# Flexible Control Scheme of a CLLC Converter

*This design note introduces a flexible control scheme for the CRD22DD12N 22kW DCDC bi-directional converter. It helps users to understand the control of the reference design to get a wide voltage gain range for a CLLC converter.*

## 1. Introduction

The trend of power conversion systems for EV (Electric Vehicles) and energy storage is toward high efficiency, high power density and bi-directional operation. The CLLC converter has become very popular in bi-directional DCDC power conversion applications due to its ZVS (Zero Voltage Switching) operation in bi-directional operation mode [1] - [3]. However, ZVS means zero voltage turn-on only. It is still hard to switch off the primary MOSFETs in a CLLC converter. To achieve high efficiency, good thermal performance and low EMI (Electro Magnetic Interference), it is critical to properly design the transformer and resonant tanks to minimize the maximum switching frequency and turn-off current for the MOSFETs under all load conditions. However, in some applications such as an EV OBC (On Board Charger) with 3-phase AC input, the required output voltage range of the DC-DC converter is wide in charging mode. Also, to support DC-AC operation in V2L (Vehicle to Load) mode with a wide battery input voltage range,

the required voltage gain range of the DC-DC converter is also wide in discharging mode. It is difficult to optimize the transformer turns ratio to achieve the required voltage gain range for the CLLC bi-directional resonant converter.

Variable DC-link voltage based OBC was studied in [4], [5]. The DC-link voltage range of an OBC with single-phase AC input is optimized to be 380V-680V in [4] and 480-800V in [5] to match a battery voltage range of 250V-450V. The CLLC bidirectional resonant DCDC converter can always operate around the resonant frequency in both charging and discharging mode. Very high efficiency was achieved at system level. However, the same control scheme is not applicable for the OBC system with 3-phase AC input. With 304~456Vac 3-phase input, the minimum DC-link is 650V. To let the DCDC converter operate around the resonant frequency and match the battery range 250V-450V, the upper voltage setting of the DC-link will be 1170V. For 2-level topologies, it is hard to get high performance cost-effective power components to support this DC-link voltage.

Two-stage structures, a Buck/Boost converter followed by a CLLC converter or a CLLC converter followed by a Buck/Boost converter, was studied in [6]. A two-stage structure allows the DC-DC converter to continue to operate around the resonant frequency, while maintaining a desired DC Link voltage better suited for 2-level topologies. However, an additional Buck/Boost converter increases the system cost and impacts the system efficiency and power density.

Relay-based flexible control was also studied in adaptor application in [7]. Mechanical relays are used to change the turns ratio of the transformer in different operation modes. In high power applications, mechanical relays and Silicon carbide (SiC) MOSFET-based solid relays solutions are also evaluated in the paper. However, the relay-based approach also increases the system cost and impacts system efficiency and power density.

A hybrid modulated reconfigurable bidirectional CLLC derived resonant topology was proposed in [8]. With two additional auxiliary MOSFETs, the reconfiguration of half-bridge and full-bridge is enabled on both the primary and secondary sides. Wide voltage gain range is achieved. However, with 4 additional MOSFETs, the system cost and the system power density are impacted.

In this design note, a flexible gain control scheme is described for a full bridge bi-directional CLLC converter. As shown in Fig. 1, both the input and output sides of the CLLC converter carry full bridges. The input is isolated from the output through a high frequency transformer, T1. Flexible control, including the conventional variable frequency control, phase shift control and reconfigurable control, are implemented in the design.
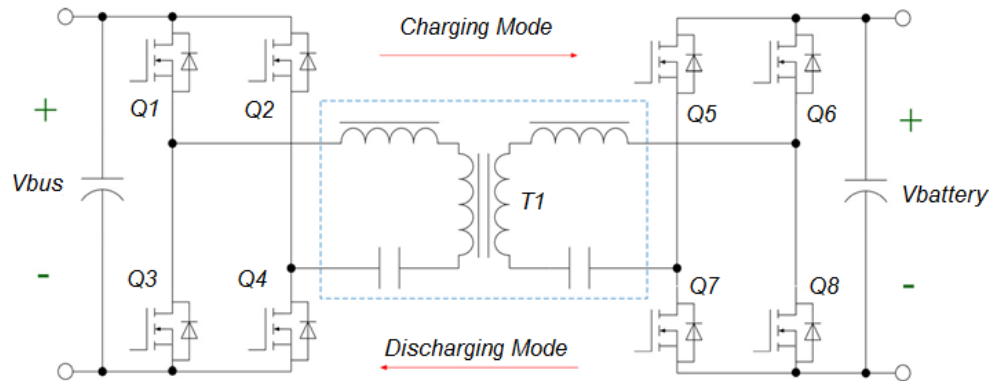


