# V2G 응용을 위한 능동클램프 회로를 가진 양방향 하이브리드 스위칭 풀브리지 컨버터

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# A Bidirectional Hybrid Switching Full-Bridge Converter with Active Clamp Circuit for V2G Applications

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## ABSTRACT

**This paper introduces a bidirectional full-bridge converter with new active clamp structure. The proposed active clamp circuit can clamp the oscillating voltage across the rectifier diodes with a smaller voltage stress of the clamping capacitor and eliminate the circulating current. In addition, the proposed converter can achieve additional advantages such as nearly ZCS switching for leading-leg switches and no recovery current for rectifier-bridge by the suitable design of the clamp capacitor to resonate with leakage inductor. Since the ZVS is achieved for both leading-leg and lagging-leg switches by the magnetizing current of the transformer, it can be achieved regardless of the load variation. A 3.3 kW prototype converter is implemented for vehicle-to-grid (V2G) application and the advantages of the proposed converter are verified by the experiments. The maximum efficiencies of 98.2% and 97.6% have been achieved for the buck mode and boost mode operation, respectively.**

*Index Terms* –V2G, bidirectional full-bridge converter, active clamp, ZVS, nearly ZCS.

## 1. Introduction

V2G is a system in which plug-in electric vehicles communicate with the power grid to return electricity. Since at any given time 95 percent of cars are parked, the vehicle'sV2G capacity can act as a distributed energy source for load leveling. It will be more important than the intermittent renewable energy sources such as solar and wind when it is added to the grid [1]. To achieve V2G function, plug-in electric vehicles require a bidirectional battery charger which is composed of a bidirectional ac-dc converter followed by a bidirectional dc-dc converter. Some bidirectional dc-dc converters can be found in the literature [1]-[2]. All of them are proposed to solve problems in terms of cost, reliability, power density and efficiency.

To solve these problems, this paper proposes a new active clamp structure for a bidirectional full-bridge dc-dc converter, as shownin $Fig. 1$. The proposed novel resonant active clamp circuit can reduce the voltage across the rectifier diodes with a small voltage stress of the clamp capacitor. All the advantages of conventional active clamp circuit such as clamping the oscillation voltage and eliminating the circulating current are retained in the proposed converter.In addition, the hybrid switching whose validity already proved in [2] is applied to the proposed converter to achieve nearly ZCS for leading-leg and no recovery loss for rectifier-bridge.Full range of ZVS forthe switch-bridges in both buck mode and boost most can be guaranteed by magnetizing current of the transformer.

## 2. Operating principle of the proposedconverter

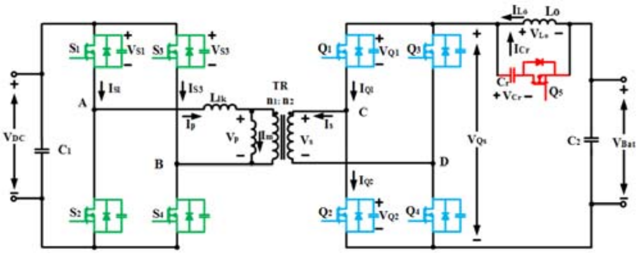


Fig. 1. Proposed bidirectional full-bridge converter with hybrid switching and resonant active clamp circuit.

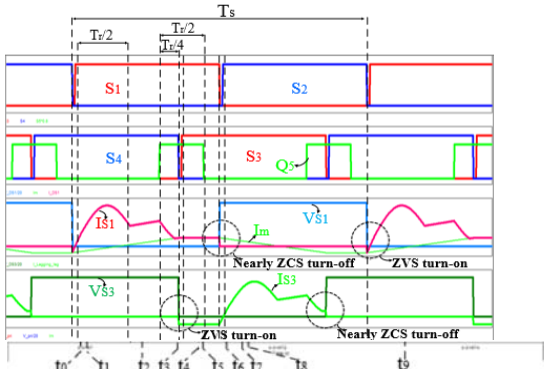


Fig.2.Key waveforms of the proposed converter in buck mode operation

$Fig. 1$ shows the circuit diagram of the proposed converter, which is composed of dual bridge switches $S_1$~$S_4$ and $Q_1$~$Q_4$. $TR$ is the transformer with turn ratio $n_1$:$n_2$, magnetizing inductance $L_m$, leakage inductance $L_{lk}$. Output inductor $L_o$ is employed at battery side and connected with active clamp circuit $C_r$, $Q_5$ in parallel.

