Efficient Charger Design using Phase-Shifted Full Bridge Converter for Lightweight Electric Vehicles

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Abstract

This paper presents a design of an efficient charger for lightweight electric vehicles. The environmental friendly, affordable and efficient vehicles are required in this age of transportation. For the sustainability and eco-friendly development of human society, electric vehicles are being considered as essential technology. The efficent charger design is the demand for being an essential component of the vehicle. The battery charger has two basic stages; the first stage is a power factor correction (PFC) rectifier and second stage is an isolated buck converter which is phase-shifted full bridge (PSFB). The rectifier ensures power factor near to 1 at the input side, that helps to ensure lower losses and also smaller current rating outlet at the input side. The PSFB converter ensures controlled current output to the battery while also providing isolation for protection of either side due to any fault. The simulation result shows the efficiency of the proposed work.

Keywords: Lightweight Electric Vehicles, Charger, Fly-Back, Power Factor Correction, Phase Shifted Full Bridge.

1 Introduction

Electric vehicles have been identified as being a key technology in reducing future emissions and energy consumption in the mobility sector. The focus of this article is to review and assess the energy efficiency and the environmental impact of battery electric cars (BEV), which is the only technical alternative on the market available today to vehicles with internal combustion engine (ICEV). Electricity onboard a car can be provided either by a battery or a fuel cell (FCV).

Since a full hybrid vehicle is able to drive electrically, it simply needs a plug and a bigger battery in order to be charged like a BEV. This way, the category of plug-in hybrid vehicles (PHEV) was created. Within the last 10 years, different drive-train concepts based on electric motors have been developed and are soon going to enter mass production. All-electric drive and hybrid electric drive have to be differentiated. In contrast to the hybrid electric drive, in the all-electric car, an electric motor is the only energy converter.

1.1 Components of an Electric Vehicle

The main components of an electric vehicle (EV) can be divided into the electric battery, the electric motor, and a motor controller as presented in Figure 1. The technical structure of an electric vehicle (EV) is simpler compared to internal combustion electric vehicle (ICEV) since no starting, exhaust or lubrication system, mostly no gearbox, and sometimes, not even a cooling system are needed [1, 2].

The battery charges with electricity either when plugged in the electricity grid via a charging device or during braking through recuperation. The charger is a crucial component since its efficiency can vary today between 60% and 97%, wasting 3% to 40% of the grid energy as heat. The motor controller supplies the electric motor with variable power depending on the load situation. The electric motor converts the electric energy into mechanical energy and, when used within a drive-train, to torque. In series EV produced so far, central engines have been used; however, hub wheel electric engines are also possible and would be available for mass production.

Modern, highly efficient electric motors are based on permanent magnetic materials from which the strongest are alloys containing the rare earth elements (REE) neodymium and samarium, respectively. Usual alloys are both NdFeB and SmCo magnets.

This has caused some concern since REEs are scarce, and their export is controlled by a few countries. However, electric motors for BEV do not necessarily contain REE. There are several types of electric motors, usually divided

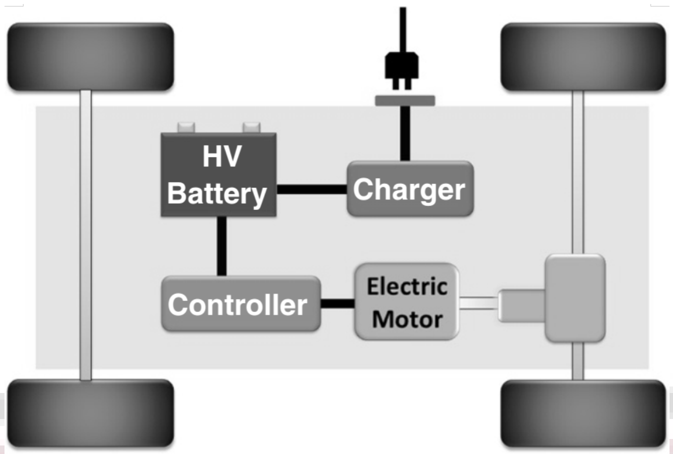

Figure 1: Important Components of Electric Vehicle

into alternating current (AC) and direct current (DC) types. There are both AC and DC electric engines built with and without permanent magnets, according to individual use [3].

