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A REVIEW OF CURRENTLY USED ISOLATED DC-DC CONVERTERS

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Abstract. This paper presents a review of the most popular isolated DC-DC converters topologies. Presented solutions are divided to two main groups. First – unidirectional soft switched isolated DC-DC converters and the second one – bidirectional soft switched isolated DC-DC converters. It introduced also a two main DC-DC converters control methods. The collected results of research, simulations and tests of individual solutions carried out with different assumptions allowed for the preparation of a summary. The formulated conclusions can define the direction of development of resonant converters and a specific starting point for further research on control algorithms as well as improving the efficiency of DC converters.

Keywords: DC-DC power converters, soft switching, electric vehicles chargers, LLC resonant converter

PRZEGLĄD OBECNIE WYKORZYSTYWANYCH IZOLOWANYCH PRZETWORNIC PRĄDU STAŁEGO

Streszczenie. W artykule przedstawiono przegląd najpopularniejszych topologii izolowanych przetwornic prądu stałego. Zaprezentowane rozwiązania podzielone zostały na dwie główne grupy. Pierwsza – jednokierunkowe izolowane przetwornice prądu stałego pozwalające na osiągnięcie miękkiej komutacji, druga – dwukierunkowe izolowane przetwornice prądu stałego osiągające posiadające możliwość pracy w trybie miękkiego przełączania. Zebrane wyniki badań, symulacji oraz testów poszczególnych rozwiązań przeprowadzanych przy odmiennych założeniach pozwoliły na opracowanie podsumowania. Sformułowane wnioski mogą definiować kierunek rozwoju przetwornic rezonansowych oraz swoisty punkt wyjścia do dalszych badań nad algorytmami sterowania jak i poprawą efektywności przetwornic prądu stałego.

Słowa kluczowe: przetwornice DC-DC, miękka komutacja, ładowarki pojazdów elektrycznych, przetwornice rezonansowe LLC

Introduction

The number of applications of DC-DC converters in the field of electrical and electronics is constantly increasing. They are used, among others, in small converters found in mobile phone chargers, through computer power supplies, photovoltaic installations, electric vehicles (EV), EV chargers and large energy storage. At present, micro-photovoltaic installations [17, 23], energy storage [27] and electric vehicle chargers [14] process the largest amounts of energy while remaining applications with the most variable load levels [12]. Such characteristics of the converters work require from engineers designing converters to take an un-conventional approach to the subject and to constantly search for the most effective solutions to minimize the burden on the energy system and thus reduce greenhouse gas emissions [29]. The multitude of converters used in electromobility as grid to vehicle (G2V) and vehicle to grid (V2G) chargers, or inside of electrical vehicles forces to continuous research into more efficient DC-DC converters with higher energy density. The article presents an overview of the latest solutions within DC-DC converters [22], focusing on the most effective ones. The focus was on a broader look at the subject of DC converters, showing not only the difference in topologies and their application, but also review of the latest control solutions. The collected results of research, simulations and tests of individual solutions carried out with different assumptions allowed for the preparation of a summary. The formulated conclusions can define the direction of development of resonant converters and a specific starting point for further research on control algorithms as well as improving the efficiency of DC converters.

This article is divided as follows: 1 – Unidirectional soft switching DC-DC converters, 2 – Bidirectional soft switching DC-DC converters, 3 – Comparison between two most popular control method. Section 5 provides a conclusions.

1. Unidirectional soft switched DC-DC converters topologies

Many of the mentioned devices require specific functionality, the most important of which is a galvanic isolation between power source and load terminals [6]. This paper are focused on currently used isolated DC-DC resonant converters solutions.

1.1. LLC series-parallel converters

Most popular DC-DC resonant converters used for one-way energy transfer is designed in series-parallel LLC/LCC topology what is shown in Fig. 1. This kind of solution is a good compromise between efficiency to cost, thanks to not so much complicated design [8].

Specific of this kind full bridge converters and synchronisation of control signals allows to achieve zero voltage switching (ZVS) in turn-on stage and zero current switching (ZCS) in turn-off stage of an opposite pair transistor when converter is working on resonant frequency [15]. Difficulties in maintaining resonance at low load mean that it should be designed to operate at medium and high % of maximum power. This disadvantages causes that LLC/LCC topology is a good and efficient option only, when load is easy to predictable and constant at the most of time or work time on low load is occasional [1, 4, 20, 38].