Fig. 1: Schematic of a bi-directional DCDC Converter

## 2. The Proposed Control Scheme for 22kW OBC

To achieve high efficiency and optimized gain range of the CLLC converter, an adjustable DC-link voltage is designed. As shown in Fig. 2, the DC-link voltage is designed to be 380V-900V in single phase AC input charging mode. The digital controller adjusts the DC-link voltage based on the battery voltage. If the battery voltage is in the range of the region C, the battery voltage is higher than the possible output voltage at resonant frequency even if the DC-link voltage reaches its upper limit of 900V. The digital controller will adjust the DC-link voltage to 900V and decrease the switching frequency to let the full bridge CLLC converter operate in Boost mode to provide the required output voltage. If the battery voltage is in the range of region B, the DC-link voltage will follow the battery voltage with a factor of turns-ratio. The full bridge CLLC converter almost works at resonant frequency, such that the best efficiency is achieved. If the battery voltage is in the operation region A, the battery voltage is lower than the output voltage at resonant frequency even `if` the DC-link voltage reaches its lower limit of 380V. The digital controller will increase the switching frequency to let the full bridge CLLC converter operate in step-down mode to provide the required output voltage. If the required voltage gain is lower than the gain at the upper limit frequency of 250kHz, the digital controller will shift the phase of the PWM (Pulse Width Modulation) of Q2 and Q4 to reduce the duty cycle and voltage gain of the CLLC converter.
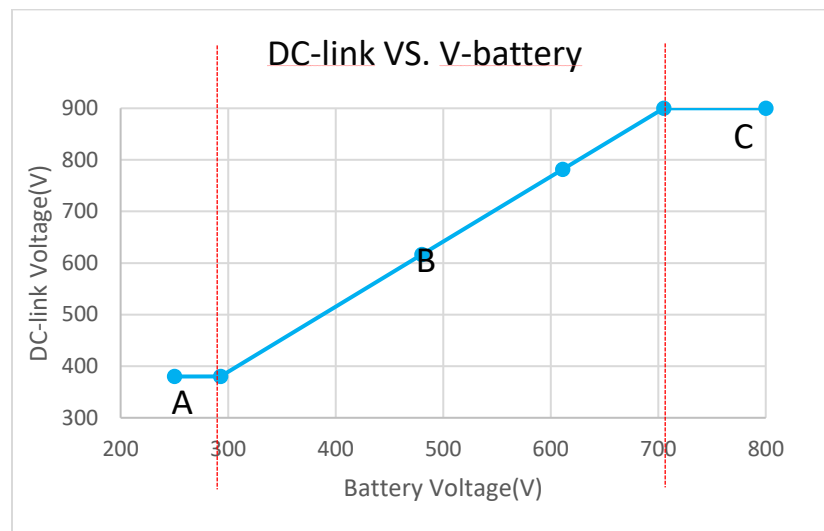
**Figure 2. Adjustable DC-link voltage VS. battery voltage in single phase AC input charging mode**

As shown in Fig. 3, the DC-link voltage is designed to be 650V-900V in 3phase AC input charging mode over 200V-800V battery voltage range. The digital controller adjusts the DC-link voltage and reconfigures the converter based on the battery voltage. If the battery voltage is in the range of the region E, the battery voltage is higher than the output voltage at resonant frequency even if the DC-link voltage reaches its upper limit of 900V. The digital controller will adjust the DC-link voltage to 900V and decrease the switching frequency to let the full bridge CLLC converter operate in Boost mode to provide the required output voltage. If the battery voltage is in the range of region D, the DC-link voltage will follow the battery voltage with a factor of turns-ratio. The full bridge CLLC converter almost works at resonant frequency and the best efficiency is achieved. If the battery voltage is in the operation region C, the required battery voltage is lower than the out voltage at resonant frequency even if the DC-link voltage reaches its lower limit of 650V. The digital controller will increase the switching frequency to let the full bridge CLLC converter operate in step-down mode to provide the required output voltage. If the required voltage gain is lower than the gain at the upper limit frequency of 250kHz, the digital controller shifts the phase of the PWM of Q2 and Q4 to reduce the duty cycle and voltage gain of the CLLC converter. If the required output voltage is in region B, as a full bridge converter with high switching frequency and large phase shift, the efficiency becomes low. The digital controller will adjust the DC-link voltage based on the required voltage and reconfigure the converter to a half bridge converter as shown as in Fig. 4. The half bridge CLLC converter almost works at resonant frequency in region B and the best efficiency is achieved. When the required voltage is in region A, the battery voltage is lower than the output voltage at resonant