In electric cars, traction motors without magnets are quite usual since they are cheaper. A subspecies of AC motors are induction motors using no REE. The Tesla Roadster is equipped with an induction motor without REE, as will be the forthcoming Tesla Model S and the Toyota RAV4EV. In a more detailed view, it can be stated that there are several electric engines available operating without REE magnets: conventional mechanically commutated DC machines, the asynchronous machines, the load-controlled synchronous machines with electrical excitation, and the switched reluctance motors. This gives the motor industry some flexibility [4, 5].

1.2 Batteries for Electric Vehicles

It is still possible and useful to equip electric vehicles with lead-acid batteries. Cars of the Californian interim electric vehicle boom in the 1990s were partly driven by lead batteries, nevertheless already offering a driving performance comparable to ICE cars. Today, for example, there are small electric trucks commercially available and equipped with lead batteries and a capacity of 13 to 26 kWh, allowing a maximum range of up to 200 km and a maximum speed of 60 km/h. Also, a certain share of today's electric cars (e.g., by the Indian company REVA) are equipped with Pb batteries. In order to diversify the future battery technology and materials, it would be useful to keep Pb traction batteries for certain applications. Electric cars for smaller ranges, as e.g., in-town driving, so-called neighborhood electric vehicles, will be much cheaper if they are operated with lead-acid batteries instead of a lithium-ion battery. Additionally, there are recent performance improvements of the lead battery, thanks to a gel matrix and gassing charge [6].

However, the enormous increase in energy density offered by Li-ion batteries is the prerequisite for the expected widespread electrification of cars. Nickel metal hydride batteries were used in the interim time when the re-electrification of the automobile started in the 1990s. However, they do not offer enough power and have a worse environmental impact compared to Li-ion batteries. The only alternative to Li-ion batteries with comparable power, the Zebra cell, is based on molten salt and, thus, only useful for continuous every day use. Today, a lot of different Li chemistry are available, and prices are continuously decreasing for Li-ion batteries. However, the price for a complete Li-ion cell set offering 14 kWh capacity, allowing a 100 km electrical range of a small-size car. Life cycle impacts of the various Li-ion chemistry differ significantly [7, 8].

2 Related Work

Many researchers proposed various efficient designs to for electric vehicles, and they have their advantages and limitations. Researches proved that batteries have various optimal factors for charging and discharging performance. Only various battery technologies affect battery performance, how the battery will be used and how it will be charged also greatly affects battery performance.

2.1 A Controllable Bidirectional Battery Charger for Electric Vehicles with Vehicle-to-Grid Capability

Melo *et al.* [9] proposed a simple and functional bidirectional PEV (or stationary battery) charger topology, which allows enhancing the capabilities of a joint operation of storage and an autonomous EMS in a residential setting, with potential benefits for end-users and utilities/system operator. The PEV role as load or power supplier is also emphasized. This charger is adjustable for charging or discharging operations using a power level provided by the EMS, instead of minimizing the charging time by using only the maximum power level.

2.2 Design and Control of Battery Charger for Electric Vehicles using Modular Multilevel Converters

Quraan *et al.* [10] proposes a new battery charger for electric vehicles based on modular multilevel converters. The converter produces an extremely low distortion of the output voltage, with direct benefits for the operations as a battery charger. For this reason, the grid filter can be eliminated with benefits on the hardware costs. The proposed charger integrates the battery management system (BMS) in the power converter control and eliminates the need for additional balancing circuits. The state of charges of all battery cells are managed by SOC balancing controllers without affecting the grid voltage and current. The battery cells are charged from the utility grid and the charging operation is controlled via a proportional resonant current controller with a phase-locked loop to charge the cells at unity power factor.

