# A Three-level Resonant Converter with Wide ZVS Range

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## Abstract

A new three-level resonant converter suitable for wide input variation is proposed. A hybrid combination of a three-level converter controlled by phase-shift modulation and a half-bridge converter is presented. Since the voltage of each switch is one half of the input voltage, it has advantages of the choice and characteristics of switches. The ZVS operation of the converter is achieved by using the magnetizing current of the transformer. To verify the theoretical analysis, experimental results of the proposed converter are presented.

## 1. Introduction

The voltage stress on semi-conductors of converters is an important consideration for designing the circuits. When the voltage rating on MOSFET is high, it has the disadvantages of the characteristics like static drain-source on-resistance comparing to those of low rating switches. Furthermore, in case of selecting switches, the cost is higher, as the voltage rating of switches is higher.

In case of a half-bridge type converter and a full-bridge type converter, which are very popular topologies in many applications, the voltage stress on each switch is the input voltage. When an input voltage of circuit is high, more than 500V, the kind of switches available for the converter is getting fewer. Various techniques for reducing or clamping the voltage stress have been proposed.

The three-level structure was proposed for high-voltage and high-power applications [1]. The voltage stress across each switch is reduced to a half of the input voltage. One leg is composed of four switches stacked in series, and two diodes are added for clamping the voltage. In some modified three-level structure, a flying capacitor is connected to two clamping diodes in parallel for making sure voltage clamping of the inner switches. Several types of the three-level converter are proposed and compared in [3]. Recently, the three-level structure with two clamping diode and a flying capacitor is researched.

Zero-voltage-switching (ZVS) is still one of most important issues of three-level converters. Despite ZVS is achieved in the three-level converter of [1], three-level converters with improved features have been presented. For compensating a narrow ZVS range of [1], divided flying capacitors and an auxiliary inductor are adopted for a wide ZVS range [2]. However, since the auxiliary inductance is large, the efficiency of the converter is sacrificed. A ZVS & zero-current-switching (ZCS) of three level converter is achieved by using a phase-shift modulation and an auxiliary switch in a rectifier in [4]. LLC series resonant type three-level converter features ZVS, ZCS and frequency modulation [5]. A hybrid full-bridge three-level LLC resonant converter is proposed in [6]. It features constant frequency phase-shift control, and ZVS along wide input and wide load variations. The hybrid full-bridge three-level converter with two transformers in [7], whose added transformer is inserted between full-bridge legs, can reduce the filter size and widen ZVS characteristics.

A three-level DC-DC Converter with wide ZVS range is proposed in this paper. The voltage stress of each switch is a half of the input voltage. ZVS is achieved under the wide variation of the input voltage. Since the proposed converter uses resonance, ZVS is achieved nearly zero to full load condition.

## 2. Operational Principles

The proposed converter is a hybrid combination of a three-level converter which uses phase-shift control and a half-bridge converter which is composed of split flying capacitors $C_{f1}$ and $C_{f2}$ and inner switches $Q_2$ and $Q_3$ of the three-level converter. Since the voltage of the flying capacitor is one fourth of the input voltage, the input voltage of the half-bridge converter section is one fourth of the input voltage, and the input voltage of the three-level converter is one half of the input voltage converter. In the half-bridge converter, all the switches are operated in one-half duty. And the three-level converter is controlled by using phase-shift modulation which controls the effective duty of the converter. The resonant capacitor $C_r$ is connected to the half-bridge transformer $T_h$ in series. The secondary of each transformer is connected in series. The leakage inductance of the transformer is reflected to the secondary as a matter of convenience of analysis.

