LLC Converter Design for EV Battery-Pack Charger using Household Electricity in Indonesia

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***Abstract*— Electric Vehicles (EVs) as one alternative of clean transportation now has a growing market. To enhance the ecosystem of the EVs we must reduce dependencies on limited number of public batteries swapping stations or public battery charging station. This research aims to create a switched-mode power supply that specific to charge EVs battery using households electricity power especially in Indonesia, which is commonly limited to 900VA. Since electric motorcycle commonly using 80V/20Ah battery this charger design must follow the maximum rated voltage and current of the LiPo batteries. To be more specific our charger equipped with active power factor correction rectifier, with efficiency >97% and power factor >99%, and LLC dc-dc converter, with efficiency >90%, to convert input voltage 220VAC (rms) into output voltage 80VDC. The charger also designed to be deliver 800W power into the batteries, so it will not surpassed the limited household power.**

Keywords*— *Battery Charger; dc-dc converter; LLC Converter; PFC

I. INTRODUCTION

Big cities in Indonesia overcome the serious pollution issue. People believe one of the sources of pollution is cars and motorcycles. To tackle this issue, people and the government are seeking a solution in clean transportation, which is Electric Vehicles (EV). For this reason, Indonesia recently has a growing market for EVs, and with government support and incentives [1], [2], [3], the most sold EVs are motorcycle type. There are 2 types of EV motorcycles that are released in Indonesia, with battery swapping or embedded battery. Both of them came with a home charger so user can charge their EV at home.

The growth of EV users in Indonesia had challenges, such as a limited number of public battery swapping stations (Stasiun Penukaran Baterai Kendaraan Listrik Umum/ SPBKLU) and public battery charging station (Stasiun Pengisian Kendaraan Listrik Umum/ SPKLU). So EV manufacturers usually include a Home Battery Charger for users to charge their EV using their household electricity. The problem arises when the household electricity has limited power. Common households are limited by the State Electricity Company (Perusahaan Listrik Negara/ PLN) to use 900-2200VA and it is about 97% of all households [4]. With this limited power, inefficient or low-power home charging systems will take forever to fill up the 72V/20Ah battery.

An efficient charger is not enough, and we need an efficient, safe, and affordable Home Battery Charger that meets the household limit to charge special-purpose battery packs for EV motorcycles. To achieve high efficiency in battery chargers, we will use the Inductor-Inductor-Capacitor (LLC) Resonant Converter topology [5]. Other advantages of LLC Resonant Converter are: wide input voltage range, low electromagnetic interference (EMI), and high power density [6], [7], [8].

II. BATTERY SPECIFICATIONS

EV motorcycles have several safety standards, including for their battery packs [9]. The most common battery pack in both swapping or embedded batteries in EV motorcycles are:

- Voltage : 72VDC
- Capacity : 20Ah
- Material : LiPo

In order to design the charger, we need to consider maximum charging voltage and maximum charging power. The maximum charging voltage are defined by the battery manufacturers is 80VDC. Maximum charging power is considering the smallest most common household power in Indonesia, which is 900VA. Even we included PFC circuits in the design, but to spare the reactive power, we will only design the charger power up to 800W.

The charger is designed into several modules/ block to ease the troubleshooting and testing. So, we will start from overall block diagram, and then go details into every block of the charger.

III. BATTERY CHARGER DESIGN

A. Block Diagrams

The First block of the diagram is an EMI Filter. Because this type of design is considered as switching mode power supply (SMPS), we need to prevent leaking harmonics in high frequency into the grid. The next block is the Active Power Factor Correction (PFC) Rectifier. Since LLC Resonant topology is mostly used in DC-DC converters, we need a rectifier to convert household electricity into DC. The