2.3 High-Efficiency Single-Stage On-Board Charger for Electrical Vehicles

Zinchenko *et al.* [19] presented an isolated single-stage on-board electric vehicle charger without an intermediate DC-link. Based on an isolated current-source topology, the converter features soft-switching in semiconductors regardless of load variation for the full AC line voltage range. Moreover, it requires no external snubber or clamp circuits. The power factor correction and voltage regulation are provided by a relatively simple phase shift modulation, while the amount of circulating energy is kept at minimum. The charger is distinguished by its efficiency characteristic – the maximum is achieved in the constant power charging mode.

2.4 An Isolated Bidirectional Integrated Plug-in Hybrid Electric Vehicle Battery Charger with Resonant Converters

Ebrahimi *et al.* [20] proposed a new three-phase bidirectional isolated soft-switched PHEV battery charger that benefits a series resonant DC/DC converter. A switching method is also proposed so that all switches of the proposed topology benefit soft-switching operation, minimizing switching losses. The conventional bulky capacitor of the DC link is eliminated as well. Moreover, their proposed structure is an integrated charger that can share the hardware of the traction mode with contactors; contrary to common battery chargers, no bulky reactive component is needed in the proposed structure, and the leakage inductance of the small high-frequency transformer can be used as the reactive element of this topology.

2.5 An Isolated High-Power Integrated Charger in Electrified-Vehicle Applications

Haghbin *et al.* [21] proposed an isolated high-power integrated charger based on a split winding ac motor can yield a charging power of half the traction power. The electric motor stator windings were reconfigured for the traction and charging modes through a relay-based switching device, which, together with a clutch, were the only extra components needed to yield a very cost-effective compact onboard three-phase isolated charger with unity power factor capability. The mathematical model of the electric machine in the charging mode has been presented in detail.

3 Proposed Charger Design Sequence

THe proposed the charger design consists of two stages. The Figure 2 below shows that each stage has its own controller which in turn, should have its own power supply.

An isolated power supply is also needed for the controller and gate drivers of the final DC-DC stage. Finally, an input EMI filter and output current monitoring protocols for CC/CV charging are also essential. With so many

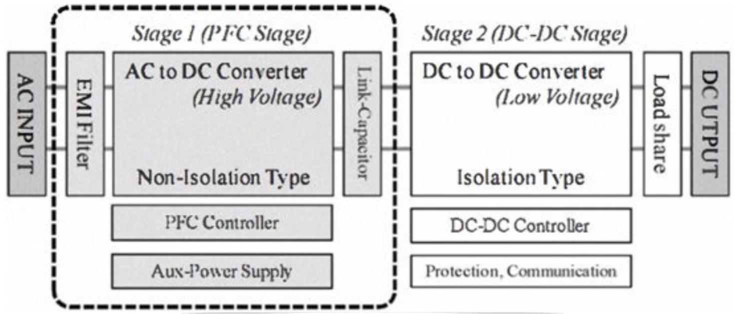

Figure 2: Block Diagram of the Proposed Charger Components

aspects to consider, a proper design sequence is essential to approach the project. Each aspect needs to be designed, fabricated and tested in a modular way before the final integration of everything involved.

Figure 3 represents the design of two output DCM flyback converter.

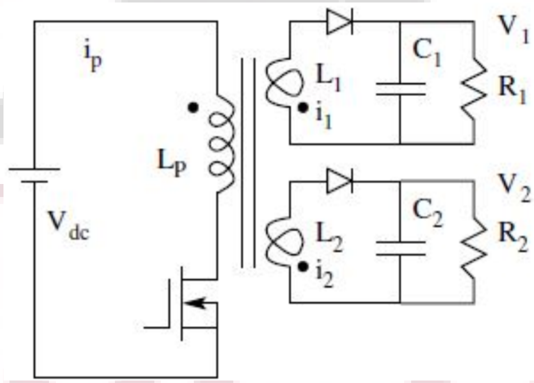

Figure 3: Two output DCM Flyback Converter

3.1 Specifications

The two outputs of the flyback converter (16 V on AC ground and 8 V on μC ground) will be supplying power mainly to ICs, that need current in the range of a few mA. Considering other aspects of the vehicle, 0.5 A is selected for the 16V winding and 2 A for the 8 V winding, including a safety margin. The maximum power rating is thus 24 W, although in nominal conditions, it will be much less. The other specifications are as follows:

- Input Voltage V_{dc}: 40 V – 60 V (since 48 V battery was available for prototyping)
- 1st Output Voltage V_1: 16 V (0.1 – 0.5 A) with $\delta V < 5\%$
- 2nd Output Voltage V_2: 8 V (0.2 – 2 A) with $\delta V < 5\%$
- 3rd Output Auxillary Voltage V_{aux}: 16V (50mA) with$\delta V < 5\%$
- Output Power P_o: 24 W (max)
- Switching frequency f_s: 100 kHz
- Minimum efficiency η: 75
- Controller IC used: NCP (ON Semiconductor)

3.2 Proposed Mathematical Calculations and Parameters

For preliminary calculations, the minimum DC voltage V_{dc}(min) = 40 V and maximum DC voltage V_{dc}(max) = 60 V are considered.

3.2.1 Input Capacitor Calculation

The input capacitance of capacitor is calculated as:

$$C_{in} = \frac{I_{in-\max} T_S}{2\delta V_{dc}} \tag{1}$$

$$= \frac{P_o}{\eta V_{dc-\min}} \frac{T_S}{2\delta V_{dc}} \tag{2}$$

Taking the ripple in the input DC bus (δV_{dc}) to be about 4 V, we get $C_{in} = 1\ \mu$F
Conduction Parameters and Conduction Times:
From Figure 3, i_{1m} (and similarly i_{2m}) through diodes D_1 and D_2 are related to the intervals $d_{21}T_S(d_{22}T_S)$ and the load currents by:

$$i_{xm} = \frac{V_x d_{2x} T_S}{L_x} \tag{3}$$

$$= \frac{V_x}{R_x} \frac{2}{d_{2x}} \tag{4}$$

Hence we get $d_{2x} = \sqrt{K_x}$ where $K_x = \dfrac{2L_x}{R_x T_s}$; $x = 1, 2$. If $d_{21} \approxeq d_{22}$ then the results of the single output flyback can be applied directly.

4 Simulation Result

The following simulation results presented in Figure 4 were obtained for the open loop operation of the flyback using the Q4344-BL transformer (with $L_p = 85\ \mu$H) at nominal duty and nominal loads. As can be seen clearly, the converter still operates at DCM. Figure 5 represents the current and output voltage waveforms.