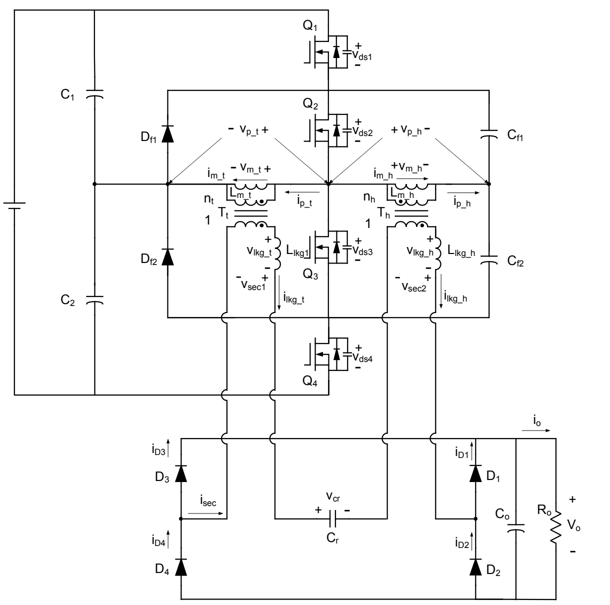


Fig. 1 Proposed Converter with wide ZVS Range

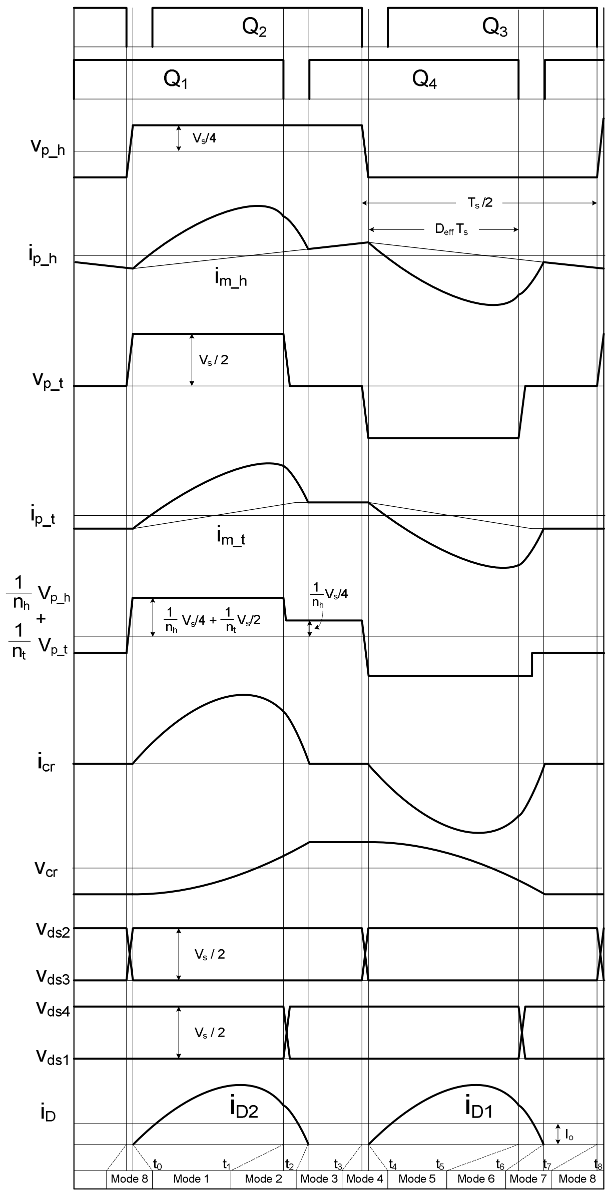


Fig. 2 Key Waveforms of Proposed Converter

**Mode 1 ($t_0$~$t_1$)** : In this mode, the power is transferred from primary to secondary. In the half-bridge section, since $V_s/4$ is applied to the primary of transformer, the magnetic current of $T_h$, $i_{m\_h}$ is increased by $(V_s/4)/L_{m\_h}$. In the three-level section, the magnetic current of $T_t$, $i_{m\_t}$ is increased by $(V_s/2)/L_{m\_t}$. $C_r$, $L_{lkg\_h}$ and $L_{lkg\_t}$ resonate each other with input voltage of $(1/n_h)V_{p\_h}$ + $(1/n_t)V_{p\_t}$. $i_{lkg\_h}$ and $i_{lkg\_t}$ have resonant current shapes. The sum of the secondary voltages of two transformers is $(V_s/4)/n_h + (V_s/2)/n_t$.

**Mode 2 ($t_1$~$t_2$)** : When $Q_1$ is turned off, $C_{oss4}$ and $C_{oss1}$ are discharged and charged by $i_{p\_h}$ and $i_{p\_t}$, respectively. After the primary voltage of transformer $T_t$, $v_{p\_t}$, decreases to zero, $D_1$ and $D_4$ are still conducting. Voltage across $L_{lkg\_h}$ and $L_{lkg\_t}$, $V_o$ - $v_{cr}$, is divided on $L_{lkg\_h}$ and $L_{lkg\_t}$ due to impedance ratio of $L_{lkg\_h}$ and $L_{lkg\_t}$, and that makes $i_{p\_h}$ and $i_{p\_t}$ decreases. The sum of the secondary voltages of two transformers starts to decrease from $(V_s/4)/n_h$ + $(V_s/2)/n_t$ to $(V_s/4)/n_h$. This mode ends when the primary current of each transformer meets the magnetizing current of each transformer.

**Mode 3 ($t_2$~$t_3$)** : In the half-bridge section, since $V_s/4$ is still applied to the primary of transformer, $T_h$, the primary current of $T_h$, $i_{p\_h}$, is increased by $(V_s/4)/L_{m\_h}$. In the three-level section, the primary current of $T_t$, $i_{p\_t}$, equals to $i_{m\_t}$, keep constant current $i_{m2}(t_2)$.

