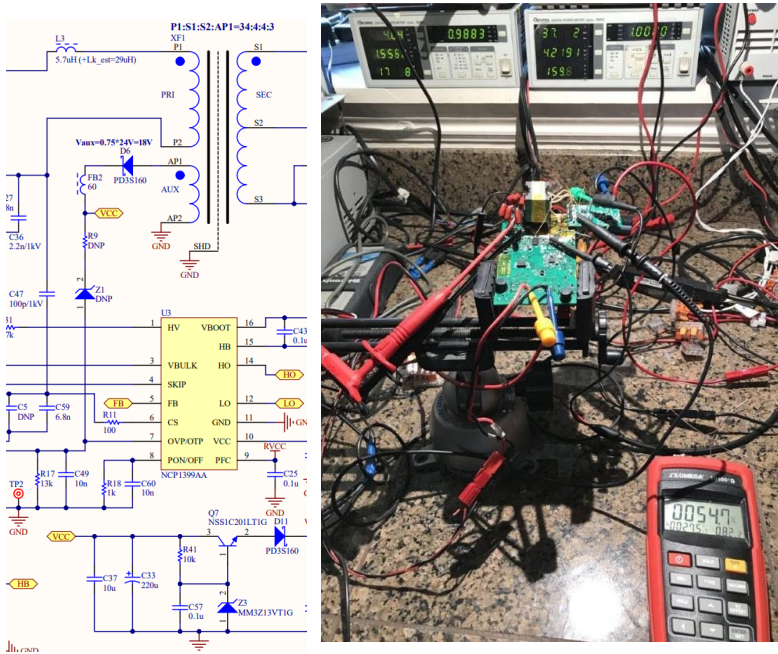
Below is a comparison plot running at 115V Vin. CCCV profile with 38 V ~ 76 V Vo 4.2 A Io is achieved with overall system efficiency staying above 91%.
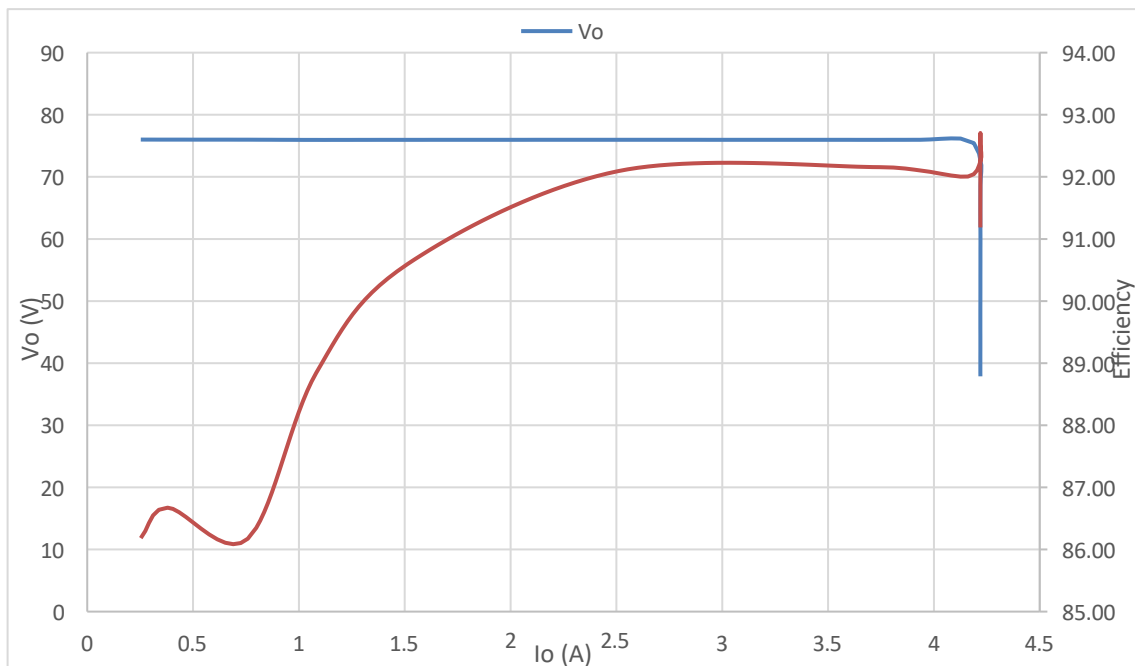
