Isolated AC/AC Converter With LLC Resonant Converter High-Frequency Link and Four-Quadrant Switches in the Output Stage

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ABSTRACT An AC-AC converter with a high-frequency link employing an LLC resonant converter operating in the vicinity of the resonance frequency was studied, in which a single output power stage is used, formed by a high-frequency AC-AC converter employing four-quadrant switches. The topology, its operation and the modulation strategy are described. The high-frequency stage switches located on the primary side of the transformer operate with soft switching of the ZVS type, while the four-quadrant switches that form the output stage operate with soft switching of the ZCS type. Experimental data obtained with a 1.5 kW experimental prototype (input 220 V\(RMS\), output 220 V\(RMS\) and switching frequency 40 kHz), which was designed, built and tested in the laboratory, are reported herein. This converter can be considered a candidate for the building block of medium voltage solid-state transformers (SST) for power distribution systems.

INDEX TERMS AC-AC converter, high-frequency link, LLC converter, soft-commutation, solid-state transformer.

I. INTRODUCTION

The isolated AC-AC converter with a high-frequency link is the basic building block of solid-state transformers [1]–[10]. Many topologies and architectures can be found in the literature, the oldest being that proposed in [1] and [2]. Its operation principle can be described using the topology shown in Fig. 1.

The AC input voltage \(V_{in}\) is chopped by the four-quadrant switches \(S_1\) and \(S_2\), generating a high frequency amplitude modulated voltage, which is applied to the high frequency transformer. A low frequency sinusoidal voltage \(V_{out}\) is reconstructed at the output terminals by the four-quadrant switches \(S_3\) and \(S_4\), modulated by phase shift and synchronized with respect to the sinusoidal input voltage. Despite its simplicity, this topology is limited in its practical use, as it presents commutation difficulties, low efficiency and subjects the semiconductors to instantaneous voltages equal to at least twice the peak value of the input voltage.

The maturing of the concept, together with the evolution of semiconductors, resulted in the architecture shown in Fig. 2, in which the 60 Hz sinusoidal input voltage is rectified by the folding bridge, generating a rectified 120 Hz sinusoidal voltage [3], [4], [7]. The second stage consists of an LLC resonant converter [11]–[15], operating at the resonant frequency, a condition that ensures soft commutation of the switches. In addition, at this frequency, the voltage static gain of this stage is dependent only on the transformer turns ratio, as the impedance displayed by the LLC converter seen from the output terminals is theoretically null.

The last stage is an unfolding bridge, operating at a frequency of 60 Hz, and synchronized with the sinusoidal input supply voltage, generating a sinusoidal voltage in the load, which is a mirror image of the sinusoidal input voltage. Several other topologies, with their own advantages and
disadvantages, make use of the LLC for converting AC-AC energy [15]–[18].

In order to reduce the number of semiconductors, the set formed by the output rectifier of the LLC resonant converter and the unfolding bridge, was replaced by a stage comprised of four-quadrant switches in [18]. A simplified description of the operation of the converter was presented, without experimental results. The studied topology, which is shown in Fig. 3, can be considered a combination of the converter shown in Fig. 1, and that shown in Fig. 2.

The second stage consists of an LLC resonant series converter operating at the resonance frequency, formed by the switches $S_{1,2,3,4}$, the resonant inductor $L_r$, the resonant capacitor $C_r$, the high frequency isolation transformer $T_1$ and the output stage. The output stage of a conventional LLC resonant converter uses unidirectional switches and generates a voltage with only positive polarity. Thus, an additional stage must be employed, operating synchronously with the input voltage, to obtain the sinusoidal voltage at the load.

In the proposed converter, the unidirectional switches have been replaced with bidirectional ones, which, when properly controlled, allow an output voltage with positive and negative polarities to be obtained, without the need for an additional stage for the reconstruction of the low frequency sinusoidal output voltage.