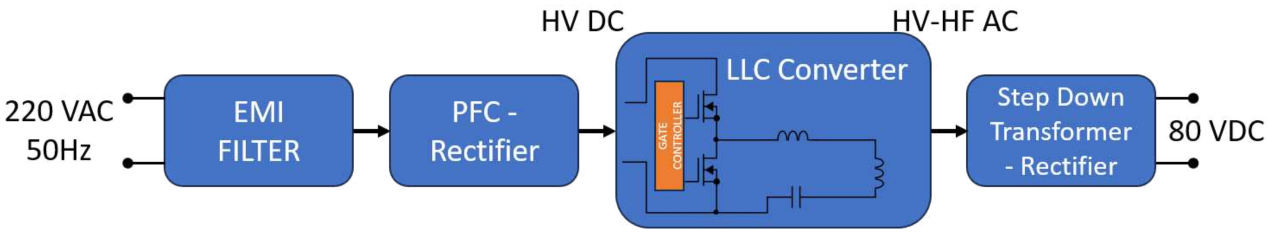


Fig. 1 Battery Charger Block Diagram

rectifier is featured with active PFC to prevent power system losses due to low power factor (PF) from the household.

The third block is an LLC resonant system (power switches & resonant tank). So, after the DC voltage is switched with a certain frequency, it is filtered into the resonant tank filter with one of the inductors as a transformer. The resonant tank filter will create the switching signal into sinusoid form, so it will efficiently pass the transformer. The next block is a transformer with a calculated ratio to tune the output voltage and the final rectifier to create DC output. The block diagram is shown in Figure 1

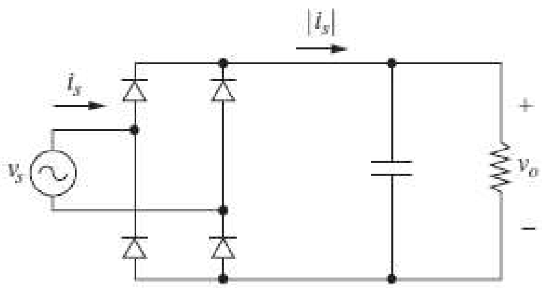
B. Rectifier with Active Power Factor Correction (PFC)

Rectifier is a common circuit in all electronics applications. Usually, linear rectifiers use a step-down transformer before being rectified by a diode. It will create an inductive load that is seen by the grid and then lowers the power factor. Furthermore, the rectified voltage and current are not in phase, creating a low power factor.

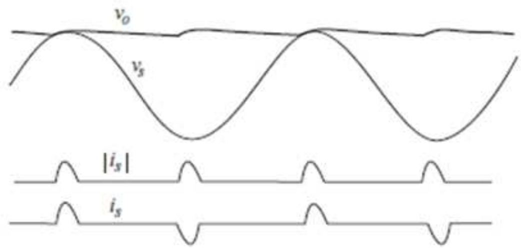
In AC circuits, the power factor is known as the ratio of real/active power (P) in watts, with a magnitude of apparent/complex power (S) in volt-ampere. Active power means the power that is consumed by an electric circuit. On the other hand, apparent power is power that is delivered to the electric circuit. To create a more effective system, we need a power factor to be as close as 1 by using a power factor correction circuit.

$$PF = \frac{real\ power\ (P)}{complex\ power\ (S)}$$

PFC circuits are widely used in an electronic device to meet international standards such as EN61000-3-2 in EU, IEC61000-3-2 in US, etc [10]. Those standards aim to reduce power distribution loss from electric company's power generators. There are two types of PFC circuits: passive and active. Since most loads are inductive, passive PFC circuits consist of many capacitors called capacitor banks. The number of capacitors is determined by the load that is used, and it is not space-efficient. The active PFC circuits use boost topology to improve the power factor, using current and voltage feedback, it can hold the power factor at a certain level with load variations.



a



b

Fig. 2 (a) rectifier circuit without pfc (b) misalignment phase of v_s and i_s

A boost converter is used as a PFC because the topology has many advantages, such as low THD (Total Harmonic Distortion) because the inductors in the input create a continuous current, which means lower dI/dt. Another one is because the MOSFET source is connected to the ground, it is easier to drive the gate. And because the boost converter can not step down the voltage, its output only becomes a higher voltage. This is another advantage because a slight voltage drop at the input will be backed up with high-voltage energy in the capacitors of the output.

