Comparison of main control strategies for DC/DC stage of bidirectional vehicle charger

Karol Fatyga
Faculty of Electrical Engineering and Computer Science
Lublin University of Technology
Lublin, Poland
k.fatyga@pollub.pl

Dariusz Zieliński
Faculty of Electrical Engineering and Computer Science
Lublin University of Technology
Lublin, Poland
d.zielinski@pollub.pl

***Abstract*—This paper presents comparison of two control algorithms for DC/DC converters in vehicle chargers. It presents operation in phase-shifting algorithm and resonant LLC algorithm, their implementation, and test results.**

***Keywords*— electric vehicles; charger; power converter; phase shifted full bridge;resonant LLC**

I. INTRODUCTION

Electric vehicles are becoming more popular around the globe, however their rise in numbers is impeded by existing charging infrastructure and electric grid capabilities. Environmental impact is too significant to be overlooked and those vehicles, with their increase in range, performance and design are becoming more appealing. However, those vehicles, while removing problem of exhaust gases, create another: high grid load when charging. In case of large number of electric vehicles being charged in same time, grid might not be able to support such high demand for electric energy. Existing chargers can be divided into two groups: unidirectional [1], and bidirectional [2]. While more expensive and complex in design, they allow not only vehicle charging, but also discharging their batteries [3]. Stored energy can be used locally, and discharged into household, or used to support grid on-peak load [4]. Fast charging of electric vehicle requires level 3 charging. Since single-phase grid is not capable of sustaining it, it enforces use of three-phase rectifiers combined with DC/DC converters as depicted in Fig. 1.

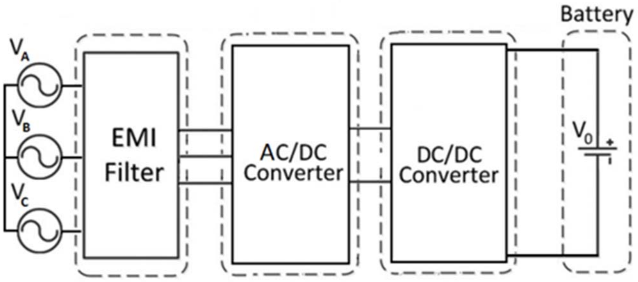


Figure 1. Three-phase isolated vehicle charger

Since the device transfers large amounts of energy, especially when we consider fast charging of electric vehicles, it requires high efficiency. For AC/DC two-level voltage source converter is used, and with proper grid synchronization, there isn't much efficiency to gain [5][6]. Stage that can impact efficiency the most is DC/DC converter. Depending on applied topology, control algorithm, and additional components, it can reach 97% or even 99% when using SiC semiconductors. This paper aims to decide which control strategy should be used to achieve better performance when charging electric vehicle. It consists of short overview of control strategies, their application and comparison.

II. BIDIRECTIONAL ISOLATED TOPOLOGY

In unidirectional charger three-phase rectifier as well as DC/DC converter rectifier are composed of diodes, as depicted in Fig 2a. This solution is cheaper and requires no control, however – lack of control can be considered a downside. Most importantly, as stated before – energy can be transferred only from grid to battery.

Replacing diodes in both rectifiers with transistors as presented in Fig 2b has several benefits, main one being ability to transfer energy in both directions [3], [4]. While charging the battery, three-phase bridge works as rectifier feeding DC bus connected to H-bridge. H-bridge controls voltage on primary winding of transformer. Secondary winding is connected to another H-bridge working as rectifier. Secondary h-bridge can be used passively, with transistor diodes working as rectifier, or actively, using transistors to rectify the current [7]. To change energy flow direction H-bridges roles are exchanged: secondary side works as inverter, while primary becomes a rectifier feeding DC bus. Three-phase bridge switches to inverter mode and transfers energy to the grid [8]. This solution is more complicated, and requires fourteen PWM channels for operation.

III. OPERATION OF DC/DC CONVERTER

DC/DC stage in electric vehicle charger works as charging current controller and galvanic isolation between grid and battery. To test its operating parameters device was built as depicted in Fig 3.

