Abstract—This paper focuses on the practical implementation of sliding mode control (SMC) in a half-wave zero current switching quasi-resonant Buck converter. SMC can manipulate efficiently the nonlinear phenomena that appear in switch mode power supplies, furthermore SMC is less affected by disturbances compared to other control techniques, and it is not operating at a constant switching frequency. Since half wave zero current switching quasi-resonant Buck converter is not operating at a constant switching frequency and it is sensitive to dynamic variation, SMC is selected in this paper as a control technique. An explanation of the implementation of SMC, and selecting its parameters is given. A detailed mathematical analysis is performed in order to select the appropriate values of the tank components elements. The tank inductor value is assumed to be small and constant, and a range of tank capacitor values is obtained. The prototype of an analog sliding mode control for the converter is constructed. In order to study the effect of SMC on the converter behavior, the system is tested in the steady state and under different load value conditions. The obtained graphs show that the performance of SMC is good, even under the worst load conditions, i.e. no load and under full load conditions.

Index Terms—half-wave zero current switching, quasi-resonant Buck converter, sliding mode control, tank inductor value, tank capacitor value.

I. INTRODUCTION

SLIDING mode control (SMC) for switch mode power supplies has been studied in literature. Many papers and researches have shown that SMC is an effective control tool for switch mode power supply [1], [2], and [3]. Unfortunately, most of these researches depended on theories or simulation results that have no practical implementation. Previous researches have shown that SMC has good immunity against disturbances and component variations [2], [4], [5]. In this paper, an analog SMC circuit is constructed using operational amplifiers in such a way that the signals generated at each stage are shown in the control circuit. Following a detailed analysis of the selection of the tank component elements is given. A prototype model of the half-wave zero current switching quasi-resonant Buck converter with its control circuit is constructed. The elements of the main circuit of the converter are shown in TABLE 1. To prove that the circuit functions correctly the output voltage waveform, main inductor current waveform, tank inductor waveform, and tank capacitor waveform are studied in the steady state, under no load and under full load conditions.

II. SLIDING MODE CONTROL AND THE CONVERTER CIRCUIT

Many researches have studied, analyzed, and designed the SMC to DC/DC converters [1], [2], [3], [4], and [5]. These researches concluded and showed great potential for the use of SMC in switch mode power supplies because it is a non-linear control and can manipulate the non-linear phenomena that appear in switch mode power supplies, it has a good immunity against disturbances, and is not operating at a constant switching frequency. Since half-wave zero current switching quasi-resonant Buck converter is not operating at a constant switching frequency and it is sensitive to dynamic variation [6], [7], [8], and [9], SMC is selected as a control technique.

The control circuit is represented by two control loops: an inner main inductor current control loop (represented in this paper by a hysteresis control) and an outer voltage control loop that is represented by proportional plus integral control (PI); the combined loops compose the SMC that is responsible for the zero current switching. Fig.1 shows a simple block diagram of the implementation of SMC in switch mode power supplies. The hysteresis parameters can be selected from the peak-to-peak main inductor current. It is difficult to find a standard procedure to determine the integral gain of the linear part. The reason for this difficulty is that the SMC is a non-linear control and can not be linearized. It is not possible to choose the linear part parameters based on the non-linear part. Choosing a low integral gain reduces the overshoot but the steady state error increases. It is left for the designer to choose the parameters depending on the application.
II. CIRCUIT DESIGN

A simplified circuit diagram of the prototype circuit for a half-wave zero current switching quasi-resonant Buck converter controlled by SMC is shown in Fig. 2. Resonant converters contain resonant $L_r$, $C_r$ networks where its voltage and current waveforms vary sinusoidally during one or more subintervals of each switching period. The main interest in resonant operation of the converters is the minimization of switching losses. Half-wave zero current switching quasi-resonant Buck converter, shown in Fig. 2, is a resonant converter, where the resonant tank capacitor ($C_r$) is placed in parallel with the main Buck converter diode $D_2$, while resonant tank inductor ($L_r$) is placed in series with the active switch. Diode $D_1$ is in series with active switch. The magnitude of the tank inductor current and hence also the DC load current can be controlled by variation of the switching frequency $F_s$ [10].

The operation of the prototype in Fig. 2 can be described as follows: The output voltage is subtracted from the reference voltage using op-amp1. The voltage difference signal is integrated using op-amp2. The output of this amplifier generates signal 1. Op-amp3 is used to detect the inductor current with a shunt resistor $R_1$, generating signal 2. In the next stage, signals 1 and 2 are compared using a comparator (LM111), in which Hysteresis is used to control the switching frequency. The output level of the LM111 signal should be translated into the voltage difference between the gate-source of the switching device IRF530. A high-side MOSFET/IGBT driver IR2117 is used for this purpose.