PFC is commonly used in the ac circuits applications such as an electric motor, transformers, etc. In the linear rectifier application somehow the biggest impact in power factor is not coming from the stepdown transformers, instead it is come from the rectifying process, bridge diode and bypass capacitors as shown in Figure 2a. The waveform in the Figure 2b shows the current $|i_s|$ only conduct when charging the bypass capacitor and it causes major misalignment phase between voltage and current. As result the rectifier circuits having lower power factor and higher THD.

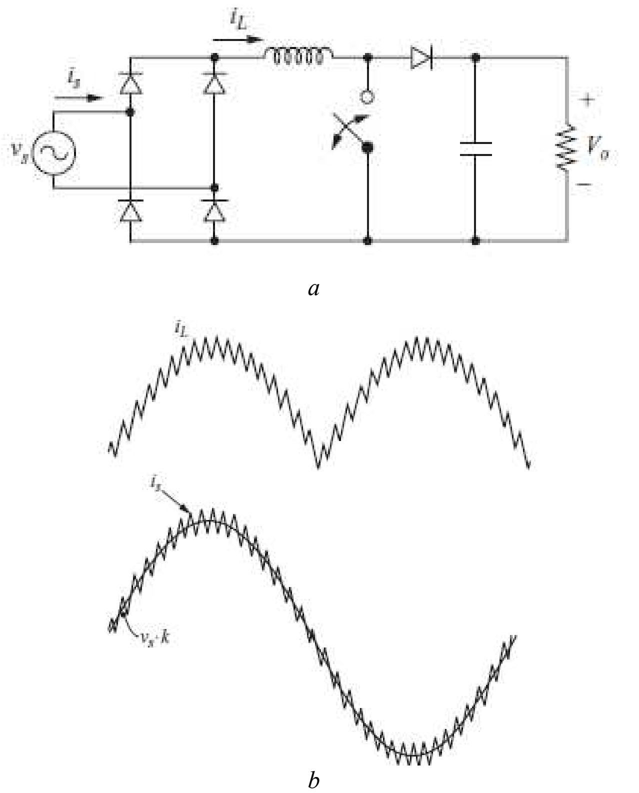


Fig. 3 (a) rectifier circuit with pfc (b) in phase waveform of v_s and i_s

To overcome this issue, the rectifier circuit is combined with boost circuit to achieve power factor correction, as shown in Figure 3a. When the switch is on, the diode not conducting and inductor current will flow straight to ground, the output will be supplied from the discharge of bypass capacitor. When the switch is off, the inductor current will having same value as before, but it will flow into the conducting diode and eventually charging bypass capacitor and into the load. It will make the current in phase with the voltage so rectifier circuits having higher power factor and lower THD[11].

For the design, we used UCC28180, which is an 18-kHz-250-kHz CCM (Continuous Conduction Mode) PFC controller to create Active PFC with specifications:

- Input Voltage (rms) : 195VAC-240VAC
- Output Voltage : 390VDC
- Max Power : 900W
- Efficiency : >97%

To achieve this specification, UCC28180 will be configured in Figure 4 [12].

C. LLC Resonant Design

There are so many dc converter topologies, but in this design, we want to use LLC Resonant converter to reduce power loss from imperfect switching. It can be done since LLC Resonant converter using soft switching, either zero-current switching (ZCS) or zero-voltage switching (ZVS). Another advantages of LLC Resonant converter in this design is the wide input voltage range, so the drop voltage of household's electricity can be compensated and create more stable output voltage.

LLC structure composed of 3 parts [13], inverter/ power switching, resonant tank, and rectifier. Power switching will create a high voltage DC input into high-frequency-high-voltage (HF-HV) AC, and there are 3 configurations that usually used, half-bridged (symmetrical/asymmetrical), full-bridged, and stacked structure. Because our application is considered low power (<1kW) and step-down the input voltage, we will use asymmetrical half bridge configurations.