The device consists of three-phase transistor rectifier connected via DC bus to DC/DC converter. Applied topology

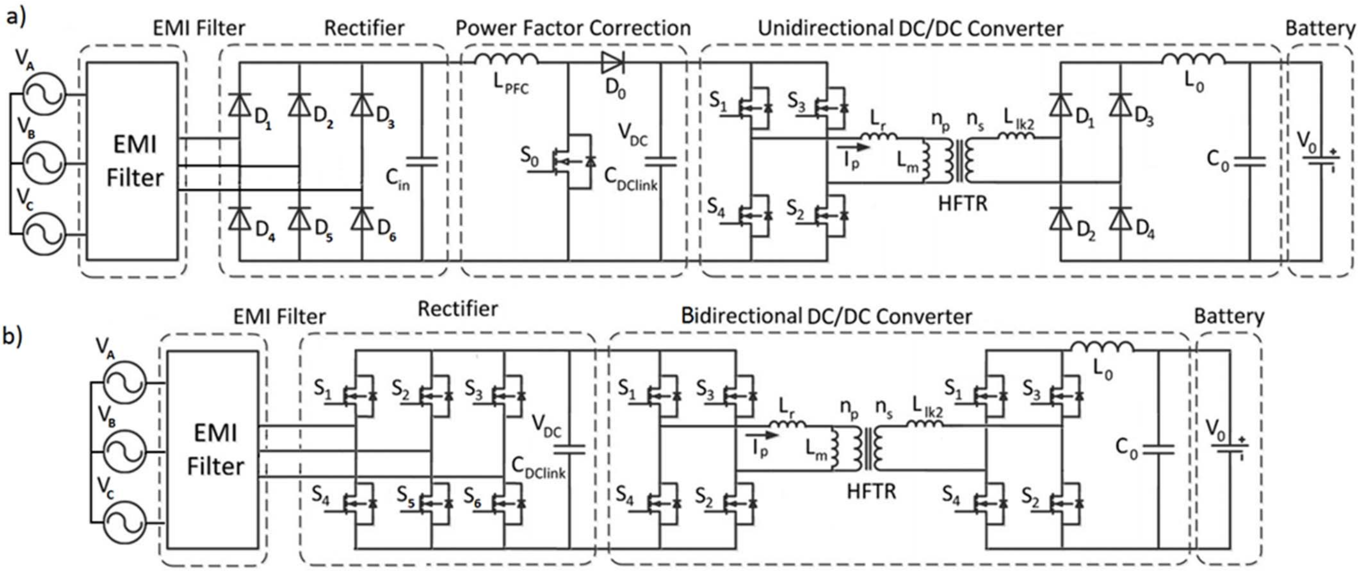


Figure 2. a) Unidirectional vehicle charger, b) Bidirectional vehicle charger

reflects solution presented in Figure 2b. DC/DC stage can operate in one of three modes: open loop, current control closed loop and voltage control closed loop [9], [10]. Mode is chosen depending on battery state: at initial charging phase, current is controlled directly, and when battery voltage Is close to nominal value, device switches to voltage control. Open loop is used for low-load testing purposes. Device was built to have 3-phase 400V AC input, and regulated DC output between 50-500 V, with maximum power of 25 kW.

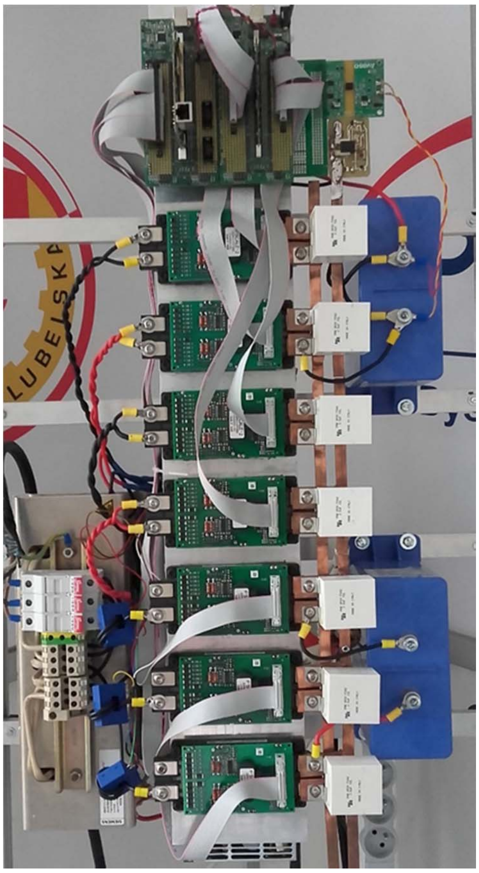


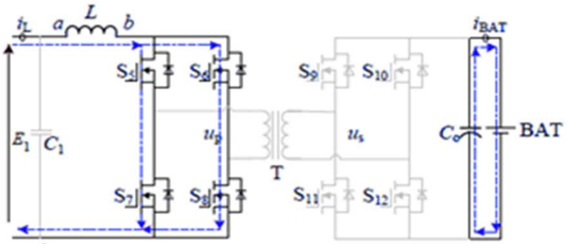
Figure 3. Prototype bidirectional charger