frequency even if the DC-link voltage reaches its lower limit of 650V. The digital controller will increase the switching frequency to let the half bridge CLLC converter operate in step-down mode to provide the required output voltage.
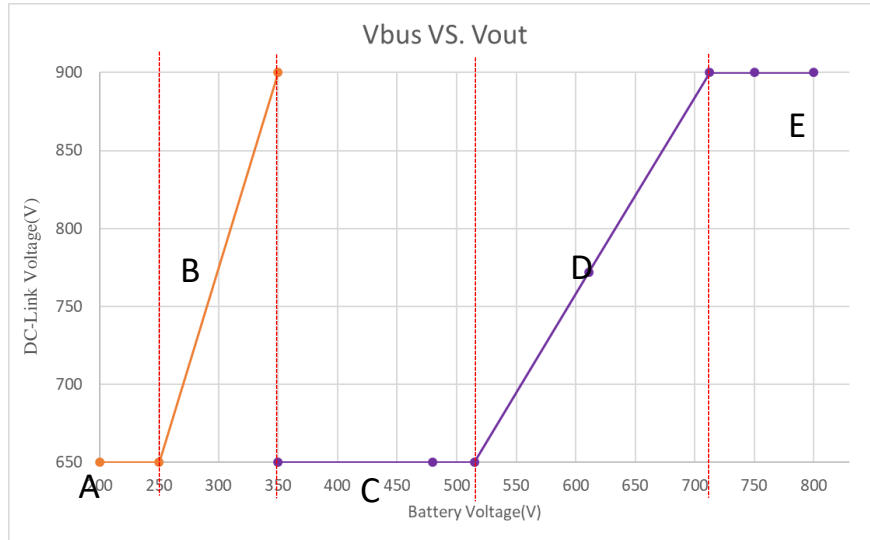


**Figure 3. Adjustable DC-link voltage VS. battery voltage in 3 phase AC input charging mode**
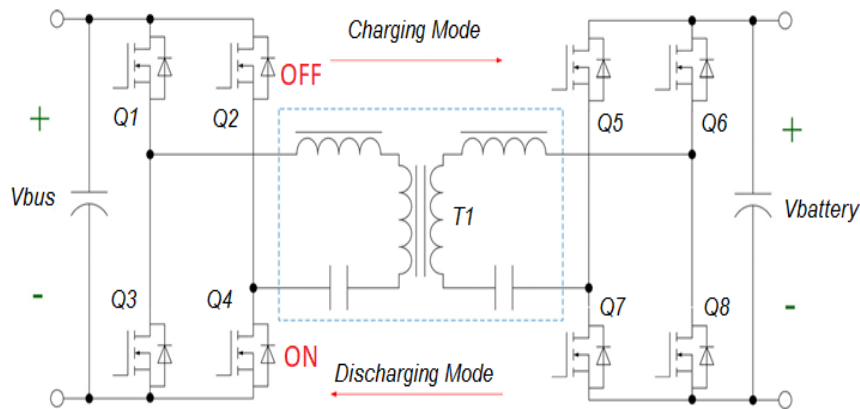