The result of power switching is a HFHV with 0,5 duty cycle square wave signal. The resonant tank purpose is to filtering the signal into its fundamental frequency so it can be HFHV sinusoid signal. It is a series circuit of resonant inductor L_r, transformer magnetizing inductor L_m, and resonant capacitor C_r. After creates HFHV sinusoid signal, transformer will do the step-down part and will rectified using diode or switched MOSFET into DC output.

In this paper there are several specifications expected from LLC Resonant converter, such as:

- Input Voltage : 375-400 VDC
- Output Voltage : 80 VDC
- Max Output Power : 800 W
- Switching Freq : 130 kHz
- Efficiency : >90%

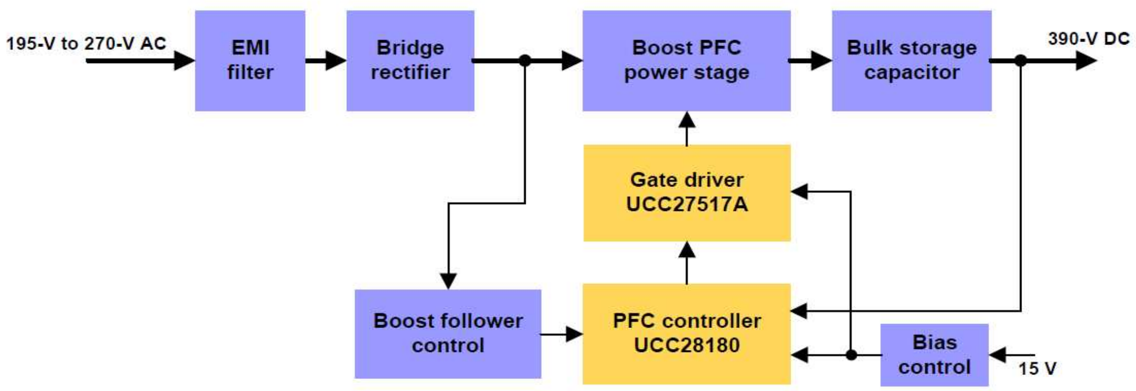


Fig. 4 UCC28180 configuration as active PFC controller [12].

To achieve the specifications design, we will follow this step [14]:

1. Calculate transformer ratio

$$n = \frac{V_{in}}{2V_o}$$

2. Calculate maximum and minimum voltage gain

$$M_{g\_min} = \frac{n \times V_{o\_min}}{V_{in\_max}/2} \qquad M_{g\_max} = \frac{n \times V_{o\_max}}{V_{in\_min}/2}$$

3. Choose inductor ratio L_n and quality factor Q_e using graph in Figure 5.

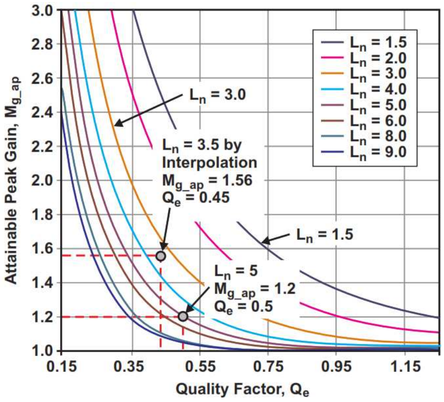


Fig. 5 Peak-gain curves [14].