Below are a few plots of system performance during the CC wide output voltage range.
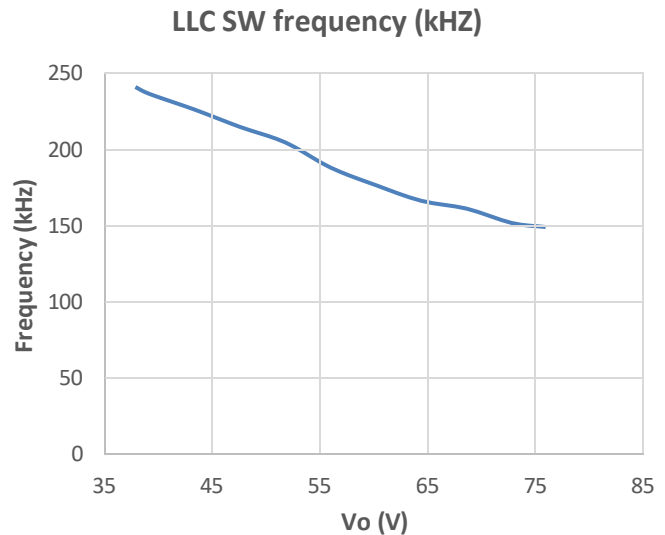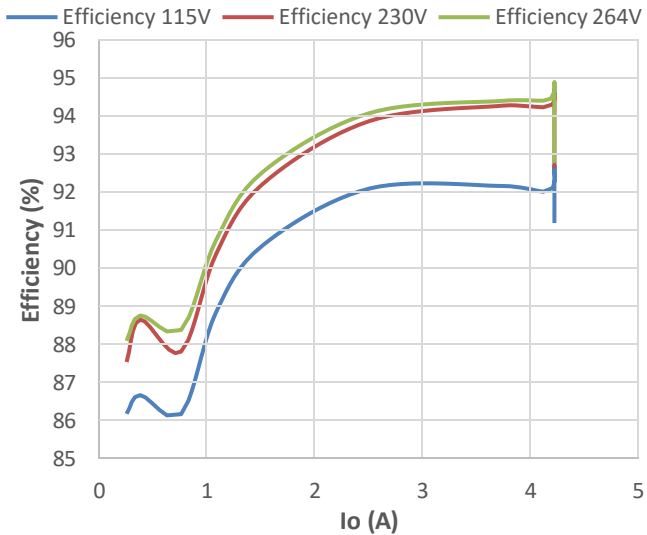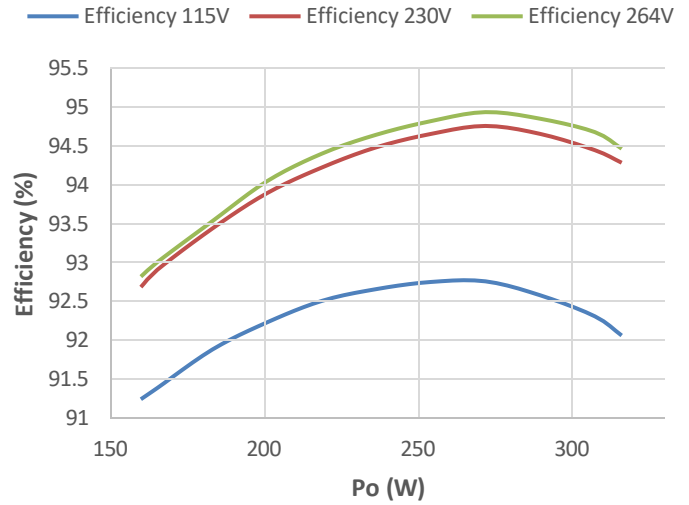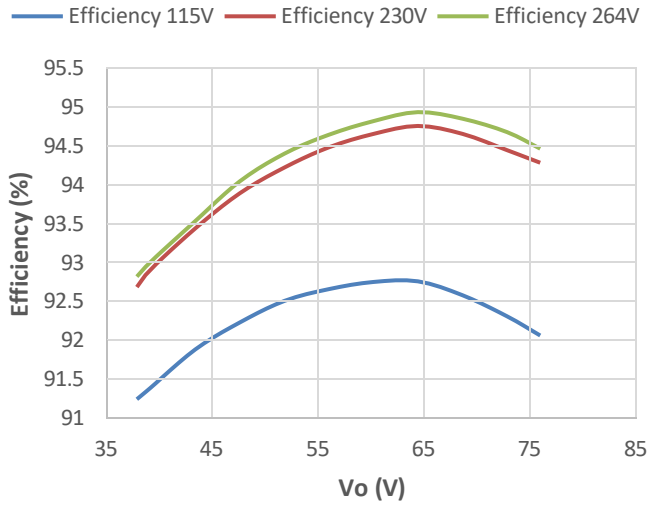