A. Phase-shifting control

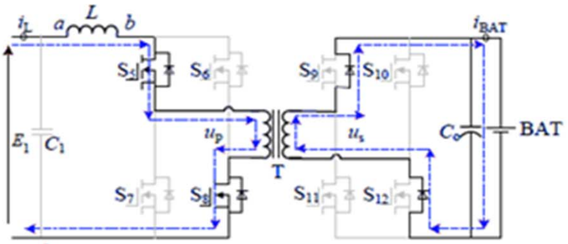
As mentioned before, DC/DC converter can be controlled in few ways. Phase-shifting control relies on changing phase between two halves of H-bridge. Figure 4 presents operation of this control strategy. H-bridge is divided in half, with left leg having fixed phase. All control signals are fixed at 50% duty cycle, and frequency of 20 kHz. Right leg of H-bridge can switch its phase in relation to left leg. By default, opposite signals are shifted 180°, when phase of right leg is changed, opposite signals start to overlap, allowing current to flow through transformer. On secondary side of transformer, diodes in transistor modules are used to rectify the current fed to DC bus [Fig. 4]. To increase efficiency at high loads, transistors on secondary side can be used for synchronous rectifying. Another method of increasing efficiency is to introduce zero-voltage switching (ZVS); this requires additional LC components on primary winding of transformer. Since applied topology is fully symmetrical, changing energy flow from charging battery to supporting grid from battery requires only role exchange between control signals of primary and secondary H-bridge. Additionally, when using phase-control, another control algorithm can be used: instead of directly controlling phase, and thus controlling length of transfer window, device is set to open transfer window for as long as current doesn't reach set value. This control algorithm is called peak current mode control (PCMC), and because it utilizes more hardware, it's faster, and less demanding on microcontroller.

B. Frequency control

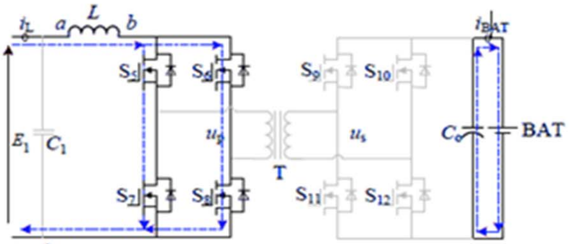
DC/DC converter can be controlled by changing frequency, using resonant LLC circuit. This is why this control strategy is called LLC resonant algorithm. In order to achieve that, additional capacitors and coils are required on both sides of transformer. Again, control signals are fixed at 50% duty cycle, however this time phase is fixed at 0° and frequency is changed. In this algorithm, current is controlled by changing frequency, so it moves towards or away from resonant frequency. Because of this, impedance of circuit changes, and current changes as a result. This algorithm allows to achieve zero voltage switching quite easily: frequency should be locked to be either even to resonant, or higher. This makes circuit character capacitive allowing for easy implementation of soft switching.



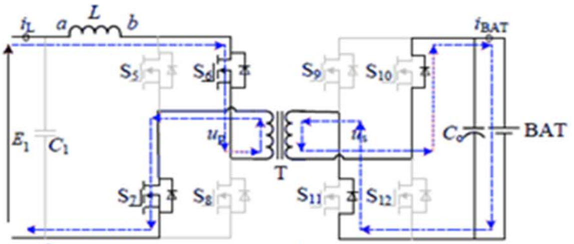
Charging: Step 1



Charging: Step 2



Charging: Step 3



Charging: Step 4

Figure 4. DC/DC PSFB operation

IV. RESULTS PRESENTATION AND DISCUSSION

Both algorithms were implemented in built device. Fed from three-phase rectifier, DC-DC converter was tested in phase-shifting mode. Afterwards, LC components were added to create resonant circuit for LLC algorithm, which was tested then. Figure 5 presents current and voltage waveforms on transformer primary winding when controlled by phase-shifting algorithm, with different phase values: full 180° phase overlap (a) and 90° overlap (b).