The circuit was constructed in the Laboratory of Applied Electronic at Lappeenranta University of Technology. Fig. 3 shows the constructed prototype for a half-wave zero current switching quasi-resonant Buck converter with SMC used in the Laboratory where the tests were performed.

![Fig. 2](image)

![Fig. 3](image)

TABLE 1 shows the main Buck converter parameters used in the prototype model.

<table>
<thead>
<tr>
<th>Parameter name</th>
<th>Symbol</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Input voltage</td>
<td>$V_{in}$</td>
<td>24 volts</td>
</tr>
<tr>
<td>Output voltage</td>
<td>$V_o$</td>
<td>12 volts</td>
</tr>
<tr>
<td>Capacitor</td>
<td>$C$</td>
<td>220 µF</td>
</tr>
<tr>
<td>Inductor</td>
<td>$L$</td>
<td>69 µH</td>
</tr>
<tr>
<td>Load resistance</td>
<td>$R_L$</td>
<td>13 Ω</td>
</tr>
<tr>
<td>Nominal switching frequency</td>
<td>$F_s$</td>
<td>100 kHz</td>
</tr>
</tbody>
</table>

III. CALCULATING AND SELECTING THE TANK COMPONENT ELEMENTS VALUES

The resonant tank elements are selected by assuming a constant and small $L_r$ value and obtaining $C_r$. There are two reasons for selecting small $L_r$ value. First, a high $L_r$ value stores a high amount of magnetic energy and since it is connected in series with switch, it may damage the switch MOSFET. Second, the tank resonant frequency should be greater than the nominal switching frequency.
\[ F_0 \geq F_s, \]  \hspace{1cm} (1)

where \( F_0 = \frac{1}{2\pi \sqrt{L_r C_r}} \) denotes the tank resonant frequency.

If \( F_0 < F_s \), the tank elements respond more strongly to the harmonics of the input voltage than to its fundamental value. In order to obtain the range of \( C_r \) values, two conditions have to be fulfilled.

**A. Condition 1**

The tank resonant frequency should be greater than the nominal switching frequency, as given in equation (1). Using equation (1) and for \( F_s = 100 \text{ kHz} \), \( L_r = 3\mu\text{H} \) we get

\[ C_r \leq 844\text{nF}. \]  \hspace{1cm} (2)

**B. Condition 2**

the DC conversion ratio (\( \mu \)) is less than one for Buck converter

\[ \mu = \frac{V_o}{V_{in}} \leq 1. \]  \hspace{1cm} (3)

To guarantee that the tank inductor current reach zero, the condition in equation (4) should be satisfied [1]

\[ \frac{V_{in}}{Z_o} \leq I_L, \]  \hspace{1cm} (4)

where \( Z_o = \sqrt{\frac{L_r}{C_r}} \) denotes the tank characteristic impedance.

By substitute equation \( Z_o \) into equation (4) and for \( L_r = 3\mu\text{H} \), and \( R_L = 13 \Omega \), it can be obtained that

\[ C_r \geq 4.5\text{nF}. \]  \hspace{1cm} (5)

Equation (4) is the second condition for selecting \( C_r \). From equation (2) and (5) the range of \( C_r \) is

\[ 4.5\text{nF} \leq C_r \leq 844\text{nF}. \]  \hspace{1cm} (6)

**IV. EXPERIMENTAL RESULTS OF THE PROTOTYPE**

To prove that the constructed circuit functions properly and that SMC can be implemented with the prototype, as well as to show that SMC is resistant to load variations, the circuit was tested in steady state and under load variations (no load and full load). The output voltage, main inductor current, tank capacitor voltage and tank inductor current waveforms were tested, and the corresponding graphs are shown in Figs. 4 to 9. The main converter parameters were given in Table 1, assuming that \( C_r = 400\text{nF} \), and \( L_r = 3\mu\text{H} \).

**A. Steady state region**

Fig. 4 shows the output voltage waveform (ch1, upper waveform) has a 0.1-volt ripple and the main inductor current waveform (ch2, lower waveform) has 4.1A peak-to-peak value in steady state. The graph shows that in steady state the converter has a good response when controlled by SMC.

Fig. 5 shows in steady state the tank capacitor voltage waveform (ch1, upper waveform) has 5.7 volt and the peak-to-peak tank inductor current waveform (ch2, lower waveform) has 4.1A peak-to-peak value in steady state. The graph shows that in steady state the converter has a good response when controlled by SMC.

**TABLE 2**

| Constant and small \( L_r \) value and two different \( C_r \) values |
|------------------|------------------|
| Small \( C_r \) value | High \( C_r \) value |
| 1 | Operate at high switching frequency |
| 2 | Slow transient response without overshoot |
| 3 | Low output voltage ripple |
| 4 | More tank waveform distortions |
| 5 | Lower peak-to-peak tank inductor current |
| 6 | Lower peak-to-peak main inductor current |

Fig. 6 shows the output voltage waveform (ch1, upper waveform) has 5.7 volt and the main inductor current waveform (ch2, lower waveform) has 4.1A peak-to-peak value in steady state. The graph shows that in steady state the converter has a good response when controlled by SMC.
that is 5.16A with negative reverse recovery. It can be seen in Fig.5 that zero current switching occurs. The \( f_s \) is 32.46 kHz, (ch2 Freq). Reducing the tank capacitor value can increase the frequency, but more distortion occurs in the signals.