As compared with TDAIO-TPH-ON-240W-RD CV adaptor, system efficiency is 1.5% lower when accommodating a wide output voltage range while working in CC mode. However this implementaition is > 3% higher than a published design [2].

Accommodating Wide Constant Current Range

The CCCV circuit in the previous section has a very slow constant current control loop. When output load draws current rapidly, the control loop does not react fast enough, allowing current to overshoot and cause instability. This circuit is only able to handle constant current after the output settles onto a constant voltage of 76 V. A full constant current of 4.2 A is achieved by slowly lowering the electronic load constant resistor value. Any load that is lower than 4.2 A at output voltage below 76 V is not possible. Powering up into any constant current value below 76 V is not possible as well due to instability.

In general, applications like battery chargers and LED lighting request lower output current than rated. The CVCC output board of previous section has been modified as below schematic for faster current regulation loop. To accommodate faster switching frequency enabled by using GaN devices, R16 value has been adjusted down. During light load operation, the LLC controller NCP1399A operates at skip/burst mode, secondary auxiliary winding AS1/AS2 may not provide enough energy for a stable 12 V supply for the secondary circuits. The BCX56 transistor circuit taps into the energy stored in the bulk capacitors C1 and C15 only when the 12 V is not maintained from AS1/AS2 auxiliary winding.
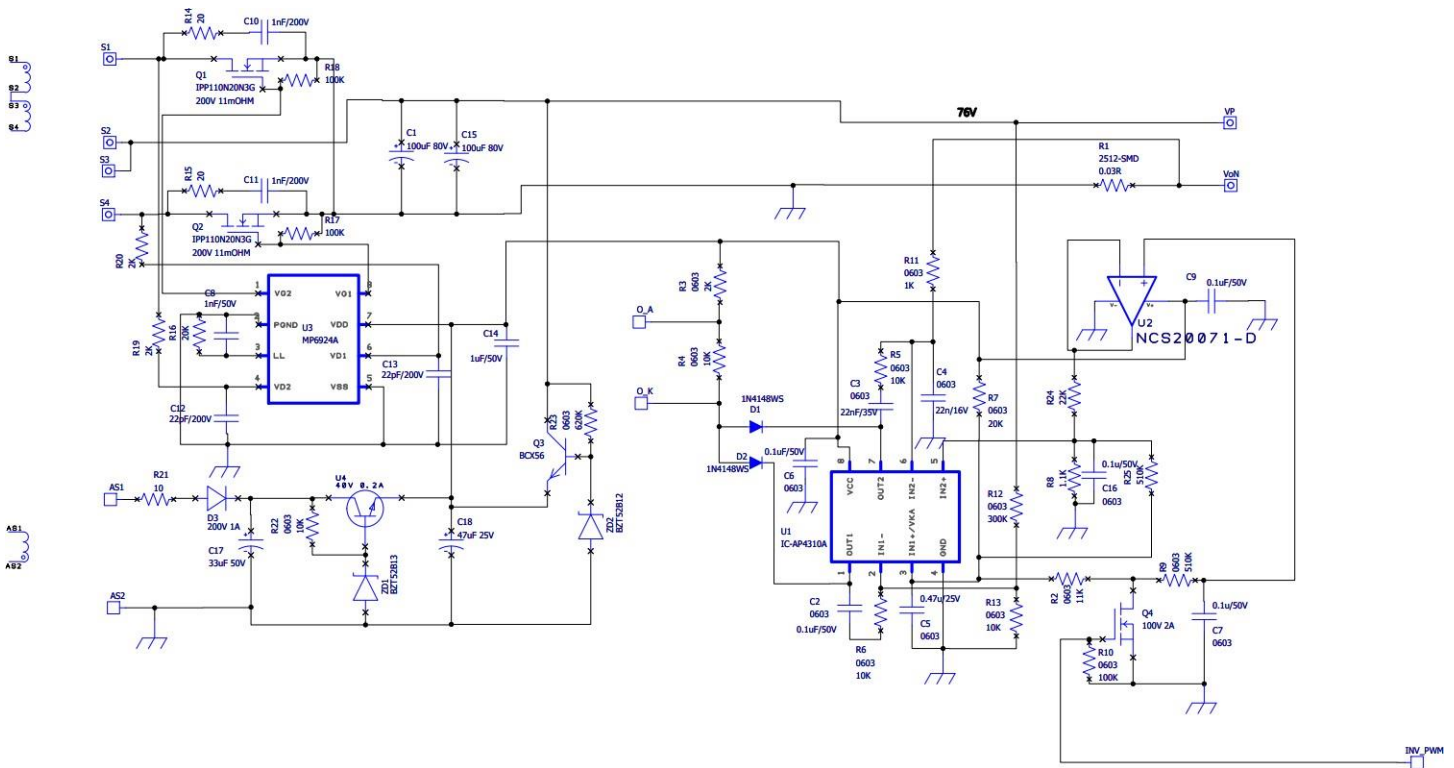
Previous CC implementation uses NCS20071 (U2) to boost the sensed current signal to compare with Vref of 2.5 V from U1 pin 3. That U2 circuit has a gain of 20. Combined system gain for current regulation is too high causing Current instability. In the new circuit above, U2 boosting function has been removed. Sensed current signal is directly introduced to pin 6 of U1. Since we remove the gain of 20 from the current feedback path, we need to scale the 2.5V down appropriately. This is done by using R24 and R8. For lower than rated current request (typically from a microprocessor), a PWM input is added. Due to Q4, this PWM signal needs to be in inverted polarity (logic high to represent 0%, logic low to represent 100%). The PWM signal uses Q4 to scale down the 2.5V Vref appropriately. The resulting chopped signal (PWM) at drain of Q4 is smoothed out by R9 and C7. Appropriate PWM signal frequency can be 1 kHz. U2 is used to provide a strong and low impedance representation voltage for C7. Unfortunately, U2's own offset at its output affects the PWM resolution at low dimming level. R24 and R8 scale this voltage down appropriately. R25 provides a rough 5% lowest current level.

Please note that R10 connects to GND. During the power up, if there is no PWM input, the adaptor will provide full current. R10 can be re-configured to 12V for minimum output current at power up.