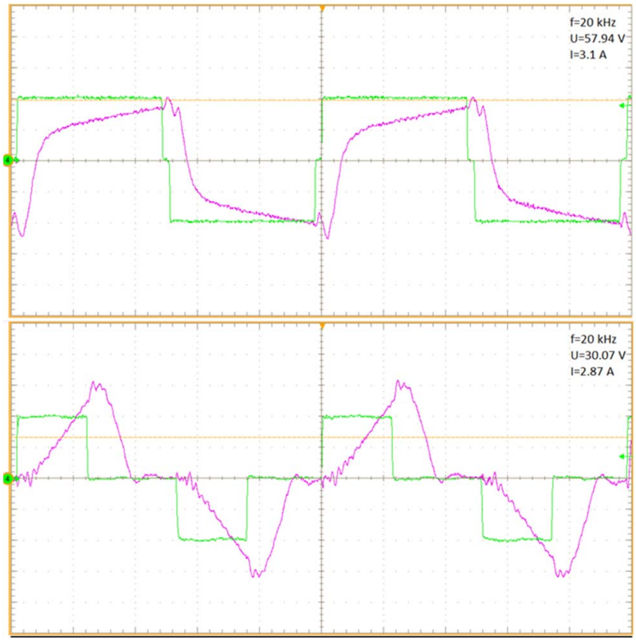


Figure 5. Phase-shifting control waveforms

Figure 6 presents current and voltage waveforms on transformer primary winding when controlled by resonant LLC algorithm, with two frequencies: f=48kHz (a), and f=25.8 kHz (b), with f=25.8 kHz being resonant frequency of the circuit.

Difference in current waveforms is significant: in LLC control, when close to resonant frequency, current becomes almost sinusoidal. Efficiency of the device tested with both algorithms is comparable, reaching just above 85% [Figure 7],

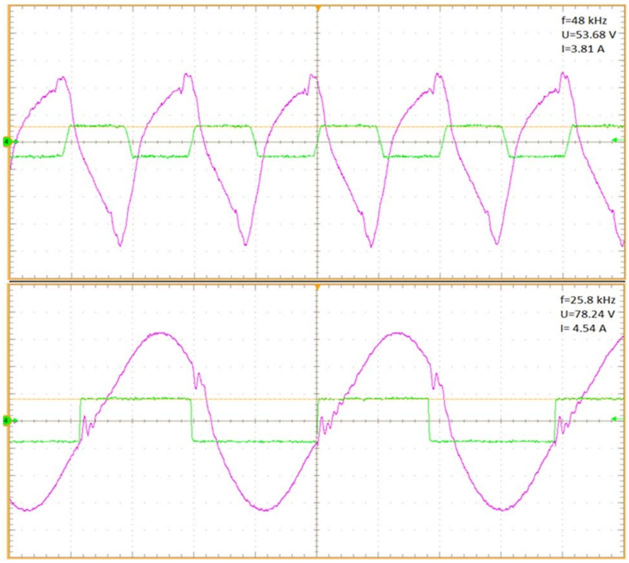


Figure 4. Frequency control waveforms

with phase-shifting algorithm being slightly more efficient, but loosing efficiency more rapidly under small loads.

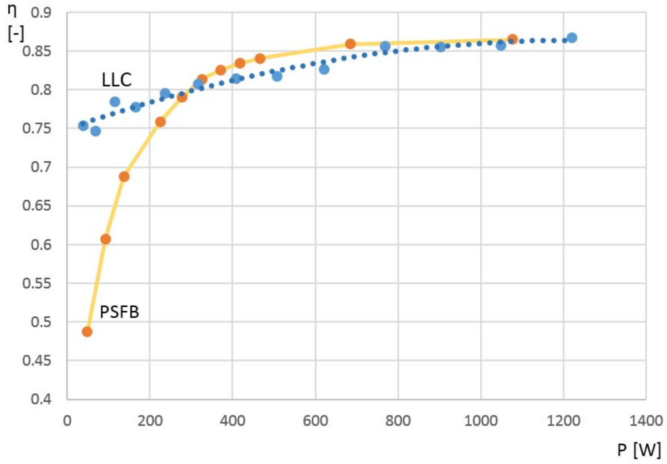


Figure 5. Efficiency of charger in two control modes

V. SUMMARY

Both tested DC/DC converter control algorithms allow to achieve high efficiency of the device. Phase shifting algorithm exceeded efficiency of resonant algorithm by 1-2 percent. With target 25 kW energy transfer, it means 500 W losses less, and because of it, less heat generated. However, when working under smaller loads, the resonant algorithm is losing efficiency way slower and doesn't go below 75%. At the same time phase shifting control causes device's efficiency to drop below 50% under similar conditions. This efficiency drop needs to be considered, since proposed device is meant as vehicle charger, and it will operate under changing loads: fast, high power charging only occurs between 30-80%, where above that, battery should be charged with low current, till it reaches 100% of charge. Because of this, it needs to be taken into consideration, what will generate more losses: fast charging with slightly lower efficiency using LLC resonant algorithm, or slow charging above 80% using phase-shifting algorithm – overall creating smaller losses, but over longer period of time. Since generating high losses while fast charging creates more issues it is better to use phase-shifting algorithm for controlling of vehicle charger, if we take aforementioned problem into consideration. Another issue with LLC resonant control is mass and volume of capacitors, which may create issues for designers.

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