**Figure 4. Half bridge CLLC converter with full bridge SR in charging mode**

In discharging mode, the DC-link voltage is designed to be 360-750V, as shown in Fig. 5. The digital controller adjusts the DC-link voltage and reconfigures the converter based on the battery voltage. If the battery voltage is in range A, the digital controller will adjust the DC-link voltage to follow the battery voltage with a factor of turns-ratio. The full bridge CLLC converter almost works at resonant frequency and the best efficiency is achieved. If the battery voltage is in the operation region B and the DC-link voltage is increased, the OBC can work. However, the OBC will work with a higher DC-link voltage in

order to provide a 220Vac output, the efficiency of the DCAC front-end will drop, and the digital controller will reconfigure the converter to a half bridge converter, as shown as in Fig. 6. The controller will then adjust the DC-link voltage to match the input voltage. The half bridge CLLC converter almost works at resonant frequency in region B and its best efficiency is achieved.
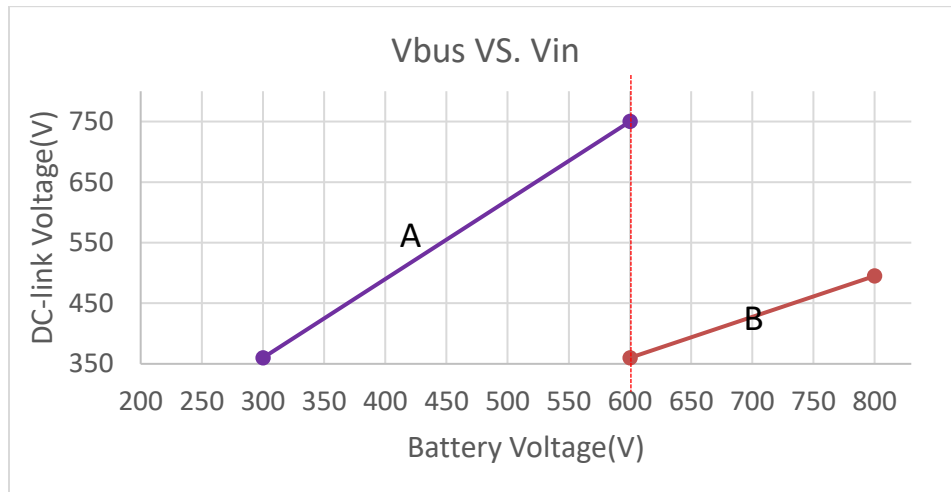


**Figure 5. Adjustable DC-link voltage VS. battery voltage in discharging mode**
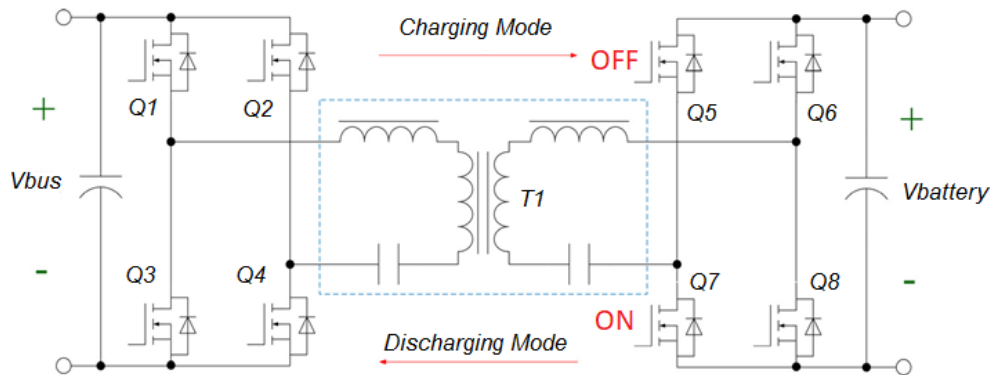