Below are a couple pictures of the bench proto implementation. Electronic load ET5411 is set to LED load with variable VLED and ILED with coefficient of 0.186. ET5411 implements the following equations for LED load.
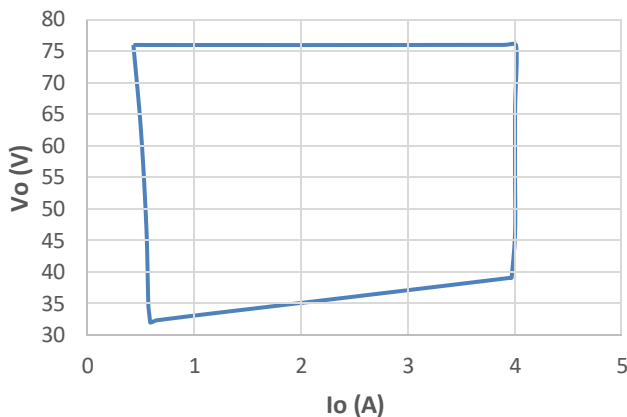
$$V_f = V_{LED}(1 - C_{oeff})$$
$$R_{LED} = \frac{V_{LED}C_{oeff}}{I_{LED}}$$

where V_f is the LED forward voltage before conducting current. R_{LED} is the equivalent resistance slope after LED conducts current. V_{LED}, I_{LED}, C_{oeff}, V_f and R_{LED} can be derived from any LED V-I characteristics curve.
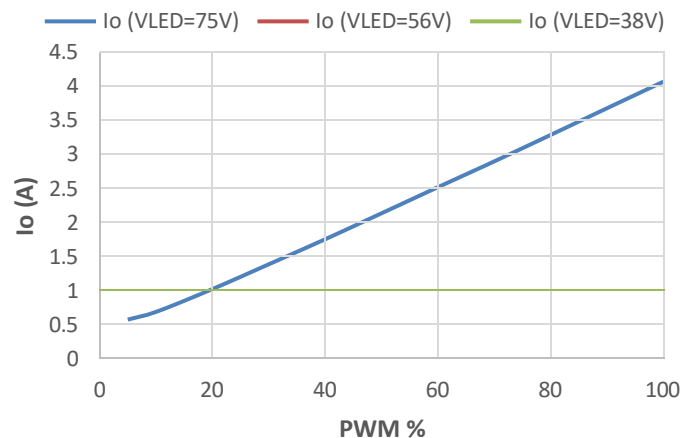

Below are the achieved output operating V-I range and PWM dimming characteristics.

Below are efficiency plots at various output voltage (V_{LED}). It is noted that there are some sudden changes in the efficiency plots. These are due to the LLC controller NCP1399A moving from continous resonant loop current to burst mode. Transition from continous resonant loop current to burst mode operation increases the peak current magnitude of the resonant current. This can reduce the efficiency by ~ 1.5%. This is evident that an LLC controller IC with as wide as possible frequency adjustable range is prefered for applications with such wide range in output votlage and output current to avoid getting into the burst mode too soon.
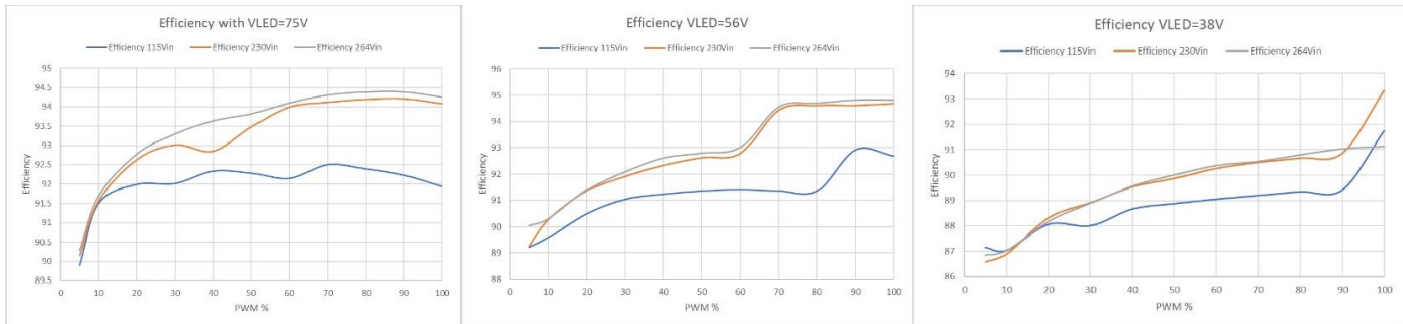