**Mode 4 ($t_3$~$t_4$)** : When $Q_2$ is turned off, $C_{oss2}$ and $C_{oss3}$ are charged and discharged by $i_{p\_h}$ and $i_{p\_t}$, respectively. Therefore, $v_{p\_h}$ decreases from $V_s/4$ to $-V_s/4$ and $v_{p\_t}$ decreases from 0 to $-V_s/2$, and secondary voltage decreases to $-(V_s/4)/n_h - (V_s/2)/n_t$.

The operations from Mode 5 to Mode 8 are similar to those from Mode 1 to Mode4, respectively.

## 3. Analysis of Proposed Converter

### 3.1 ZVS Characteristics

In case of a conventional phase-shift full bridge converter, ZVS of leading leg switches is achieved by a reflected current from an output inductor. However, ZVS of lagging leg switches is not achieved at a light load condition. To achieve ZVS on lagging leg switches at a light load condition, a leakage inductance supplying energy for charging/discharging the output capacitance of switches, can be becomes larger, and that makes the more circulating current, hence that lowers an efficiency of the converter.

In proposed converter, ZVS of leading leg and lagging leg switches is easily achieved. In Mode 2, the primary current of each transformer, $i_{p\_h}$ and $i_{p\_t}$, is the sum of the magnetizing current and the reflected current of secondary. In Mode 4, the primary current of each transformer is the magnetizing current of each. In aspect of the energy, the condition for ZVS is expresses as follows.

$$\frac{1}{2}L_{lkg\_t}\left(i_{p\_t}(t_1)\right)^2+\frac{1}{2}L_{m\_t}\left(i_{m\_t}(t_1)\right)^2 \ge C_{oss}\left(\frac{V_s}{2}\right)^2 \qquad (1)$$

$$\frac{1}{2}L_{m\_h}\left(i_{m\_h}(t_3)\right)^2+\frac{1}{2}L_{m\_t}\left(i_{m\_t}(t_3)\right)^2 \ge C_{oss}\left(\frac{V_s}{2}\right)^2 \qquad (2)$$

From (1) and (2), it can be seen the energy of the magnetizing inductance of each transformer is used for ZVS. Since output capacitances of $Q_4$ and $Q_1$ are discharged and charged by $i_{p\_t}$, and output capacitances of $Q_2$ and $Q_3$ are discharged and charged by the sum of $i_{p\_h}$ and $i_{p\_t}$, ZVS of all switches is easily achieved.

In addition, the minimum dead-time is necessary for completing ZVS. Assume the output capacitances of $Q_1$~$Q_4$ are identical to $C_{oss}$ and switches are discharged/charged by the magnetizing current. For achieve exact dead time for ZVS, an integration of each primary current for Mode 2 is required, however, it is too complex and hard to get closed form solutions.

Thereby, approximate dead time which is sufficient for ZVS is calculated. First for $Q_1$ and $Q_4$, in light load condition, $i_{p\_t}$ is not built up so large that the $i_{m\_t}$ and $i_{p\_t}$ are not much different. Therefore,

$$T_{sufficient\ dead\ time\ for\ Q_1\ \&\ Q_4}=\frac{2C_{oss}V_s}{i_{m\_t}(t_1)} \qquad (3)$$

is achieved. In heavy load condition, the time required for ZVS is much shorter than (3), because of the contribution of the leakage inductance having a large current to help ZVS.

For $Q_2$ and $Q_3$, the currents for ZVS are $i_{m\_h}$, which is still building up, and $i_{m\_t}$, which is constant during Mode 4. So, the sufficient dead time can be expressed as follows.

$$T_{sufficient\ dead\ time\ for\ Q_2\ \&\ Q_3}=\frac{2C_{oss}V_s}{i_{m\_h}(t_3)+i_{m\_t}(t_3)} \qquad (4)$$

Furthermore, ZVS of all switches is achieved by energy from the magnetizing inductances of $T_h$ and $T_t$, the circulating current and the duty loss caused by large leakage inductance can be minimized.