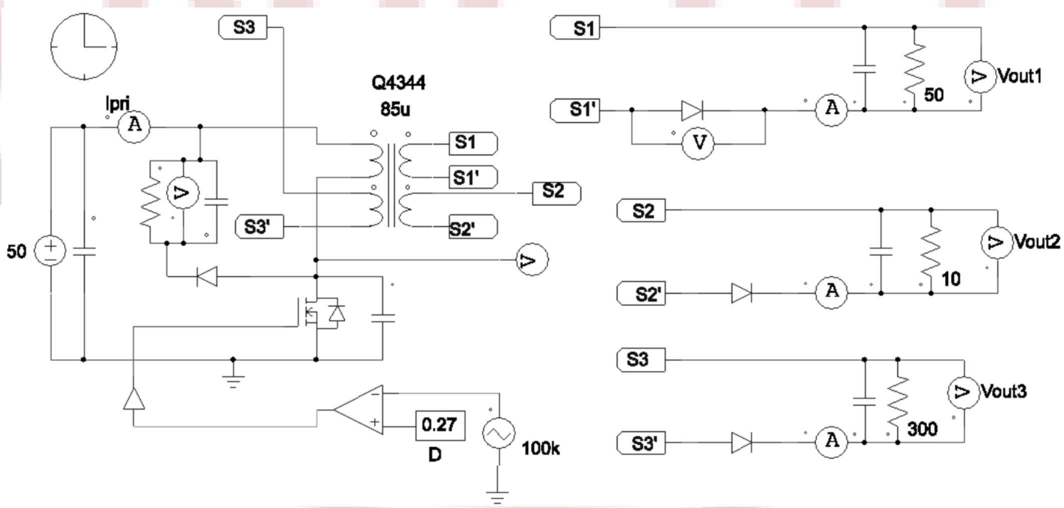

Figure 4: Flyback Simulation with Q4344 transformer

4.1 Hardware Results

The following hardware results were obtained on testing the flyback converter in closed loop with the non-conductive pastes (NCP) integrated circuit (IC). The output voltages were just as expected, and the regulation under varying loads was very fast. Different snubbers (combinations of R-C values) had to be used to ensure a proper V_{ds} across the mosfet. An efficiency of about 83% was obtained.

The hardware simulations are carried out using RIGOL waveform generators. One of the important features of RIGOL's oscilloscopes is its low noise floor. The oscilloscope offers the industry's leading small range of 500

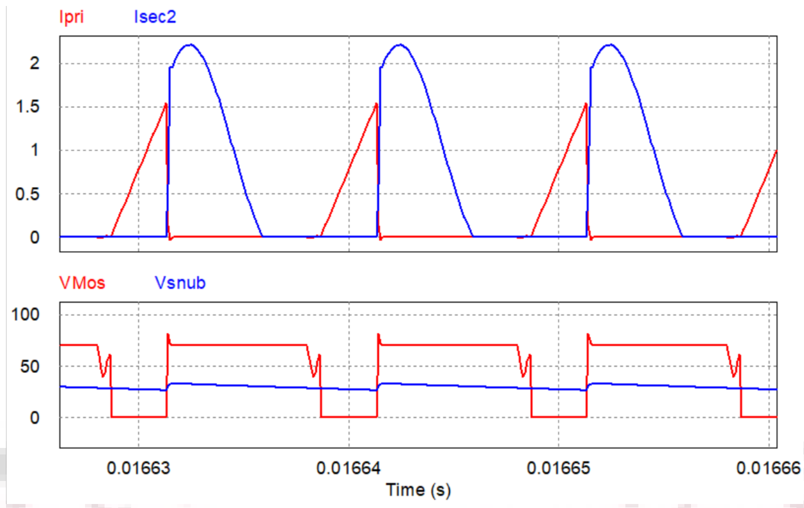

Figure 5: Current and Output Voltage Waveforms

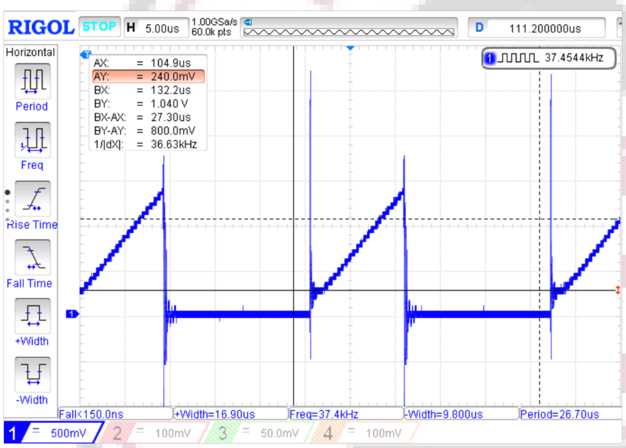

Figure 6: Primary current (DCM)