Below are a couple plots for the LLC resonant frequency with full output current while varying output voltage. This is the linear range for resonant frequency that NCP1399A can adjust to before burst mode is used. The range ratio is ~ 1.7, consistent to the estimated range of 1.8 in the previous Analysis and re-Design sections.
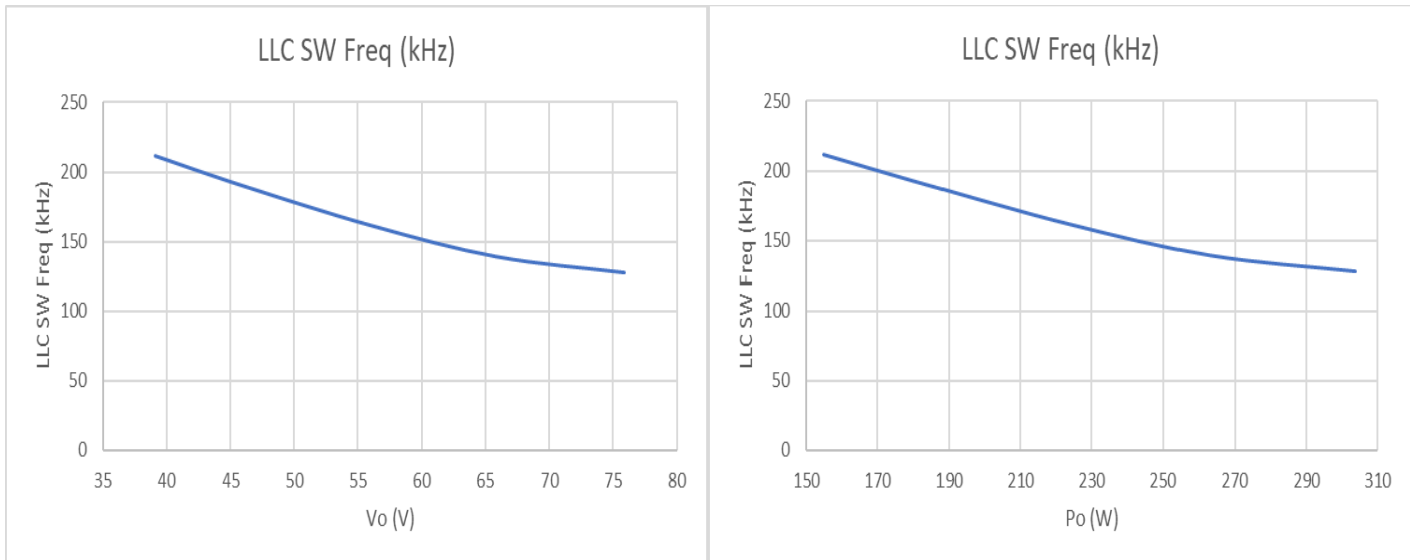
Simpler Application Architectures

A traditional battery charging system is depicted in the block diagram below. The fuel gauge circuit collects battery charge and health information for a battery management microprocessor (BMSP) for control, display, and warning purposes. In the event when the battery needs charging, the BMSP sends commands to a processor on the AC-DC adaptor side. The adaptor processor (AP) interprets the commands and translates them into appropriate

command format (mostly analog) for the CCCV loop in the adaptor. The adaptor is built with CCCV capability.
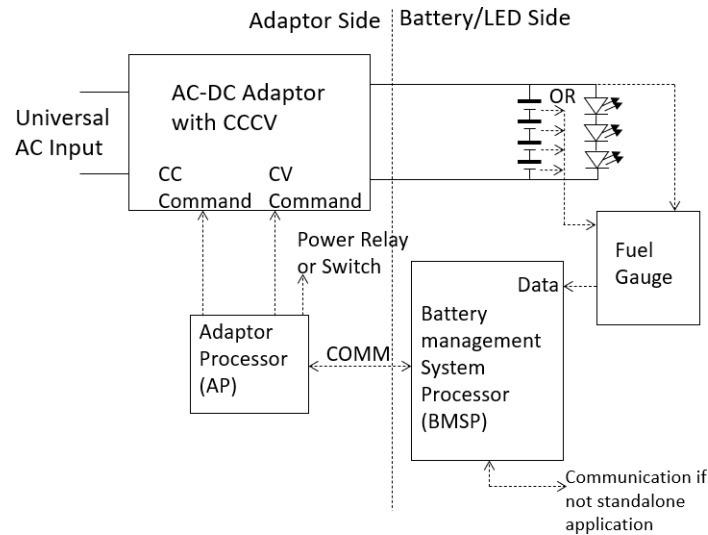
Although the adaptor processor (AP) circuit and programming are simpler as compared with the BMSP implementation, requiring a processor on the adaptor side burdens system cost and size. For smaller systems, the battery may sit relatively close to the charging adaptor, the BMSP may be able to issue commands directly to the adaptor control loop.

This new design implements the power section of a battery charger or a dimmable LED driver with above compact system architecture requirement by providing only one command input in PWM format, which can be issued directly by any microprocessor including a BMSP. Typical application scenarios can be illustrated by the block diagram below. This design, the green block, takes universal input line voltages from 90 Vac to 264 Vac. Its output ranges from 38 V ~ 76 V and 0 A ~ 4.2 A DC. The output voltage is set to 76 V under no load condition. The output current is limited to 4.2 A. This reference design has a PWM input port converting a PWM input signal to an internal current command, suitable for battery charging or dimmable LED driver applications. Only the green block in the block diagram is implemented as the reference design board.
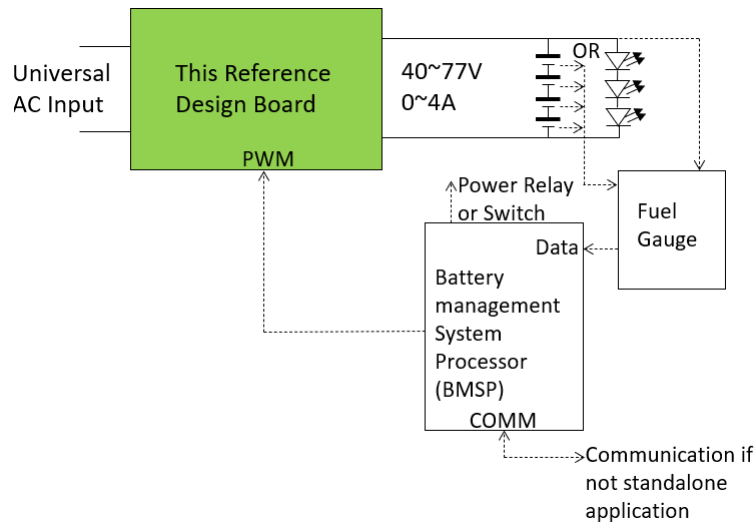
For a battery charger application, a charging profile specific to the battery type is stored and managed by the battery management system microprocessor (BMSP). The microprocessor collects fuel gauge information such as the battery terminal voltage, charge level, health, and determines an appropriate current level to charge. The current level is represented by the PWM duty cycle output from the microprocessor to the green reference design board. A duty cycle of 100% will have the reference design board outputting 4.2 A full current. A duty cycle of 0% will reduce output current to its minimum. Additionally, the microprocessor can manage a power relay or switch to disconnect the battery from this reference design board if desired. If this is a part of a bigger system, like in an electric vehicle (EV), the microprocessor can accept commands from other parts of the system as well. This system is simpler, smaller in size, and lower in cost system as compared with traditional charging system while maintaining high system efficiency.