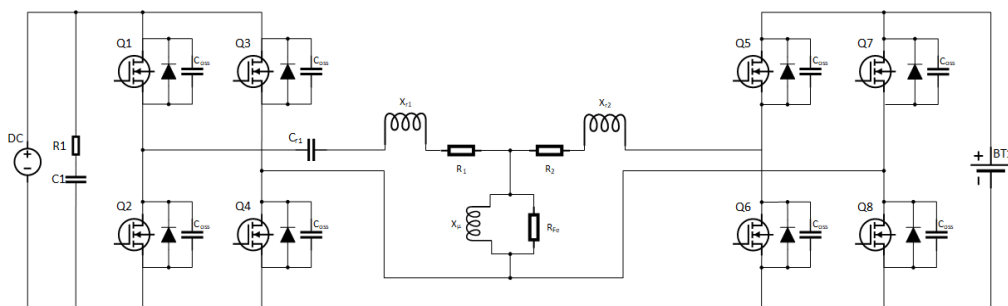


Fig. 1. Dual Active Bridge LLC resonant converter simplified topology

1.2. Multi output LLC converter

Every of battery electric vehicle (BEV), plug in electric vehicle (PEV) and fuel cell electric vehicle (FCEV) needs to be useful minimum a few power converters inside [8, 13].

In typical EV, one of power converters is needed to transfer power between high voltage (HV) battery and engine(s) inverter(s) [7, 11], second between HV battery and wall charger, third one between HV line to low voltage (LV) line for charging a LV battery – usually 12 V or 24 V in truck and buses which is needed to supply onboard LV devices as lights or audio system and the last one – DC/AC inverter to supply high voltage air conditioner (HVAC) [7]. As was shown on Fig. 2 in FCEV is another one of converter- working in step-up mode- to boost voltage from fuel cell which is typically at low value – for example 165 V in 45 kW fuel cell generator designed

for buses [43]. Many converters in one vehicle, working on different voltages and power levels increasing weight, cost and total mass of entire vehicle. A partial solution to this problem has been proposed in [10] and named as multi output LLC converter.

Proposed converter topology is based on a basic LLC converter but with modified transformer, simplified structure is shown on Fig. 3. In multi output converter topology, transformer has been exchanged to multiple winding transformer. Properly designed of each part of converter allows to reach a soft switching similar to typically LLC topology [34] but with reducing time when converter is working unstable – on very low load. That allows to integrate two or more DC-DC isolated converters to one device with different voltage outputs.

Integrated solutions reduce total net mass of the vehicle, and takes up less space that can be devoted to increasing the usable space.