4. Confirm and iterate step 3 using graph in Figure 6

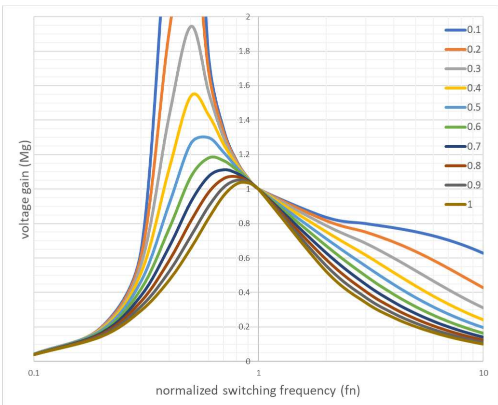


Fig. 6 Voltage gain curve with varied Q (L_n = 4)

5. Calculate load resistance seen by primary

$$R_e = \frac{8 \times n^2}{\pi^2} \times \frac{{V_o}^2}{P_{out}}$$

6. Calculate resonant capacitor

$$C_r = \frac{1}{2\pi f_{SW} R_e Q_e} \times \frac{{V_o}^2}{P_{out}}$$

7. Calculate resonant inductor

$$L_r = \frac{1}{(2\pi f_{SW})^2 \times C_r}$$

8. Calculate magnetizing inductance

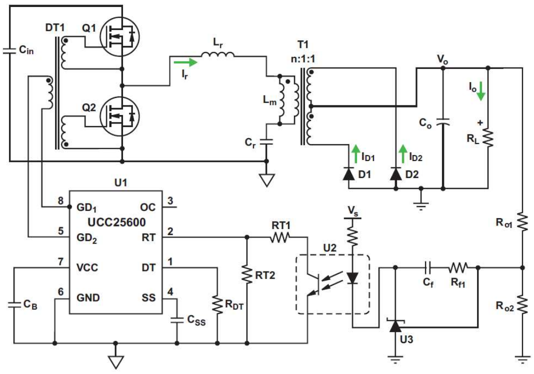


Fig. 7 UCC25600 in a circuit as LLC Resonant controller [14].

$$L_m = L_n \times L_r$$

After LLC Resonant parameters known using previous steps, it's time to implementing it into circuit. This design using UCC25600 High-Performance Resonant Mode Controller configured in Figure 7.

D. Transformer Design

A Transformer in a switching power supply has many purposes, it can be a gate driver, it can step-down voltage, and it can isolate input and output circuits. There is one similarity purpose which is transformer ideally use to transfer energy from primary side to secondary side, and not keeping the energy. But practically, there is always small energy stored due to mutual inductance and leakage inductance. This inductance is a feature in LLC converter to complete inductor-inductor (using transformer)-collector circuits.

Because switching power supply works in medium/high frequency (>100 kHz), so does the transformer. To make transformer work in high frequency we need to specify the core material and core size of transformer [15]. For this design, we will use EE42 with specifications:

- Primary RMS current : 4,7 A
- Secondary RMS current : 8,8 A
- Max Power : 900W
- Magnetizing L : 66,5 µH
- Turns Ratio : 2,94
- Core Material : Ferrite
- Core Type : EE
- Core Size : 42mm

IV. TESTING POINTS

After all blocks from Figure 1 (block diagram) is explained, next step is to integrate into a full schematic as shown in Figure 8. But before integrating into single circuits, it better to test each block output and circuit functionality. So we prefer to create board as modules following the block diagram in Figure 1, to ease the testing and troubleshooting.