Thus, during the positive half-cycle of the alternating input voltage, the switches of the high frequency stage are controlled so that the voltage in the load is always positive. During the negative half-cycle of the input voltage, they are controlled so that the voltage is negative. As the LLC resonant series converter operates in the vicinity of the resonance frequency, its voltage static gain is dependent only on the transformer turns ratio and its equivalent circuit seen from the output terminals has theoretically zero series impedance. Thus, an output voltage that is an image of the input voltage is obtained, without the need for closed loop control.

The output capacitor $C_o$ is selected to absorb the high frequency current harmonics, and must have the lowest possible capacitance, to avoid causing the circulation of unnecessary reactive power inside the converter.

In this paper, an in-depth analysis of the converter is presented, with the inclusion of experimental results obtained from an experimental prototype designed, built and tested in the laboratory, with the purpose of verifying its performance and its potential to be used as a building block in solid-state transformers.

II. PROPOSED CONVERTER

The AC-AC converter with high frequency isolation, using the LLC series resonant converter, is shown in Fig. 3 [18], and is composed of two stages. The first stage, formed by the power semiconductors $S_{a,b,c,d}$, the inductor $L_f$, and the capacitor $C_f$, is an folding bridge, which converts the sinusoidal voltage of 60 Hz at the input into a sinusoidal voltage rectified at its output with a frequency of 120 Hz ($V_{CC}$). The filter comprised of $L_f$ and $C_f$ is designed to filter only high frequency voltages and currents, without affecting the shape or value of the fundamental voltage waveform. The use of controlled devices instead of diodes, in this stage, allows the circulation of reactive power from non-resistive loads or produced by the high frequency input and output filters, without causing distortion of the rectified voltage at zero voltage crossing of the input sinusoidal voltage.

Thus, during the positive half-cycle of the alternating input voltage, the switches of the high frequency stage are controlled so that the voltage in the load is always positive. During the negative half-cycle of the input voltage, they are controlled so that the voltage is negative. As the LLC resonant series converter operates in the vicinity of the resonance frequency, its voltage static gain is dependent only on the transformer turns ratio and its equivalent circuit seen from the output terminals has theoretically zero series impedance. Thus, an output voltage that is an image of the input voltage is obtained, without the need for closed loop control.

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III. OPERATION PRINCIPLE

The operation of the high-frequency stage of the converter with ideal components can be divided into four stages, two of which occur during the positive half-cycle of the sinusoidal input voltage, and two during the negative half-cycle.

In the first operation stage shown in Fig. 4 (a), while the sinusoidal input voltage is positive, $S_1$ and $S_4$ are gated simultaneously with $S_{F1}$. In the second operation stage, shown in Fig. 4 (b), the sinusoidal input voltage is still positive, and $S_2$ and $S_3$ are gated simultaneously with $S_{F2}$, at the instant the resonant current polarity is reversed.

These first two topological states are repeated at the switching frequency until the instant the input sinusoidal voltage becomes negative. The corresponding typical waveforms are shown in Fig. 5.

The first topological state, during the negative half-cycle of the sinusoidal input voltage, is shown in Fig. 6 (a), where switches $S_2$ and $S_3$ are gated simultaneously with switch $S_{F1}$. During the second topological state, shown in Fig. 6 (b), switches $S_1$ and $S_4$ are gated simultaneously with switch $S_{F2}$, at the moment the direction of the current in the resonant inductor reverses.

Typical waveforms for these two operating stages are shown in Fig. 7.
FIGURE 3. AC-AC converter with high-frequency isolation using the LLC series resonant converter. Relevant voltage waveforms are represented in blue and current waveforms in green.

FIGURE 4. First (a) and second (b) operation stages of the converter during the positive half-cycle of the sinusoidal input voltage.

FIGURE 5. Relevant waveforms during the positive half-cycle of the sinusoidal input voltage.

FIGURE 6. First (a) and second (b) operation stages of the converter during the negative half-cycle of the sinusoidal input voltage.

FIGURE 7. Relevant waveforms during the negative half-cycle of the sinusoidal input voltage.