For a LED driver application, the PWM input is the dimming command. A microprocessor may not be required. A 0 V – 10 V to PWM circuit is sufficient. LED current under dimming has significant ripple < 1kHz. A bigger output bulk capacitor may be required to reduce this ripple content.

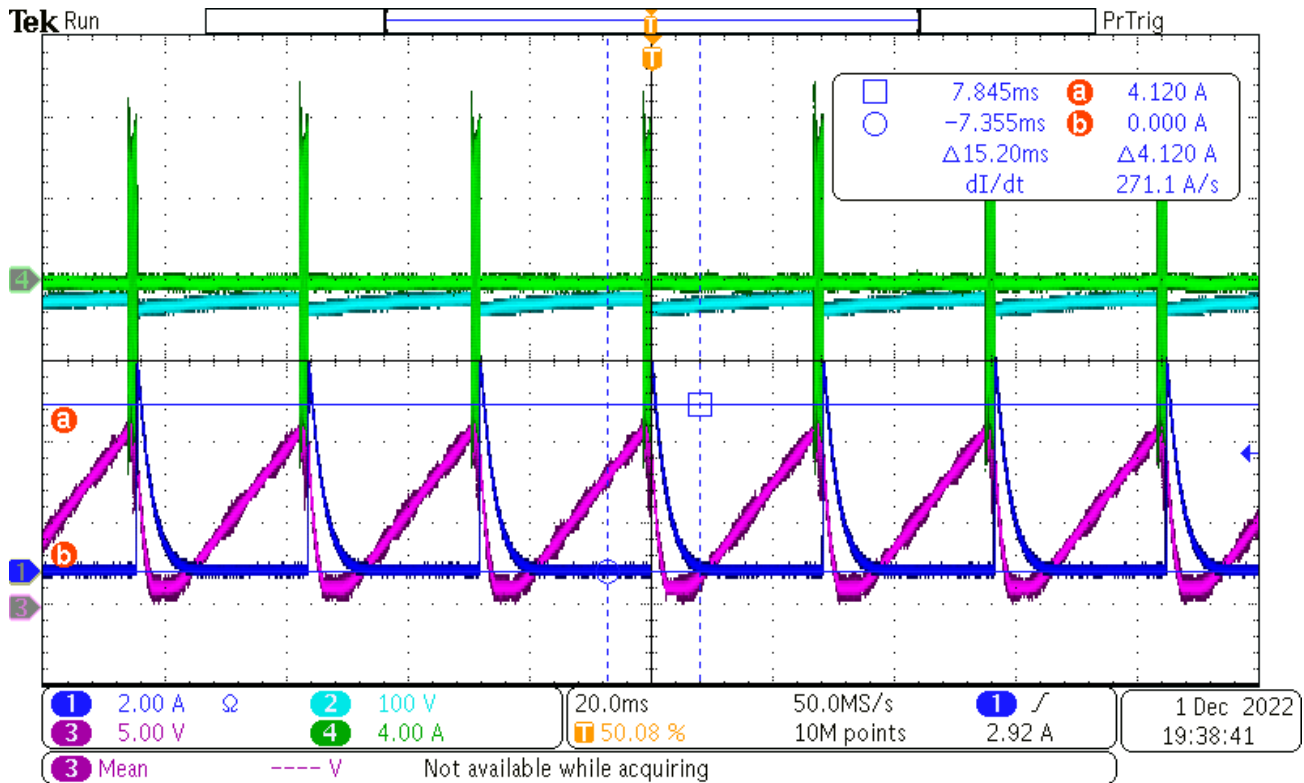## How about Deep Dimming for LED Lighting?