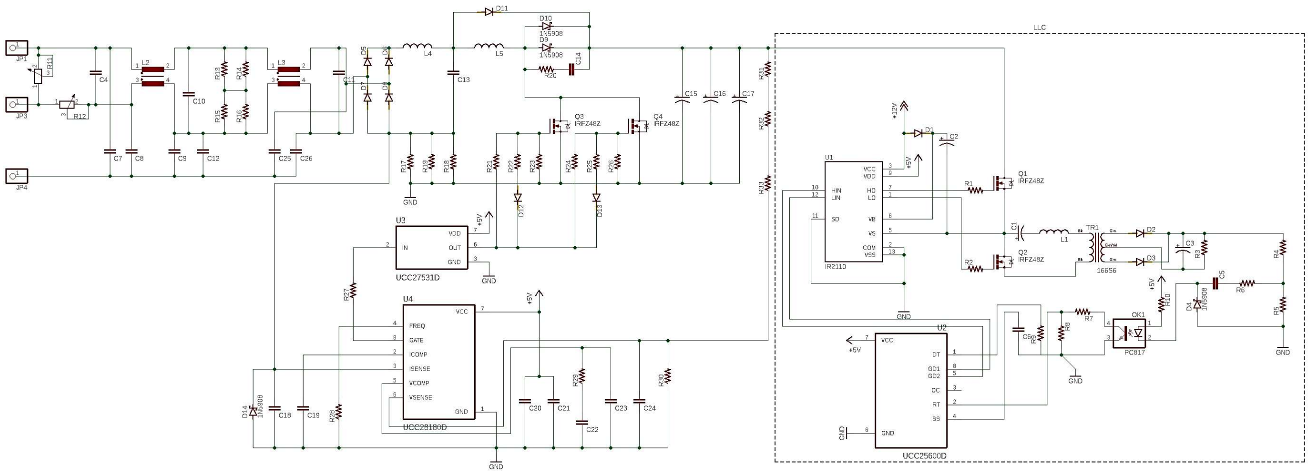


Fig. 8 Final designs for battery-pack home charger using LLC Resonant converter.

A. PFC Rectifier Testing Points

Testing environment for the PFC Rectifier circuits to simulate real condition are:

- Input: 220VAC (5A fused)
- Output: Resistor 200Ω - 8kΩ, high wattage

The load resistance is varied to create varies value in the current sense pin, and smaller load resistance must have higher wattage, for example in 8kΩ load it is safe to use 20W resistor. As seen in the Figure 4, test points of the PFC circuits will be:

- Output voltage of bridge rectifier, typical value 390VDC.
- Current sense pin (ISENSE) UCC28180, typical value -24 to 7 VDC [16].
- Voltage sense pin (VSENSE) UCC28180, typical value -0,3 to 7 VDC [16].
- Output waveform of UCC28180, square-wave signal typical value 0-VCC. When ISENSE and VSENSE value varied, it will create varied duty cycle in this output.
- Final output voltage, typical value 390VDC

B. LLC Corverter Testing Points

Testing environment for the LLC converter circuits to simulate real condition are:

- Input: 390VDC (2A fused)
- Output: Resistor 4Ω, high wattage

The testing can be done with output transformer or without output transformer, using an inductor to simulate L_m and a resistor to simulate the load resistance. But it must consider the turn ratio for the resistor. As seen in the Figure 7, test points of the LLC circuits will be:

- Output of $\mathrm{GD_1}$ and $\mathrm{GD_2}$ pin of UCC25600, square-wave signal typical value 0-VCC with 50% duty-cycle. As shown in Figure 7, when resistor in RT pin is varied, it will create varied frequency in this output. $\mathrm{GD_1}$ and $\mathrm{GD_2}$ is having inverted waveform with about 50 ns dead-time [17].
- L_m waveform is filtered version of UCC25600 output, with matching frequency it will create a sinusoids waveform. When the frequency tuned down it would raise the amplitude, on the other hand tuning up the frequency will reduce the amplitude as shown in Figure 6.
- Final output voltage if using the final output transformer and rectifier, typical value 80VDC

Most challenging step is to properly drive Power MOSFET using high voltage, because one missing step, the MOSFET will dissipate much larger power than it can, and will end up burning. So before testing it to high voltage, make sure the MOSFET is working using lower voltage first is a wise move.

V. CONCLUSIONS

Switch-mode power supply that specifically designed to charge EVs battery pack with household electricity as the input is presented. Using combination of PFC Rectifier – to improve the power factor when rectifying household electricity voltage rating – and LLC Converter – to convert high voltage dc into battery voltage rating. This circuit is designed to deliver high power into output to maximize charging time of the battery. The final schematic can be seen in the Figure 8.

Our next work is to compare real measurement with our design calculation and testing value, and finally make a adjustment to meet the specifications.

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