Flying-Capacitor-Based Hybrid LLC Converters To Achieve High Conversion Efficiency Through ZVS Operation

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Abstract:
The flying capacitor and LLC converter are integrated with the ZVS operation. Using of ZVS, it will achieve the high conversion efficiency. This project is enable to high step-down conversion in the high input voltage applications. The inherent flying capacitor branch in the primary side can effectively halve the primary switch voltage stress compared with the half-bridge LLC converters. The input voltage can be equally shared and automatically between the two series half-bridge modulus without additional balance circuit or control strategies due to the built-in flying capacitor cell. The flying capacitor is also known as charge pump. It is kind of DC to DC converter. Moreover, the inherent soft switching performance during wide load range that exists in the LLC converters is still kept to reduce the switching losses. The converter are further decreased the voltage stress by means of employing stacked connection. Input voltage balance is achieved and the voltage of each switch is clamped and minimized, which ensures the converters to operate with the high input voltage. Compared with the proposed system, instead of center-tapping transformer, windings get reduced in this project. If the ZVS operation for the power switches and ZCS operation for the rectifier diodes are achieved during a wide input voltage and load conditions, it may also increase high conversion efficiency.

Introduction
High voltage dc/dc converters have been widely employed in the three-phase communication power supply systems, dc transmission for large offshore wind farm and dc distribution as the interface between the dc transmission and distribution system or energy storage components. However, high input voltage and high step-down dc/dc converters are still challenging in the power electronics community due to the technological limitations of semiconductors with high blocking voltage. Apart from the pulse-width modulation converters, such as the phase-shifted converters, LLC series resonant converters are the popular candidates because they can achieve soft switching performance for all power devices from light to full loads. By adjusting the switching frequency, the controlled constant output voltage can be achieved with a wide input voltage variation. However, in the high voltage applications, such as the secondary conversion stage following a three-phase 380Vac/dc converter, where the dc bus voltage is approximately 600–800V, the primary switches of the conventional half-bridge LLC (HB LLC) converter, as shown in Fig. 1(a), suffer from relatively high voltage stresses. In this case, high-voltage IGBTs are required. However, compared with MOSFETs, the switching frequency of IGBTs is limited. As a result, the high power density requirement cannot be fulfilled.

In order to solve this problem, the input-series-output-parallel technique provides a selectable solution to sustain the high input voltage and large output current requirements. However, how to balance the voltage and current during each converter module is a big concern. Generally, additional control loop is required, which increases the control complexity and impacts the system response. Three-level LLC series resonant converters are another optimized solution to reduce the high voltage stress on the primary switches. By employing the three-level configuration in the primary side, the voltage stress across each power switch is effectively clamped to only half of the input voltage. At the same time, the advantages of the conventional HB LLC series resonant converters, such the soft switching performance, remain unchanged. However, the
The voltage gain is equal to 1 for all load conditions at the resonant frequency. When the switching frequency is higher than the resonant frequency, the gain is always less than 1, and the zero voltage switching (ZVS) for primary switches can be achieved. When the switching frequency is lower than the resonant frequency, either ZVS or the zero current switching (ZCS) for the primary switches can be achieved. For MOSFETs, the ZVS operation is preferred. The gain will be always higher than 1 if the converter works.

There are several ZVS operation modes of LLC resonant converter according to the relationship of switching frequency to resonant frequency.

### III Proposed converter and its operational principle

The proposed hybrid LLC converter consists of two half-bridge modules connected in series, and a flying capacitor is utilized to achieve the voltage balance between the two input capacitors. An LLC series resonant tank is connected across one switch, resulting in a square wave tank, whose amplitude is half of the high input voltage. A full-wave diode rectifier is employed as an example in the secondary side. As shown in Fig. 1(d), S1, S2, S3 and S4 are the primary-side power switches; CS1, CS2, CS3 and CS4 are the parallel capacitors. CSS is the flying capacitor, and Lss is inserted series inductor to limit the current surge across CSS, which consists of the circuit equivalent parasitic inductor and the additional inductor. In the LLC resonant tank, Cr is the series resonant capacitor; Lr is the series resonant inductor, which is composed of the equivalent leakage inductance of the transformer and an additional inductor; and Lm is transformer magnetizing inductance. Do1 and Do2 are the output rectifier diodes. The transformer has a turn ratio of n = n1/n2. In the presented converter, switches S1 and S3 are driven with a constant 50% duty cycle simultaneously, while the switches S2 and S4 are both complementary to S1 and S3.

There are two operational modes for the proposed hybrid LLC converter. When CSS is paralleled with C1, C1 mainly provides energy to the LLC resonant tank, and C2 is charged by the same amount. The resonant tank obtains its energy from both C1 and CSS. In the other mode, when CSS is in parallel with C2, C2 provides the supplement energy to CSS, and C1 is charged by the same amount. Resonance in the LLC tank continues but no external energy is provided for the resonant tank.

### IV Equivalent circuit for LLC converter

The LLC resonant converter looks very similar to the LC series resonant converter (SRC) apart from the addition of the inductor Lm. The value of Lm is
normally around 3 ~8 times larger than the resonant inductor \( L_r \), in most practical designs. \( L_m \) can be practically realized by using the magnetizing inductance of the transformer, hence the symbol notation of \( L_m \). In order to analyze the LLC converter, its AC equivalent circuit is derived based on AC analysis techniques.

![Fig 1: Equivalent circuit for LLC converter](image)

**Simulation Results**

![Fig 2: Proposed Model](image)

![Fig 3: Input Voltage](image)

<table>
<thead>
<tr>
<th>DESCRIPTION</th>
<th>VALUE</th>
</tr>
</thead>
<tbody>
<tr>
<td>True power</td>
<td>2 kw</td>
</tr>
<tr>
<td>Power factor</td>
<td>Almost unity</td>
</tr>
<tr>
<td>Efficiency</td>
<td>94%</td>
</tr>
<tr>
<td>Input ac voltage</td>
<td>220 v</td>
</tr>
<tr>
<td>Max. Output dc voltage</td>
<td>700v</td>
</tr>
<tr>
<td>Voltage THD</td>
<td>0.09%</td>
</tr>
<tr>
<td>Current THD of Passive rectifier</td>
<td>31.1%</td>
</tr>
<tr>
<td>Current THD of Hybrid rectifier</td>
<td>11%</td>
</tr>
</tbody>
</table>

**Conclusion**

In this paper, the new input voltage auto-balanced hybrid LLC series resonant converters with flying capacitors have been proposed, which have the following clear advantages.

First, input voltage balance is achieved and the voltage of each switch is clamped and
minimized, which enables the converters to operate with a high input voltage.

Second, ZVS operation for the power switches and ZCS operation for the rectifier diodes are achieved during a wide input voltage and load conditions, which ensures high conversion efficiency.

Third, high and adjustable step-down voltage conversion is achieved due to the combination of the flying-capacitor cell and the LLC series resonant converter. It can be concluded that the proposed hybrid LLC converter is an excellent candidate for the high input voltage, high step-down and high efficiency dc/dc systems.

Reference