## 4. Experimental Results

A 600W prototype of the proposed converter was built to verify the analysis. Table. 1 shows the components and parameters used for the experiment. The experimental operating waveforms in fig. 3 are similar to the analyzed key waveforms. In fig. 4 and fig. 5, the voltage stress of each switch is well-clamped to half of the input voltage $V_s$ without any voltage spikes. The proposed converter achieves ZVS of the leading and the lagging leg switches on 10% load condition shown in fig. 4 and fig. 5. $V_{sec1} + V_{sec2}$ is the sum of the secondary voltages of transformer $T_h$ and $T_t$, and the voltage is applied as an input voltage to the resonant tank compromising $L_r$, which is the sum of leakage inductances and an external inductance for a resonance, and a resonant capacitance Cr. The input voltage of the resonant tank is distorted because of the voltage of leakages of two transformers. The value of $L_r$ and $C_r$ are 55.8uH and 38nF, respectively, and the resonant frequency of the proposed circuit is 109.3kHz.

| | | | |
|---|---|---|---|
| Vs | 600V | $Q_1$, $Q_4$ | FQP 9N50C |
| Vo | 100V | $Q_2$, $Q_3$ | IRFP31N50L |
| $P_{max}$ | 600W | $D_{f1}$, $D_{f2}$ | F20U40S |
| fs | 90kHz | $D_1$~$D_4$ | F20U40S |
| $n_h$ : 1 | 3:2 | $C_1$, $C_2$ | 220uF |
| $n_t$ : 1 | 3:1 | $C_{f1}$, $C_{f2}$ | 100uF |
| $L_r$ | 55.8uH | $C_o$ | 330uF |
| $C_r$ | 38nF | | |
| $L_{m\_h}$ | 800uF | | |
| $L_{m\_t}$ | 650uF | | |

Table. 1 Components and Parameters of Prototype Converter

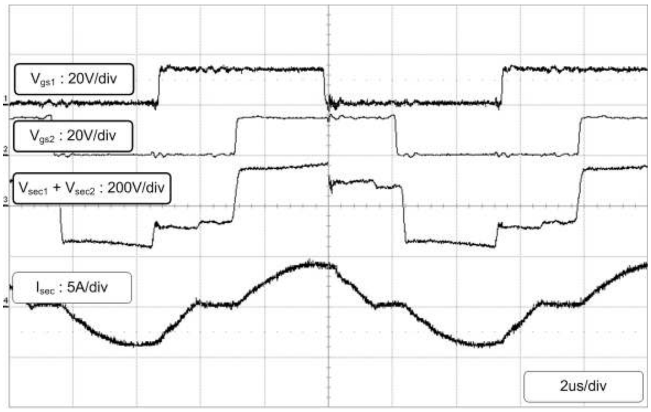


Fig. 3 Operating Waveforms at 30% Load Condition

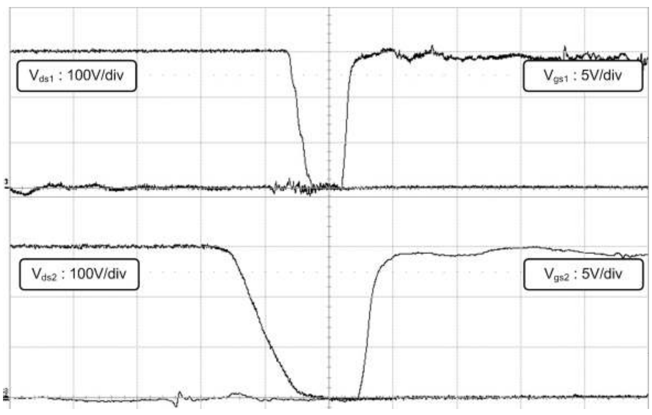


Fig. 4 ZVS of Leading Leg Switch $Q_1$ at 10% Load Condition

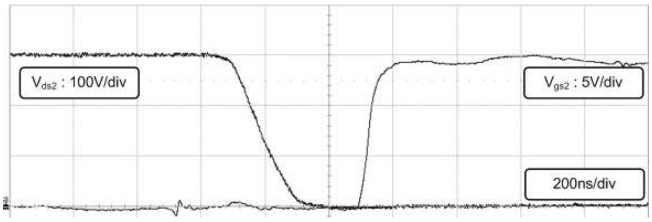


Fig. 5 ZVS of Lagging Leg Switch $Q_2$ at 10% Load Condition

## 5. Conclusion

A new three-level resonant converter is proposed. The proposed converter is a hybrid combination of a three-level converter and a half-bridge converter, and the secondary of each transformer is connected in series with the resonant capacitor. Since the voltage stress is one half of the conventional full-bridge converter, it has advantages of the choice and characteristics of switches. The ZVS operation of the converter from a nearly no load condition to a full load condition is achieved by using the magnetizing current of the transformer. In secondary side, the series connection of the reflected leakage inductances, external resonant inductor and external resonant for resonance make a resonant tank with the multi-level input voltage. The multi-level input voltage is determined by turn ratios of transformers and the effective duty controlled by phase-shift modulation. Therefore, the proposed converter is suitable for the wide input. The experimental result is presented to verify the theoretical analysis.

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