Ben Gurion University of the Negev
Department of Electrical and Computer Engineering
Power Electronic Laboratory

Senior Project: P-2013-049
Digital controller for a resonant converter

Students: Bar Halivni and Nadav Cohen

Supervisor: Prof. Shmuel (Sam) Ben-Yaakov
Mr. Michael Evzelman

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Abstract

Traditional Switched Capacitor Converters (SCC) suffer from switching losses, to overcome this problem a DC-DC resonant convertor with Zero Current Switching (ZCS) is used. To successfully control a system of this type, advanced design and programming of a control system based on digital microcontroller is required. Zero Current Switching requires us to perform the switching when there is no current flowing through the circuit; therefore there is no power loss during the switching time. By using a resonant converter the current flows in a sinusoidal pattern created by the resonant components in the circuit, enabling ZCS.

Nowadays the control system of the convertor we are about to use in this project is performed by an open loop method that requires an outside interference which takes time and human resources to achieve optimal performance.

The project goal is creating an automated control system with a closed loop feedback, which changes the duty cycle of the switches and tracks Zero Current Crossing, that doesn’t demand manpower. Implanting zero current crossing control grants us benefits in pricing and efficiency such as: lower power-loss, programming time and achieving more accurate switching times for changing conditions within the system.

The challenges we expected to run in to at this project were: finding a microcontroller that answers all the requirements needed for the control system, coping with circuit’s noise and optimizing zero current crossing track. We will be tracking the progress of the project by simulations and experimental tests.

Resonant Converter

Resonant converters belong to the family of DC-DC converters called SCC (Switching Capacitor Converters). The SCC converters use capacitors as energy storage and delivery component. The basic topology of the SCC has two phases: A charging phase which charge the capacitor from the source and then discharge the capacitor to the load (Figure 1).

In case of resonant SCC a coil is added in serial connection to the capacitor, forming the LC pair in order to create sinusoidal capacitor current. The coil inductance will determine the resonant frequency of the sinusoidal current that will dictate the switching frequency of the control system. The three phase resonant converter (Figure 2) used in this project developed at the Power Electronics Laboratory, including three switching phases: Charging, Discharging and Auxiliary.

Figure 1: The basic topology of SCC (Cf is flying capacitor)

Figure 2: The basic topology of Resonant Converter
Design System

In order to achieve the goal of the project we designed and build a control system which consists of an FPGA digital controller and Current Sense Network which allow us to perform ZCS accurate as possible.

The switching cycle can be divided into two main processes, the first is the detection of the zero current crossing which performed by the current sensing network, that convert the converter analog current signal to a digital signal using an analog comparator. The second part of the processes is the reaction stage, at this stage the FPGA use the signal received from the sensing network to determine if ZCS did accrued using the software algorithm (Figure 5) and then change the state of the switches if need (Figure 3).

The current sensing network – contains of four main parts, the first part is the current transformer which gives us a duplicate image of the capacitor current that we want to detect for zero current crossing. The second part is a full diode bridge resulting a positive polar current signal regardless of the input polarity; this step is required due to the capability of the digital converter to receive only positive voltage inputs. The second stage is a conversion of the current signal to a voltage signal using a conversion resistor of a 330 Ohm. The final part of the network is the high speed analog comparator converting the analog voltage signal to a digital signal which can be read by the FPGA, to protect the FPGA from high voltage level we used a open collector comparator with a digital 3.3V output level (see Figure 4).

For a digital controller we selected the Altera's CycloneIV FPGA using his high speed operating and programming versatility to create the best conditions for a successful ZCS. Using those attributes while programming the controller by the algorithm presented at figure 5 using Verilog, we were able to achieve real time ZCS as shown at the experimental results chapter.