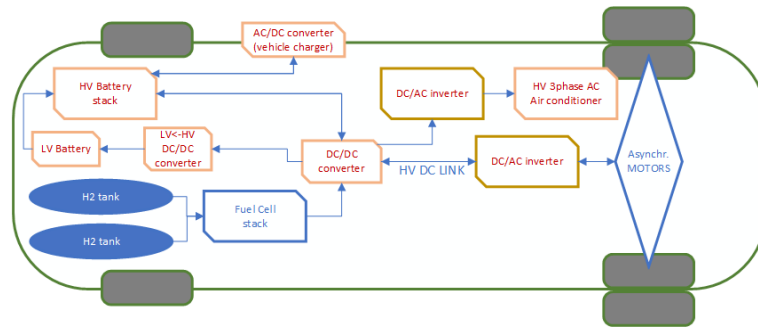


Fig. 2. Main power converters in Fuel Cell Buses and energy flow directions

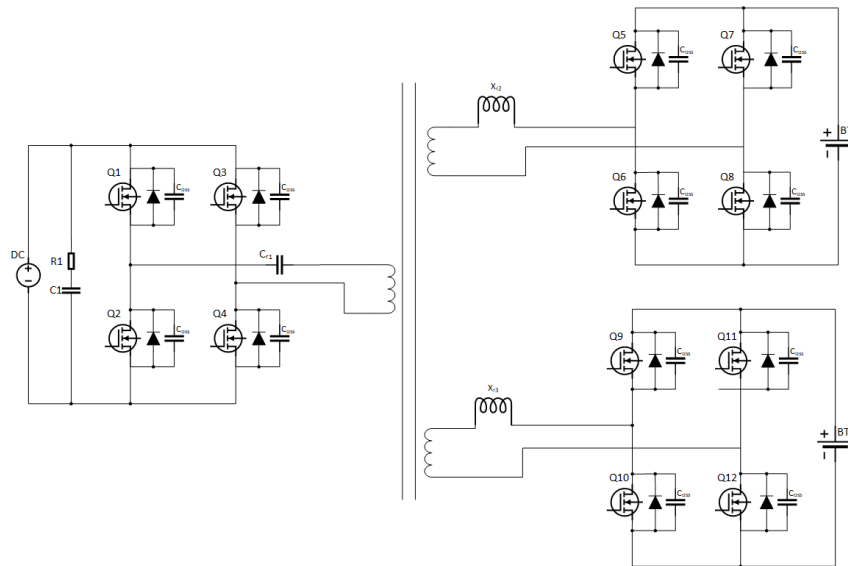


Fig. 3. Multi output Dual Active Bridge LLC (unidirectional soft switched) converter simplified topology

2. Bidirectional DC-DC converters topologies

Bidirectionality – next to efficiency and isolation – one of the most important functionality required on electromobility power converters market. Due to the continuous increase in the number of all kinds of EVs, from scooter, EVs, light commercial electrical vehicles (LCEVs), FCEVs to trucks and FC trains, energy system is getting more and more unstable. To limit this process it is necessary to provide a new services, one of them is bidirectional energy transfer between grid and users. Traditional system is working in one way, customers uses energy from grid and that's all, but now it's not enough.

For several years, research has been carried out on the possibilities and improvements of bidirectional energy transfer through isolated DC-DC converters. One of the proposed solutions is G2V-V2G service, the main assumption is sharing energy stored in EVs with the grid in hours when it is not needed for EVs customer, for example when owners are in work. Then the grid

operator could use EV batteries as huge energy stores, provided that they are charged before the designated time (e.g. end of EV owners' working hours). Thanks to V2G services, the network receives decentralized energy storage at predictable hours and capacities without incurring the cost of their purchase. On the other hand, the customers get the opportunity to purchase energy at reduced costs. Second perspective to using bidirectional transfer by EVs owners or road assistance services is Vehicle to Vehicle (V2V) energy transfer. To clarify in most popular vehicles – with internal combustion engines- when they run out of fuel then it is possible to call on road assistance or friend who can deliver fuel in a canister. In EVs, such problems can happen even more often than in internal combustion cars- long route, frost or sweltering heat, traffic jam and running out of battery energy reserves. These are also the assumptions of the services like V2V energy transfer. Inside V2V service is a special devices based on bidirectional isolated DC-DC converter and charging regulator which allows to transfer energy directly between vehicles.

A mentioned problems are a two main reasons why bidirectional energy transfer possibilities are so important.

2.1. CLLC dual bridge- series-parallel converters

The disadvantages of LLC topology and the requirements from electromobility market as a high efficient bidirectional energy transfer possibilities led to creating a dual active bridge [19] (DAB) CLLC converters. [2, 9, 11, 28].

Main difference between LLC and CLLC [36] topology is an expansion of resonant tank up to four or more elements involved to resonance what is shown on Fig. 4. In the V2G direction, the magnetizing inductance is not used in resonance, leaving typical series LC resonance [9, 31]. That system simplification causes losing a soft switching and decreasing a gain under 1, thus limiting the possibilities of adjusting the output voltage. Thanks to extended resonant tank now it is possible to achieve work in resonance frequencies in both, grid to vehicle (G2V) [25, 26], and vehicle to grid (V2G) way of energy transfer. Similarly to LLC converters- working near resonance frequencies, it enables soft switching in ZVS/ZCS mode [28], which significantly reduces switching losses and improve the performance of the entire device [3, 8, 9]. Described more deeply in [2, 3, 8, 9] advantages of CLLC DAB isolated DC-DC converters proves superiority of this topology than LLC converters in systems where bidirectional transfer is required.