$Fig. 2$shows the key waveforms of the proposed converter in buck mode operation.

**Mode 1 [$t_0$~$t_1$]:**At $t = t_0$, $S_2$ is turned off with nearly ZCS, and magnetizing current $I_m$ starts to discharge output capacitance of switch $S_1$.

**Mode 2[$t_1$~$t_2$]:** At t=t_1, $S_1$ is turned on with ZVS which was achieved in the mode 1. In this mode, the power is transferred to the battery through the output inductor and the clamp capacitor.

**Mode 3 [$t_2$~$t_3$]:** At $t = t_2$, the resonant current flowing through the body diode of $Q_5$ reaches zero because this resonant frequency is designed to be higher than the switching frequency.

**Mode 4 [$t_3$~$t_4$]:**At $t = t_3$, the switch $Q_5$ is turned on with ZCS. The clamp capacitor is discharged while the output inductor continues to operate as current source.

**Mode 5 [$t_4$~$t_5$]:**At $t = t_4$, the rectifier current $-I_{Q1}$ reaches zero and the current of switch $S_1$ equals to the magnetizing current $I_m$.

**Mode 6[$t_5$~$t_6$]:** At $t = t_5$, $S_3$ is turned on with ZVS which was achieved in mode 5. A small circulating current $I_m$freewheels in the primary side during this mode.

**Mode 7[$t_6$~$t_7$]:** At $t = t_6$, the switch $Q_5$ is turned off to balance the voltage on the clamp capacitor.

**Mode 8[$t_7$~$t_8$]:** At $t = t_7$, $S_1$ is turned off with magnetizing current $I_m$ which can achieve nearly ZCS.

**Mode 9[$t_8$~$t_9$]:**The other half switching period is symmetric with the operating modes from Mode 1 to Mode 8.

## 3. Design of the proposed converter

### A. Design of the resonant frequency

There are two operating principles behind the proposed hybrid switching scheme with resonant active-clamp circuit. $T_{on} = DT_s$: Turn-on time of primary switches$S_p$.

$T_r = 2\pi\sqrt{n^2 L_{lk} C_r}$: Resonant period of leakage inductor and clamp capacitor.

To obtain thenearly ZCS turn-off of the leading leg switches in the proposed converter, resonant frequency should be selected to satisfy the equation (1).

$$T_{on} \geq \frac{3}{4} T_r \tag{1}$$

In order to achieve the minimum turn-off current of the primary switches the resonant frequency should be designed carefully to satisfy the equations (2) and (3).

$$D_{min} T_s \geq \frac{3}{4} T_r \tag{2}$$

$$f_r \geq \frac{3 f_s}{4 D_{min}} \tag{3}$$

### B. Full ZVS range of all switches

The proposed converter only requires small magnetizing inductance of transformer to achieve the soft switching condition for all the primary switches. Hence, the ZVS condition can be achieved regardless of the load since it is achieved by the magnetizing current.

### C. No reverse recovery loss of the rectifier switches

In the proposed converter, rectifier switches can achieve ZCS turn-off at both buck mode and boost mode operation. As analyzed in the previous section, if the resonant frequency $f_r$ is satisfiedby (3), the proposed converter can operate with ZCS of rectifier switches and nearly ZCS of primary switches regardless of the load variations in the buck mode operation.

### D. Comparison of the voltage clamping capability

Table 1 shows the voltage clamp capabilities of the several topologies.

$Table$ 1.Voltage clam capability of each topology

| Topology | $V_{Osci\_peak}$ equation | $V_{Osci\_peak}$ Value |
|---|---|---|
| [2] | $2\frac{n_2}{n_1}V_{DC} - V_{Bat}$ | 670V |
| [3] | $\frac{n_2}{n_1}V_{DC} + V_{Bat}$ | 880V |
| Proposed | $\frac{n_2}{n_1}V_{DC} + \frac{2}{\pi}(\frac{n_2}{n_1}V_{DC} - V_{Bat})$ | 594V |

### E. Voltage stress of clamp capacitor

In the proposed converter, active clamp circuit is connected in parallel with the output inductor $L_o$, therefore voltage stress of clamp capacitor is just equal to the inductor voltage:

$$V_{Cr\_proposed} = V_{Lo}(t) \tag{4}$$

It is higher in the conventional active clamp circuit as shown in (5)

$$V_{Cr\_Conventional} = V_{Qs} = V_{Bat} + V_{Lo}(t) \tag{5}$$

## 4. Experimental results

The specification of the proposed converter can be found in the Table 2.