Only the gating of the output stage switches is modified. The LLC stage inverter bridge switches maintain their operation. Thus, the current is reversed in the output stage, following the input voltage and current. The voltage across the resonant capacitor is also shown. Because the capacitor is in series with the resonant current, its voltage will be $90^\circ$. 

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out of phase. Its peak value, chosen by the designer, has an influence on the peak voltage of the output stage switches. The waveforms of the input stage voltages and currents are shown in Fig. 8.

The theoretical voltage and current waveforms of switches $S_1$ and $S_4$ of the LLC converter are shown in Fig. 9. The waveforms of switches $S_2$ and $S_3$ are identical to those of switches $S_1$ and $S_4$.

The waveforms of the currents through the power semiconductors $S_{F1}$ and $S_{F2}$ of the output stage are shown in Fig. 10.

The sinusoidal voltage and current at the output terminals of the converter are shown in Fig. 11.

IV. STEADY-STATE ANALYSIS

A. VOLTAGE STATIC GAIN

The input rectifier stage operates at a much lower frequency than the switching frequency of the LLC converter. For this reason, the LLC converter can be considered to be powered by direct voltage and represented by its equivalent circuit in steady state. The voltage static gain of the LLC converter with a transformer turns ratio equal to unity is given in [19].

$$M = \frac{\mu_o^2}{\sqrt{[\mu_o^2 (\lambda + 1) - \lambda]^2 + [\mu_o \cdot Q (\mu_o^2 - 1)]^2}}$$

where

$$\lambda = \frac{L_r}{L_m}, \quad \mu_o = \frac{f_s}{f_r}, \quad Q = \frac{1}{R_{dc} \sqrt{L_r / C_r}}, \quad \text{and} \quad R_{dc} = \frac{8}{\pi^2} R_o.$$

The resonance frequency of the converter is dependent only on the capacitance $C_r$ of the resonant capacitor and the inductance $L_r$ of the resonant inductor, and is determined by

$$f_r = \frac{1}{2 \cdot \pi \cdot \sqrt{L_r / C_r}}$$

Fig. 12 shows the voltage static gain of the LLC converter as a function of the normalized switching frequency, with a transformer turns ratio equal to unity, for different quality factors [19].

When the switching frequency $f_s$ is equal to the resonant frequency, the static gain of the ideal converter is unitary and independent of the load. Therefore, this operating frequency is selected, and the gain of the converter is determined by the transformer turns ratio.
FIGURE 12. Voltage static gain of the LLC converter as a function of the normalized switching frequency for the transformer with turns ratio equal to unity, and different values for the quality factor $Q$.

B. POWER SEMICONDUCTOR VOLTAGE AND CURRENT STRESS

For the proper selection of the power semiconductors, it is necessary to calculate their average, effective and maximum current values and maximum voltage. The expressions for calculating these quantities are shown in Table 1.

TABLE 1. Expressions for calculation of power semiconductor voltage and current stress.

|                      | $s_{0}$, $s_{1}$, $s_{2}$, $s_{3}$ | $s_{0,2,3}$ | $s_{1,3}$ |
|----------------------|-----------------------------------|-------------|----------|
| Peak Current         | $V_{\text{out}}/V_{\text{in}}$ | $V_{\text{out}}/V_{\text{in}}$ | $V_{\text{out}}/V_{\text{in}}$ |
| Average Current      | $V_{\text{avg}}/R_{o}$ | $V_{\text{avg}}/R_{o}$ | $V_{\text{avg}}/R_{o}$ |
| RMS Current          | $V_{\text{rms}}/V_{\text{in}}$ | $V_{\text{rms}}/V_{\text{in}}$ | $V_{\text{rms}}/V_{\text{in}}$ |
| Peak Voltage         | $V_{\text{peak}}/V_{\text{in}}$ | $V_{\text{peak}}/V_{\text{in}}$ | $V_{\text{peak}}/V_{\text{in}}$ |

With these data in hand, it is possible to select the components of the power stage that will withstand these stress values and provide the correct converter operation.