2.2. Multi module resonant converters

Similar to multi output [18, 33] LLC resonant converter topology, but instead of providing different voltage levels for loads from single source – this kind of converter is designed to allow to supply DC link from different sources [16, 30]

Another bidirectional isolated DC-DC converter is presented at [12]. Presented topology is a combined system of a single source, and multi full active bridges (FAB) or multi half active bridges (HAB) on secondary side delivering power to single load. Dividing total load to multi FABs while maintaining soft switching allows to switching on higher frequencies without increase power losses [5].

In [16] multi input FABs converter is presented, that kind of topology will be used to supply DC link – load by different voltage sources, each of them have their own transformer winding tap. Presented in Fig. 5 combined mode allows to connect via converter for example HV battery on 400VDC, fuel cell stack with 200 V from primary side to load (engines inverters [41] connected to DC link) 500 V, or to receiving energy from engine recuperation braking to HV batteries, disconnecting fuel cell module maintaining of soft switching mode.

Multi module isolated DC-DC converters that achieve soft switching modes like ZVS and ZCS, could be a optimal solutions for most of EVs and FCEVs which allow to simplified a vehicle cooling system and HV/LV harnesses or power line system.

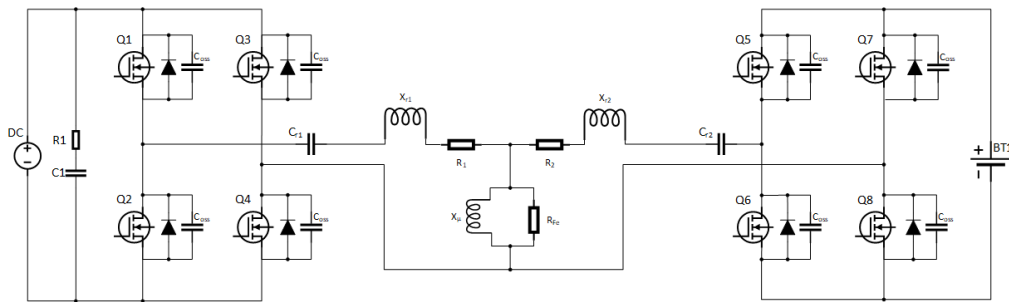


Fig. 4. DAB CLLC (bidirectional soft switched) resonant converter simplified topology

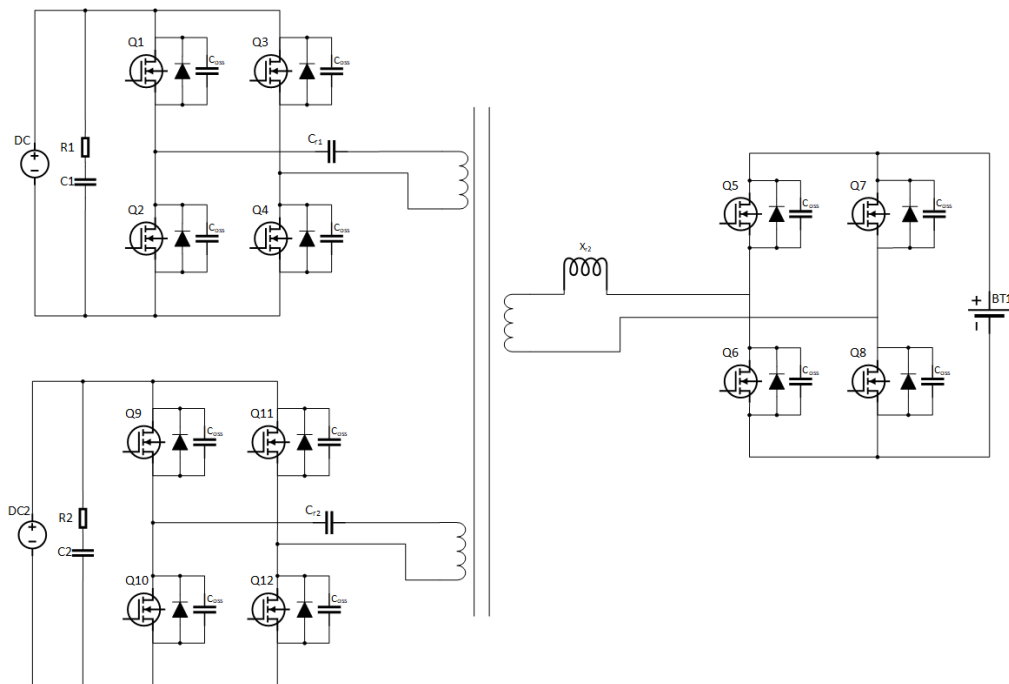


Fig. 5. Multi source DAB (bidirectional soft switched) DC-DC converter simplified topology