**Figure 6. Half bridge CLLC converter with full bridge SR in discharging mode**

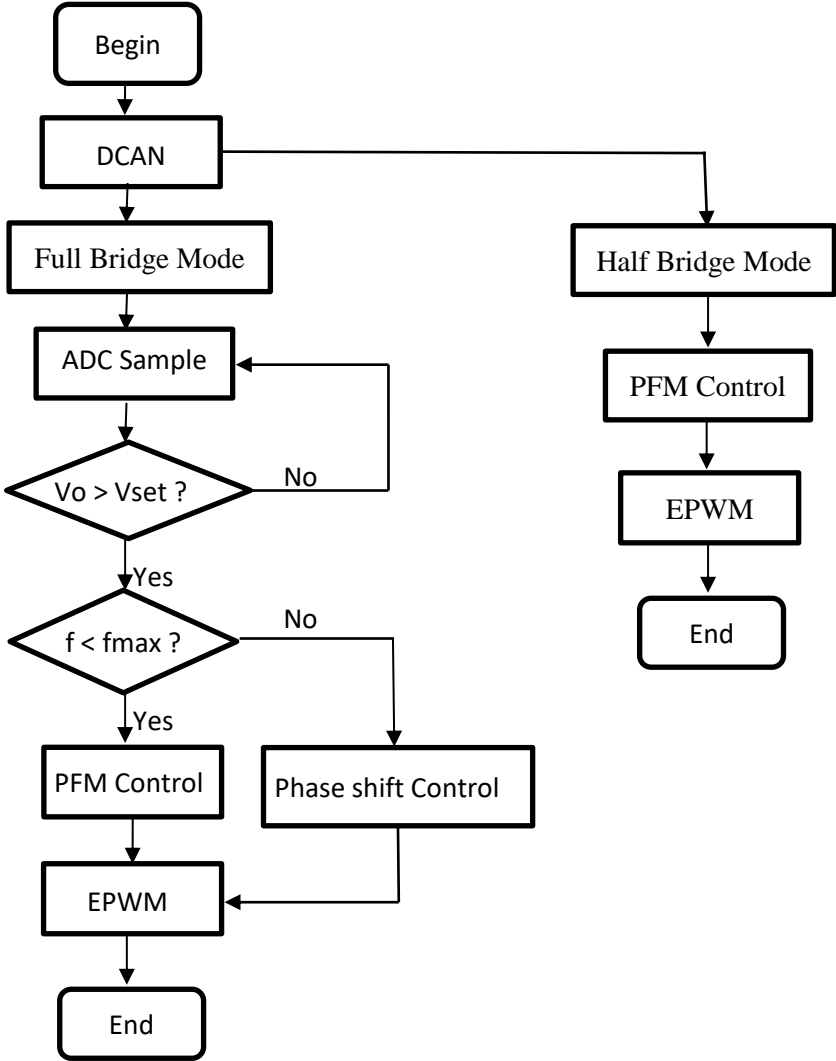The flow chart of the control of the DCDC converter in OBC is as shown in Figure 7.

Figure 7. Flow chart of the control method for OBC

### 3. The Control Method for CRD22DD12N 22kW Bi-directional Converter

In this design, the OBC are separated to an AC-DC converter and a DC-DC converter (CRD22DD12N). Without the battery voltage sensor and the info from AC-DC stage, the users have to set the operation mode and configuration of the converter by GUI (Graphic User Interface) manually, at which point the flow chart of the control is as shown in Figure 8.
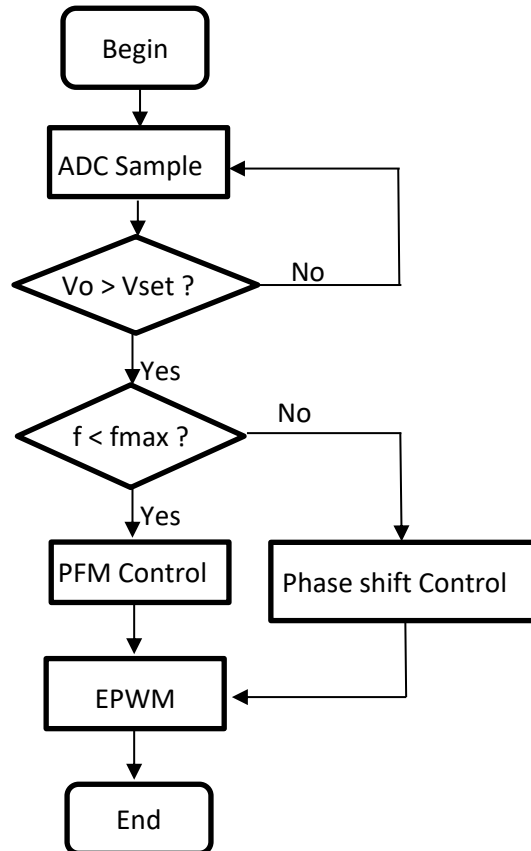
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                    ┌──────────┐
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            ┌──────►│ADC Sample│◄──────────────┐
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            │            │Yes
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            │            │Yes              │
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            │      │PFM Control │   │Phase shift Control│
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                   ┌─────▼──────┐
                   │    End     │
                   └────────────┘
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**Figure 8. Flow chart of the control method in CRD22DD12N 22kW DCDC converter**

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**Revision History:**

| Date | Revision | Changes |
|---|---|---|
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