Fig.5 The tank capacitor voltage waveform (Ch1, upper waveform) and tank inductor current waveform (ch2, lower waveform) of the half-wave zero current switching quasi-resonant Buck controlled by SMC in steady state. (Ch2 Freq) shows the frequency of the converter

\( f_s \) is 32.46 kHz, (ch2 Freq).

**B. Load variation**

To study the effect of SMC on the behavior of the converter under load variations, two tests were performed on the converter with different load values, which are considered to be the worst cases.

First case is when the converter is operating under no load (2kΩ). Fig. 6 shows the output voltage and main tank inductor current waveforms under no load condition. The mean output voltage is 12.1 volts (Ch1 Mean, upper waveform). The peak-to-peak main inductor current is 3.68A (Ch2 PK-PK, lower waveform) and the frequency at which the converter operates under no load is 24.52 kHz (Ch2 Freq).

Fig. 6 The output voltage (Ch1, upper waveform) and main inductor current (Ch2, lower waveform) of the half-wave zero current switching quasi-resonant Buck converter controlled by SMC under no-load conditions. The switching frequency is 24.53 kHz (Ch2 Freq).

Second case is when the load changes from its nominal value to full load (the full load value is 1Ω). Fig. 8 shows the output voltage waveform (upper waveform) and main tank inductor waveform (lower waveform). The mean output voltage is 12.3 volts (Ch1 Mean) and a ripple voltage is equal to 3.6volts (Ch1 PK-PK). The peak-to-peak main inductor current is 3.12A (Ch2 PK-PK), while the switching frequency of the converter under full load is 48.22 kHz (Ch2 Freq).

The converter in this case is operating in discontinuous conduction mode (DCM), and the SMC is functioning in a way that it keeps the converter stable with no load condition that is considered to be one of worst load variation cases.

Fig. 7 shows the tank capacitor voltage waveform equal 44 volts (Ch1 PK-PK, upper waveform) and the tank inductor current waveform with a peak-to-peak value equal 3.56A (Ch2 PK-PK, lower waveform) under no load conditions.

Fig. 7 The tank capacitor voltage waveform with 44volt (Ch1, upper waveform) and tank inductor current waveform = 3.56A (Ch2 peak-to-peak, lower waveform). The half-wave zero current switching quasi-resonant Buck converter is under no-load conditions.

Fig. 8 The output voltage waveform (upper waveform) and main inductor current waveform (lower waveform) of the half-wave zero current switching quasi-resonant Buck converter controlled by SMC under full-load condition. The converter is stable but high output voltage ripple occurs.
Fig. 9 shows the tank capacitor voltage waveform and tank inductor current waveform under full-load condition. The peak tank capacitor voltage is 58 volts (Ch1, upper waveform), while the peak-to-peak tank inductor current waveform is 8.9 A (Ch2 PK-PK, lower waveform). It can be said from Fig. 8 and Fig. 9 that although the converter is working under full load, the converter is still stable and SMC has an efficient influence against disturbances.

III. CONCLUSIONS

Sliding mode control (SMC) was implemented in a half-wave zero current switching quasi-resonant Buck converter. The reason behind the selection of SMC to this kind of converter was that: first, many researches studied theoretically the implementation of SMC to power supply and proved that it is an efficient control technique to switch mode power supply. Second, SMC is not operating at a constant switching frequency and resonant converters have a highly nonlinear and time-varying nature. Any change in operating conditions leads to significant changes in system dynamical model so that desired performance and even stability can be lost. Due to the reasons mentioned the paper linked the theoretical researches to a real prototype model.

SMC was implemented by dual control loops; an inner main inductor current loop represented by hysteresis control (non linear part) and an outer voltage loop represented by PI control (linear part).

A prototype of the controller with the converter was constructed and a detailed analysis performed to ascertain how the signals are generated by the operational amplifiers at each stage. The controller was designed using analog operational amplifiers.

The values of the main converter parameters were given and a mathematical analysis performed to select the tank inductor and tank capacitor values, where zero current switching occurs.

To prove that the prototype model is effective and that SMC can be implemented in real applications of a half-wave zero current switching quasi-resonant Buck converter, the circuit was tested in steady state and under load variations (no load and full load). Our analysis demonstrated that SMC gives acceptable results, not only from theoretical point of view but also in practical applications, and that SMC is an effective control tool for keeping the converter stable even in the worst cases (no load and full load).

REFERENCES