3. Frequencies vs phase shifted control method differences

The multitude of isolated DC-DC converters topologies, and pursuit of the highest efficiency resulted in development of few control methods. First from two of the most popular is control by changing frequency, using resonant algorithm. In this type of control method, time phase is fixed at 0° and power is regulated by changing frequency that means – converter is working at resonance point, below or under resonance freq. To achieve a ZVS it is necessary to work near below, at point or above resonant frequency. Second is control via changing phase shift angle to regulate the output voltage [21, 35]. Comparison of the advantages and disadvantages are listed in the table 1.

Table 1. Comparison of disadvantages and advantages between frequency and phase shifted control method [8, 21, 24, 35, 37, 39, 40]

| Parameter | Phase shifted control method for DAB converter (PSFB) | Frequency control method for DAB converter |
|--|---|--|
| Efficiency for max. load lower than 15% | Higher than freq. | Low, instable below 10% of max. load |
| Efficiency for max. load higher than 15% | Lower than freq. | Higher than PSFB |
| Soft switching | ZVS | ZVS and ZCS |
| Frequency | Constant | Flexible |
| Power destiny | Lower per 1 kW | Higher per 1 kW |
| Bidirectional transfer | Possible but complicated | Possible and easiest than PSFB |
| EMI | Higher than freq. | Lower, signal close to sinus |
| Synchronisation | Easiest than freq. | Complicated |

Phase shifting control is a method which is realized by changing phase between first and second half of H-bridges. This type also allows to use full bridge DABs (FBDAB) topology for synchronous rectifying. If resonant tank are designing like fully symmetrical it is possible to achieve bidirectional fully synchronous isolated DC-DC transfer by changing steering role between H-bridge on the primary with H-bridge on the secondary side of transformer [14]. Control algorithm which is based on PSFB control method is called peak current mode control (PCMC), this is the one of the fastest control method.

Presented review of control method features are more deeply described in [2, 14, 21, 32, 35]. Issues like low efficiency or instable work in load lower than 10% of maximum designed or large switching frequency operating range to satisfy voltage gain requirements causes that frequency control method is a good solution if load parameters are predictable and stable. Otherwise despite lower efficiency at high load, phase shifted control method allows to work in constant frequency and easy way to synchronise DABs in full range of load.

4. Conclusions/summary

The collected results of research, simulations and tests of individual solutions carried out with different assumptions allowed for the preparation of a summary. A multitude of applications where DC-DC power converters can be use shows that is every day and future-proof technology. Series-parallel resonant converters LLC-type is an optimal solutions to transfer energy via isolated converter if power level is predictable and repeatable, and also bidirectional transfer is not required, for example in phone or notebooks chargers. In bidirectional applications it should be applying CLLC DABs resonant or symmetrical DABs topologies with PSFB or frequency changing control method. Designing multi source multi active bridge converters with soft switching allows to supply one DC link from different sources with different voltage levels.

Combination of multi active bridge multi input or multi output converters are one of the possible directions to simplify electric vehicles power lines. Simplification of EVs harnesses allows to designing and routing it on the best way and insulation in conjunction with electromagnetic compatibility requirements of vehicles approval. Another advantage is possibility to design more compact solution in one case (one module) with combined cooling interface. Common heat dissipation system can reducing weight of system integration in the vehicle- not each converter connected with separated valves and steel pipes but one valve on input and one on the output of multi DC-DC converter cooling port. All possible ideas to reduce curb weight are desirable because they affect to available maximum range.

Deeply focusing on details of topologies and control methods must be the starting point to designing more efficient, better matched for application power converters.

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