C. HIGH FREQUENCY TRANSFORMER

The dimensioning of the transformer of an LLC converter used in converters in which the switching frequency is variable is complex, due to the large number of variables involved and the high number of degrees of freedom in the choice of parameters.

However, as mentioned in the previous section, in the proposed architecture the LLC converter operates in the vicinity of the resonant frequency with constant switching frequency, facilitating the transformer design. In this region of operation, the voltage static gain is constant and determined by the transformer turns ratio, defined by

$$a = \frac{V_{\text{out}}}{V_{\text{in}}} \quad (3)$$

The primary and secondary winding currents are almost sinusoidal and the ferrite core cross-sectional area is dependent on the maximum flux density, the switching frequency and the primary number of turns. The magnetizing inductance, which is a critical parameter, determines the ferrite core air gap thickness [20].

V. COMMUTATION QUALITATIVE ANALYSIS

In order to achieve high efficiency and electromagnetic interference (EMI) reduction, soft switching of the converter switches is required. Since the first power conversion stage operates at a low frequency, its switching losses can be neglected.

A. COMMUTATION OF THE POWER SEMICONDUCTORS OF THE LLC CONVERTER

To ensure soft switching of the LLC converter switches, a dead time is added between the gate signals from the same leg of switches. In addition to preventing short-circuit of the converter leg, the dead time allows the commutation capacitors of the switches to charge and discharge properly, allowing zero-voltage switching (ZVS) of the power semiconductors. Fig. 13 illustrates correct (a) and incorrect (b) dead times.

FIGURE 13. Dead time between the gate signals of the power semiconductors in one leg of the resonant LLC converter.

It is possible to use the intrinsic capacitance of the actual switch, if its value is appropriate. If it is too small or non-existent, a capacitor with the appropriate capacitance is added in parallel with the converter power semiconductors.

For soft switching to occur, it is important that the resonant current ($i_{Lr}$) has an appropriate value when each switch is turned OFF. An important feature of the LLC resonant converter is the fact that even when the power delivered to the load is zero, the peak value of the magnetizing current is able to charge and discharge the commutation capacitors and ensures ZVS, contrast to many other DC-DC converters.

In an LLC converter, the magnetizing current amplitude is dependent on the voltage applied to its transformer. Therefore, when the sinusoidal input voltage is at its peak, it will
have a maximum peak magnetizing current. On the other hand, when the input voltage is close to zero, the magnetizing current is smaller, making the charging and discharging of the capacitors slower.

![Figure 14. Voltage peaks at the transformer terminals due to the dead time.](image1)

A consequence of the inclusion of dead time is the presence of voltage spikes across terminals of the transformer, as illustrated in Fig. 14, which are subsequently reflected to the output stage switches at the instant they are turned OFF. Their value can be calculated by

\[ V_{Lm} = \pm (V_{in} + V_{Lr} + V_{Cr}) \]  

(4)

**B. COMMUTATION OF THE OUTPUT STAGE POWER SEMICONDUCTORS**

In order to have zero-current switching (ZCS) in the output stage switches, the switching frequency is slightly reduced in relation to the resonance frequency. Due to the nature of the LLC resonant converter, in this region of operation there are small time intervals of discontinuity in the current in the secondary stage of the transformer, as shown in Fig. 15. However, this reduction in the switching frequency, being very small, maintains the voltage static gain of the converter close to unity.

![Figure 15. Transformer secondary current (i_{SF}) and resonant inductor current (i_{Lr}) of the LLC converter.](image2)

During the time intervals in which the current in the four-quadrant switches of the output stage is zero, they must be turned OFF, so that soft switching of the ZCS-type occurs, as shown in Fig. 16.

![Figure 16. Gate signals and current in the power semiconductors of the output stage.](image3)

![Figure 17. Examples of incorrect gating of the output stage switches, in which the zero-current switching does not occur.](image4)

If the switch is turned OFF too soon, there will be hard switching as there will still be current flowing, as shown in Fig. 17 (a). If it is turned OFF too late, there will be reverse current flowing (due to the voltage and current bidirectional of the four-quadrant switch), and there will also be dissipative switching, as shown in Fig. 17 (b).