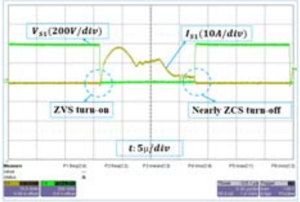
TABLE 2. SPECIFICATION OF THE PROPOSED CONVERTER

| **Parameter** | **Designator** | **Value** |
|---|---|---|
| DC-link Voltage | $V_{DC}$ | $380 - 420\ [V]$ |
| Battery Voltage Range | $V_{Bat,min} - V_{Bat,max}$ | $250 - 420\ [V]$ |
| Power Rating | $P_o$ | $3.3\ [kW]$ |
| Switching Frequency | $f_s$ | $30\ [kHz]$ |
| Resonant Frequency | $f_r$ | $107.3\ [kHz]$ |

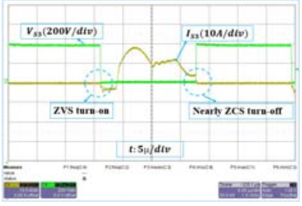
$Fig.3 - Fig.5$ show the measured waveformsin the buck mode operation.$Fig.$3provesthat the ZVS can be achieved with maximum battery voltage ($V_{DC} = 400V$; $V_{Bat} = 420V$; $P_o = 3.3\ kW$ and $D_{max} = 0.9$). $Fig.$4shows the waveform of switch $S_4$. ZVS turn-on of this switch is always ensured by the magnetizing current flowing through the body diode during freewheeling interval. $Fig.$5 shows the current and voltage waveforms of switch $Q_5$achieving ZCS turn-on.

$Fig.6 - Fig.8$show the measured waveforms in the boost mode operation.$Fig.$6verifiesthe ZVS condition with maximum battery voltage ($V_{DC} = 400V$; $V_{Bat} = 420V$; $P_o = 2\ kW$; and $D_{min} = 0.1$). $Fig.$7 shows themeasured waveform of switch $Q_1$.$Fig.$8shows the current and voltage of active clamp-switch $Q_5$achieving ZCS turn-on.

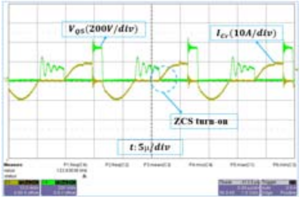
The efficiency of buck mode operation is shown in $Fig.$9 with wide range of the battery voltage from 260V to 420V.The efficiency of boost mode operation is shownin $Fig.$10.



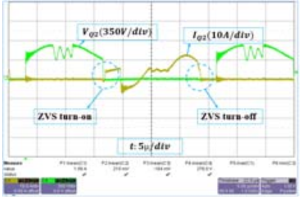
$Fig.$3. The waveform of $S_1$



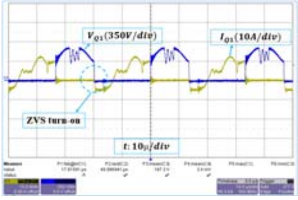
$Fig.$4. The waveform of $S_3$



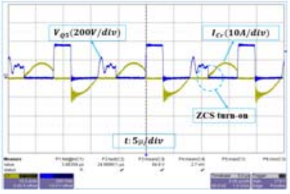
$Fig.$5. The waveform of $Q_5$



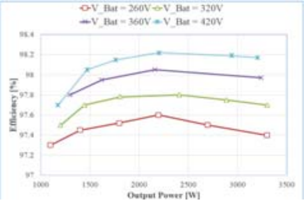
$Fig.$6. The waveform of $Q_2$



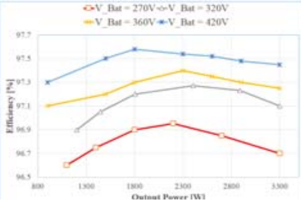
$Fig.$7. The waveform of $Q_1$



$Fig.$8. The waveform of $Q_5$



$Fig.$9. The buck-mode efficiency



$Fig.$10.The boost-mode efficiency

## 5. Conclusion

In this research a novel bidirectional full-bridge with active clamp circuitis proposed for V2G application. The proposed converter exhibits a high efficiency characteristics all over the operating condition. A3.3 kW prototype have beenimplemented to verify the validity of the proposed converter.

## References

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