When the output demands less load outside of NCP1399A linear frequency range, it uses burst mode. Below shows a few signals on scope. CH1 (blue) is output current. CH2 (light blue) is DC bus voltage. CH3 (purple) is CC control voltage at U1 pin 7. CH4 (green) is resonant loop current. Although the output current is still at full current (~ 4.2 A), the LLC is already in burst mode because output voltage is close to 38V. Due to burst mode, resonant loop current magnitude is higher. The burst interval is about 900 μs. As such the output current already presents higher ripple current. This ripple content is OK, both magnitude and frequency wise, for LED lighting.
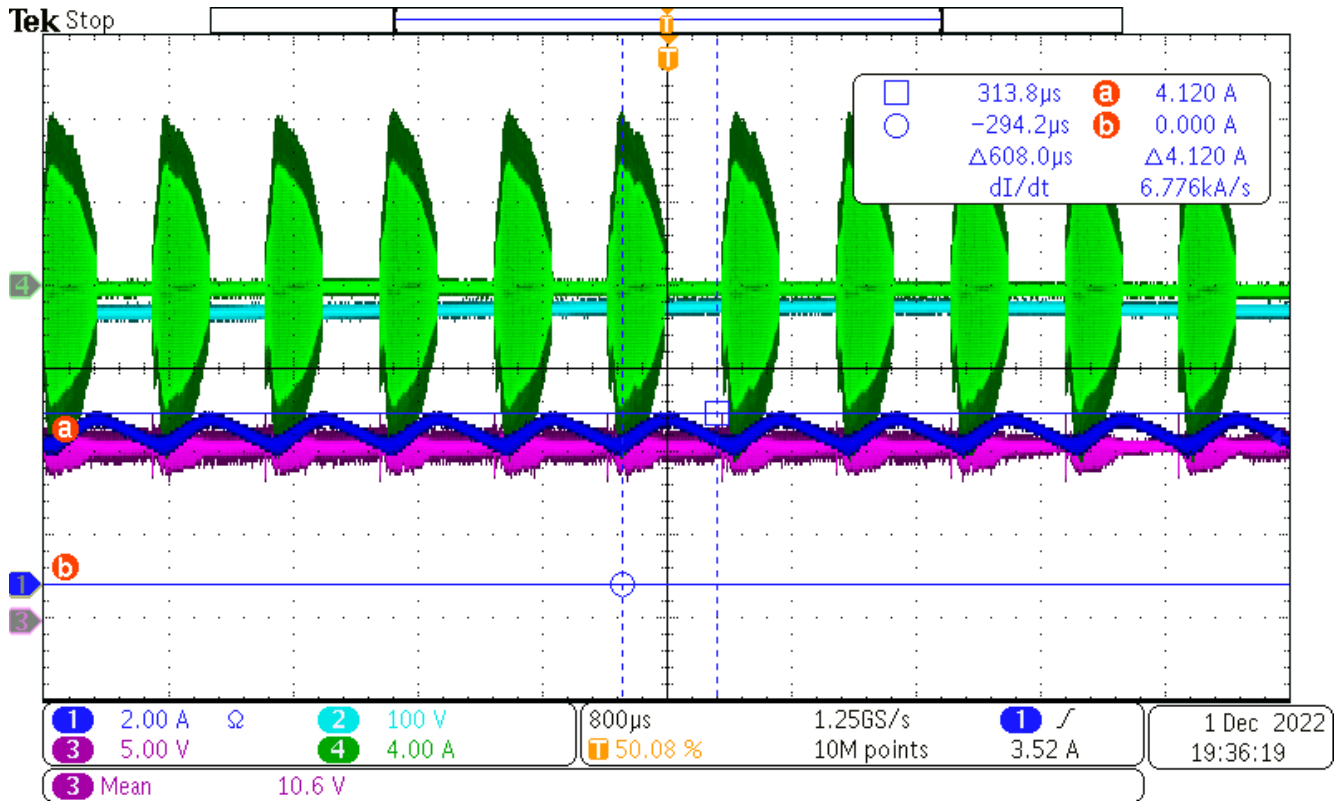
Below is a scope picture of the same signals when PWM is dimmed down to ~ 10%. Burst interval is active at ~ 5 ms (200 Hz). As a result, the output current touches zero and becomes DCM. This is usually not good for LED lighting. CC control voltage has higher ripple. Resonant loop current has higher magnitude.
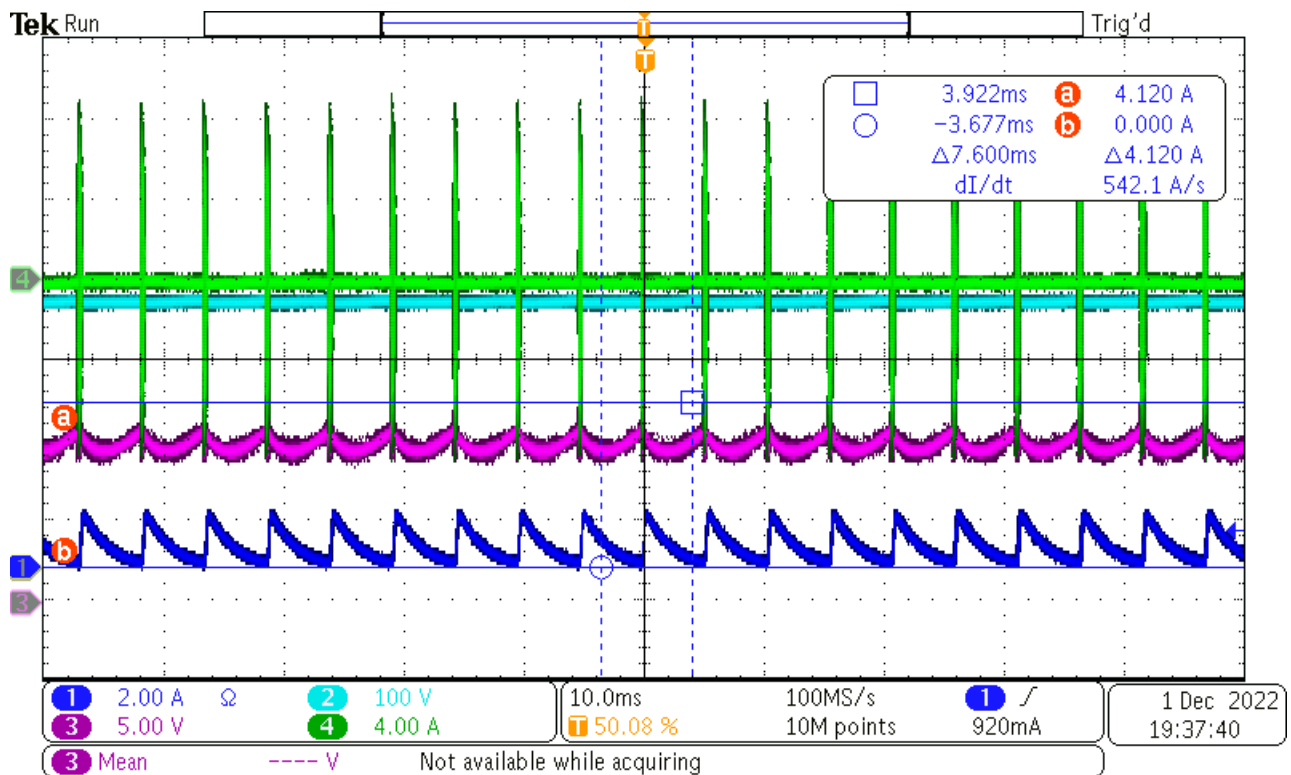
When PWM dims down < 5%, below is a scope picture. Burst interval is 30 ms (~ 33 Hz). Output cap voltage can not stay up for a stable 12 V supply for the output control circuit.