**VI. EXPERIMENTAL RESULTS**

**A. DESIGN SPECIFICATIONS AND SELECTED COMPONENTS FOR THE PROTOTYPE CONSTRUCTION**

The design specifications of the power converter are shown in Table 2.

| Symbol | Symbol | Quantity | Value |
|--------|--------|----------|-------|
| P_o   | Output power | 1.5 kW  |
| V_i   | Effective value of the input voltage | 220 V   |
| V_o   | Effective value of the output voltage | 220 V   |
| f_r   | Resonance frequency | 40 kHz  |
| f_s   | Switching frequency | 40 kHz  |

From the design specifications, the components of the power stage of the converter were selected, which are shown in Table 3. In order to reduce current stress in the capacitors, a parallel and series arrangement was used.
TABLE 3. Experiment parameters.

| Components  | Type                          | Value or Specification       |
|-------------|-------------------------------|------------------------------|
| Sa, Sb, Sc, Sd | IGBT Module | 600V/40A/ FNB34060T (On Semiconductor) |
| S1, S2, S3, S4 | CoolMOS MOSFET | 600V/30A/ IPZQ60R060P7 (Infineon) |
| Sf1, Sf2 | SiC MOSFET | 1200V/24A/ C3M0075120K (Cree) |
| Cc, Ca | Film Capacitor | 8x470nF/650Vdc (Kemet R76 Series) |
| C1, C2 | Film Capacitor | (2x100nF + 1x47nF)/2000Vdc (Kemet R76 Series) |
| Lr | Resonant Inductor | Ferrite Core N87 / 63μH (TDK) |
| Im | Transformer magnetizing inductance | 305μH |
| Tr | Transformer data | Ferrite Core N87 (TDK) |
| a | Transformer turns ratio | Litz Wire 400x38AWG |

For the semiconductors of the input rectifier stage, which operate with the frequency of the sinusoidal input voltage (equal to 60 Hz), an IGBT module was used, since it is robust and ideal for high power and low frequency applications. For the inverter bridge of the LLC converter, the CoolMOS MOSFET was chosen, due to its low series resistance and its ability to operate at high switching frequency. Finally, the SiC MOSFET technology was found to be one of the most attractive options for use in the output stage, due to its ability to withstand high voltages, and its low conduction losses.

B. EXPERIMENTAL PROTOTYPE, CURVES AND RELEVANT WAVEFORMS

The designed and built experimental prototype is shown in Fig. 18 and the main components used are indicated by arrows.

It should be noted that to limit the maximum junction temperature of the power semiconductors and prevent possible failures, an aluminum heatsink was used together with forced ventilation to remove the heat produced by the converter power stage components.

The experimental prototype was tested in the laboratory, with resistive load. Starting with the low frequency waveform analysis, Fig. 19 shows the sinusoidal input voltage, the rectified voltage at the output of the first stage and voltage waveforms across the power semiconductors.

A 120 Hz sinusoidal rectified voltage in phase with the input voltage can be noted. The peak voltage across the switches in this stage is equal to the peak voltage of the 60 Hz sinusoidal input voltage.

Fig. 20 shows the voltages across the power semiconductor of the resonant LLC stage (V_s1 and V_s2 ~ 100 V/div), resonant current (i_Lr ~ 5 A/div) and low frequency output current (i_out ~ 2 A/div). Time scale (4 ms/div).

Fig. 20 shows the voltages across the power semiconductor of the resonant LLC converter, along with the rectified output current and the resonant inductor current.

It is interesting to note that the peak voltage of the switches follows a 120 Hz envelope, due to the rectified voltage waveform. Its highest value is equal to the peak voltage of the sinusoidal input voltage, which is the same as the rectified voltage. The same occurs with the resonant current, which also follows the low frequency envelope.
Fig. 21 shows the current before and after the filtering capacitor $C_o$, which retains the switching frequency currents, allowing only the 60 Hz component at the output terminals or the load.