![Figure 3: (a) System Block Diagram (b) wavefoems](image1)

![Figure 4: Current Sense Network & Analog Comparator](image2)
2. **Switches Operating system** – 15V high speed floating drivers.
3. **Input Power Source Filter**.
4. **Current Sense Network and Analog Comparator** – Current sensing components with a LM319N comparator.
5. **Input Capacitors**.
7. **Resonant system** - LC Tank contains of the resonant coil and capacitor.
8. **Switches** – Three switches build from six IRFP3077 MOSFET with a back to back connection.
9. **Output Capacitance**.
10. **Load** – Grid of a 50 ohm power resistor to create any wanted output resistance manually.
Specifications of Resonant Converter:

<table>
<thead>
<tr>
<th>Specifications</th>
<th>Details</th>
</tr>
</thead>
<tbody>
<tr>
<td>Switching Rate</td>
<td>50KHz-200KHz</td>
</tr>
<tr>
<td>Input Voltage</td>
<td>10V-60V</td>
</tr>
<tr>
<td>Output Voltage</td>
<td>10V-60V</td>
</tr>
<tr>
<td>Input Output Voltage Ratio</td>
<td>Converter with whom we work capable of producing variable Input Output ratio. Attenuation or amplification up to four.</td>
</tr>
<tr>
<td>Power</td>
<td>~100W</td>
</tr>
<tr>
<td>Number of Switches</td>
<td>3 switches two - directions include 6 type MOSFET transistors IRFP3077.</td>
</tr>
<tr>
<td>Input Capacitance</td>
<td>28mF</td>
</tr>
<tr>
<td>Output Capacitance</td>
<td>1500µF</td>
</tr>
<tr>
<td>Switches Operating System</td>
<td>Drivers float with a 15V operating voltage.</td>
</tr>
<tr>
<td>Resonant Capacitance</td>
<td>235nF</td>
</tr>
<tr>
<td>Resonant Coil</td>
<td>6.8µH</td>
</tr>
</tbody>
</table>

Figure 7: Specifications of Resonant Converter

Experimental Results

After the completion of the control system design and build, we applied the finished system on to the resonant converter with a view to perform tests and measurements to check the performance of our control system compared to the old manual system. The tests were performed on four different ratios of input-output voltage: **1:2.75 increase, 1:1.4 increase, 1:2 decrease, 1:3 decrease**.

The results were gathered from two voltmeters to measure input and output voltages, active current probe and voltage probes using a scope for the circuit waveforms. The tests measurements are presented and compared over different test conditions using the following graphs:

1. Voltage Measurements

As demonstrated in figure 8, we tested the system over a wide range of conversion ratios, showing that the control system capable of operating the converter in a wide range of input and output voltages.
2. Power Measurements

![Figure 9: Input (Blue) Output (Red) power by conversion ratio](image)

From the results as showed at the graph above (Figure 9) we can see that over all the operating conversion ratings the input and output power are very close, showing high efficiency of the converter using our control system.

In previous tests we managed to achieve output power of 30W, but because of its proximity to the maximum voltage of the switching transistors we preferred to do the measurements using lower power rates in order to avoid any circuit damage.

3. Switching Error

In order to evaluate the most important goal of the project, which is an accurate ZCS, we defined the switching error criteria. Using the switching error we can compare and evaluate the accuracy of ZCS.

The switching error is examined by a new criterion that we define as:

\[
\varepsilon = \frac{|\delta|}{\Delta} \times 100[\%]
\]

The error parameter \(\varepsilon\) is calculated by the ratio between the error current measured in a transistor at the end of the phase (\(\delta\)) and the amplitude of phase (\(\Delta\)). Since \(\varepsilon\) represents the absolute error for switching, we use the absolute value of the error current which can be positive or negative current. As the goal of the project is to perform an accurate ZCS we want the switching error to be as small as possible, which means we achieved better accuracy.

![Figure 10: Switching Error by Conversion Ratio](image)
From figure 10, we can see that our highest error is less than 12%. The error measured at the charge phase for each conversion ratios as shown above is almost constant in value of 11%. The graph shows that for a voltage increase conversion ratio, a smaller error is obtained for the discharge and auxiliary phases due to their small amplitudes, which indicate the lower current slope is we receive a lower the switching error.

The graph above shows that for the charge phase which has the largest amplitude and thus the largest slope, an 11.6% average switching error is shown for all the conversion ratios. For the discharge phase we receive a minimum average error of 6% as shown in Figure 11.

The control system results on the live circuit are shown by the waveforms above, for different ratios of input-output voltage: 1:2.75 increase, 1:1.4 increase, 1:2 decrease, 1:3 decrease (Figure 12). The pink waveform describes the shape of the real capacitor current achieved by a active current probe, the yellow waveform describes the shape of the copied capacitor current after alignment using a full diode bridge using the current transformer, the green waveform describes the comparator reference voltage and the blue waveform describes a control signal to one of the switches.
References