The achievable dimming range for output current is 10% ~ 100%. Pulsating with high ripple output current < 1 kHz is not desirable for LED lighting. Any deep dimming request is better accomplished by an additional buck stage under microprocess control.

Conclusion

Traditional battery charger architecture is an AC-DC power adaptor in constant voltage (CV) mode followed by a dedicated buck constant current (CC) converter to a Li-Ion battery. For a laptop computer, the AC-DC power adaptor is a stand-alone piece outside of the laptop while the battery and the buck charger are built into the laptop.

There are other applications that can integrate the AC-DC CV power adaptor more closely to the battery. In this scenario, one prospect arises if the CV architecture of the power adaptor can be modified to add CC function to directly charge the battery without needing a buck stage for cost and size improvement. High performance AC-DC power adaptor has an LLC stage as the output providing CV operation.

Investigation by putting a CCCV daughter card to the output of a Renesas design TDAIO-TPH-ON-240W-RD (PFC+LLC) AC-DC adaptor and modifying the adaptor optocoupler feedback path shows good CCCV characteristics. However, efficiency drops significantly when output voltage is more than 20% lower than rated 24 V. Thermal monitoring is a must to the LLC section of TDAIO-TPH-ON-240W-RD to prevent adaptor over thermal damage in abnormal long period operation at low battery voltage.

Redesigning the LLC section for wide output voltage of 38 V ~ 76 V 4.2 A shows the efficiency can stay high during the entire battery charging range. This removes the concern of using LLC stage alone for battery charger application.

Traditional LLC converter is optimized for constant voltage output application. It is not suitable for wide output voltage constant current applications such as battery chargers due to controller IC limitation. Re-designing the resonant loop component values to compact frequency range, the controller IC can be accommodated to yield satisfactory result. In this way, a post adapter buck regulatory is not needed for battery charging, achieving higher overall efficiency, and lower cost for the system.

Using GaN FETs, such as Renesas SuperGaN TP65H150G4PS, it boosts system efficiency by ~ 3% as compared with published data using Silicon FETs [2].

Battery charger or LED lighting may request lower than rated current from time to time. This requires wide output current range on top of the wide output voltage range. A faster constant current regulation loop is needed. The CC loop has been re-tuned and a PWM input circuit is added for desirable current level. The resulting circuit is capable of wide output voltage and wide output current applications.

Because the LLC controller IC uses burst mode for light load operation, output current quality is affected. Deep dimming for LED is not appropriate. Operating the output current range between 10% to 100% is feasible. It would be more appropriate to add another buck converter stage if deeper dimming current is desired.

Reference

[1] TDAIO-TPH-ON-240W-RD 240W 24V 10A adaptor User Guide -
https://www.Transphormusa.com/en/reference-design/tdaio-tph-on-240w-rd/
[2] Infineon, "130 W dimmable constant current LED driver using ICL5102 in PFC and LLC topology,"
https://www.infineon.com/dgdl/Infineon-EngineeringReport_130W_dimmable_constant_current_LED_driver_ICL5102-ApplicationNotes-v03_02-EN.pdf?fileId=5546d4626102d35a01612de7a06b6fb3.