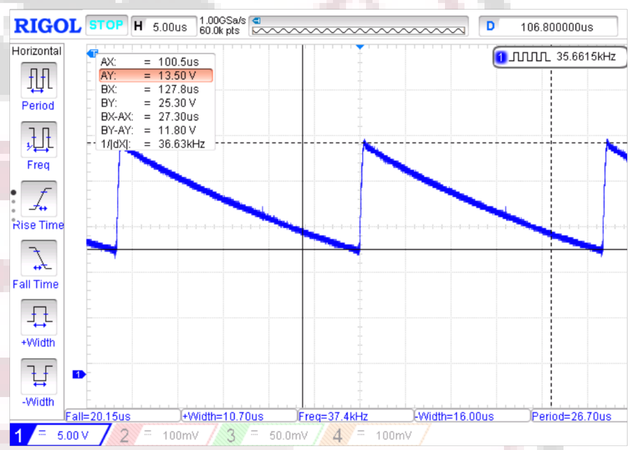

Figure 7: Snubber Voltage

uV/div, making it ideal for testing small signals such as power ripple. The probe offers a 1:1/10:1 attenuation ratio. The probe ratio can provide up to 35 MHz of bandwidth for direct ripple testing. UltraPower Analysis software provides ripple analysis function modules.

Power ripple is an important parameter to evaluate DC power supply. The ripple and noise consist of rectified main ripple, switching noise, PWM frequency ripple, and random noise. To make an accurate testing of ripples, it is required that the ripple of the test instrument itself is as low as possible and the test system has a minimal impact on the test results. RIGOL oscilloscopes support power testing. The high-voltage differential and current probes equipped with the oscilloscopes can meet a wide range of testing needs.

Figure 6 represents the primary current in discontinuous conduction mode (DCM), Figure 7 represents the snubber voltage. Figure 8 represents the faulty switching due to high frequency ringing, whereas, Figure 9 represnts faulty ringing improved but high peak voltage.

Figure 10 represents the voltage across drain-source of MOSFET due to various snubbers that is the improved performance and Figure 11 shows the further improved performance of the charger. Figure 12 represents out voltage across regilated at 16 V, and Figure 13 represents the skip cycle mode of operation of non-conductive pastes (NCP).

5 Conclusion

The complete research of this paper can be summarized as:

- Flyback Converter design, fabrication and testing.