The voltage across the power semiconductors $S_{F1}$ and $S_{F2}$ of the output stage, illustrated in Fig. 22, shows that these switches operate in four quadrants, that is, they must conduct current in both directions and also block positive and negative voltages. As with the LLC converter switches, such switches are also subjected to peak voltage values equal to the low frequency voltage peak value.

The output and input sinusoidal voltage and current waveforms for operation with 1138 W are shown in Fig. 23 and Fig. 24, respectively.

The sinusoidal waveforms of the voltage and current at the load can be noted, with the same frequency (60Hz) as the sinusoidal input voltage, which is the fundamental characteristic of a transformer. Also, the output to input voltage ratio is equal to unity, which is a consequence of the operation of the LLC converter in the vicinity of the resonance frequency and the high frequency transformer turns ratio equal to unity.

Fig. 25 shows the voltage generated by the power semiconductors of the resonant LLC converter, the current through the resonant inductor ($i_{Lr}$) and the corresponding load current, which is almost constant during the high-frequency switching period.

As previously mentioned, due to operation slightly below the resonance frequency, small time intervals of discontinuity of the output current occur, allowing operation in
discontinuous conduction mode (DCM) and thus enabling the zero-current switching of the four quadrant power semiconductors in the output power stage.

The voltages at the primary \( V_{T1p} \) and secondary windings \( V_{T1s} \) of the high frequency transformer, in the region close to zero crossing of the low frequency input voltage, are shown in Fig. 26, together with the winding current in the primary side \( i_{T1p} \).

It can be noted that at the instant the current in the secondary winding of the transformer reaches zero, the current in the resonant inductor in the primary winding of the transformer is equal to the magnetizing current. This characteristic can be seen by the triangular primary current close to zero crossing of the sinusoidal input voltage.

In Fig. 27, the currents in the output stage switches are shown in detail, while the voltages across the power semiconductors of the same stage switches are shown in detail in Fig. 28.

As predicted by the theoretical analysis of the converter operation, the current before the capacitor \( i_{SF} \) is the sum of the currents of each switch of the output stage, which conduct the secondary current of the transformer alternately. While one switch is conducting, the other is blocked, or vice versa.

Peak voltage can be observed across the switches at the beginning of each switching period, which is caused by the dead time and was expected, as stated earlier.

The relevant waveforms in the power semiconductors of the LLC resonant converter are shown in Fig. 29 and confirm the soft commutation with ZVS.

It can be seen that switch \( S_1 \) is only gated ON after its voltage reaches zero. Due to the dead time and the magnetizing current, the commutation capacitor connected in parallel with \( S_1 \) is completely discharged and soft commutation takes place.

Fig. 30 shows the ZCS-type commutation of the output stage power semiconductors, for the positive half-cycle of the low frequency sinusoidal input voltage.

In order for switches to benefit from ZCS-type soft switching, they are turned off at the instant the secondary current reaches zero.

Fig. 31 shows the measured efficiency of the nonoptimized experimental prototype in the laboratory, against the
FIGURE 30. Waveforms of the gate signals ($V_{GS1}$ and $V_{GS2}$ − 10 V/div) and current in the power semiconductors of the output stage ($i_{SF1}$ and $i_{SF2}$ − 2 A/div), showing the ZCS-type commutation. Time scale (4 µs/div).

FIGURE 31. Measured efficiency versus the effective value of the sinusoidal input voltage, for different processed powers.

FIGURE 32. Measured input power factor and efficiency versus the processed power.

VII. CONCLUSION

An AC-AC converter with a high-frequency link employing a resonant LLC converter operating in the neighborhood of the resonant frequency was studied. The topology has a single output stage, consisting of four quadrant switches, in contrast to the conventional solution that uses two power conversion stages. An experimental prototype rated at 1.5 kW, with the high-frequency link operating with 40 kHz was designed, constructed and tested in the laboratory and the theoretical results were verified. The architecture studied is suitable for application as a building block of medium-voltage power distribution solid-state transformers.

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