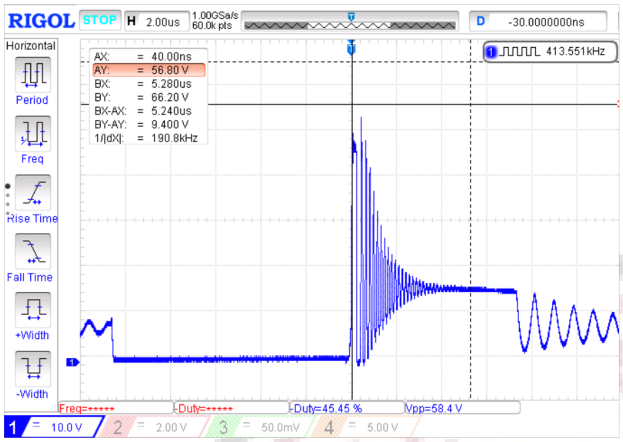

Figure 8: Faulty Switching due to High Frequency Ringing

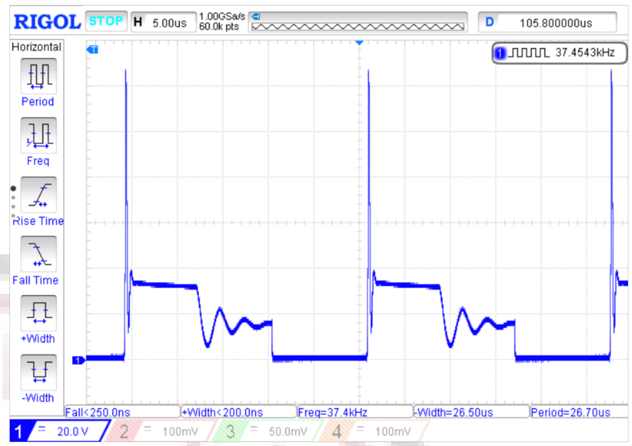

Figure 9: Faulty Ringing Improved but High Peak Voltage

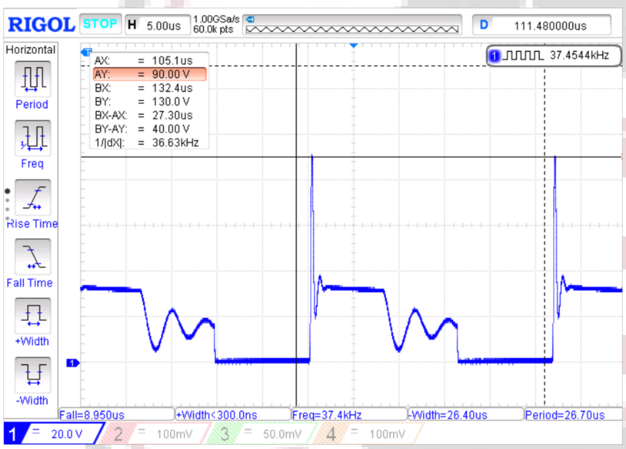

Figure 10: Improved Voltage Across Drain-Source of MOSFET

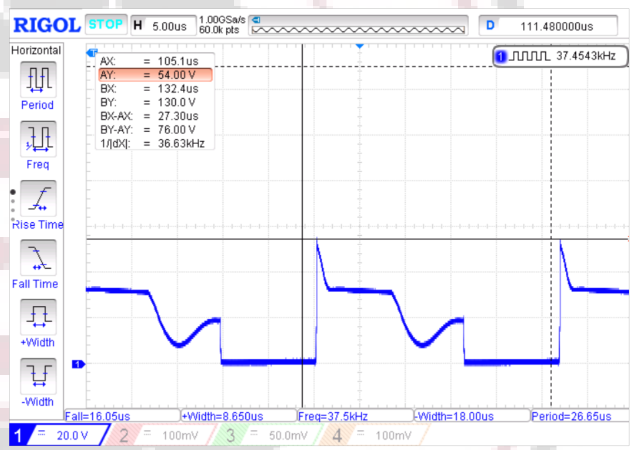

Figure 11: Further Improved Voltage Across Drain-Source of MOSFET

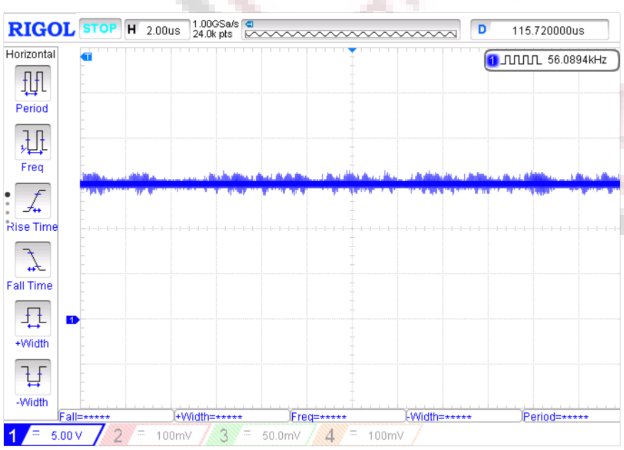

Figure 12: Output Voltage across Regulated at 16 V

Figure 13: Skip Cycle Mode of Operation of Non-Conductive Pastes (NCP)

- Buck converter design, fabrication and testing (the new design has been sent for fabrication).
- Manual enable features were included for the auxiliary power supply (one cause of problems).
- Simulations of PFC rectifier in closed loop.
- Fabrication and testing of PFC hardware.
- Simulation of PSFB converter with current control.
- Although it was not possible to fabricate and test the hardware owing to the unprecedented lockdown, the schematics were prepared.

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