Comparative Analysis of Semiconductor Power Losses of Galvanically Isolated Quasi-Z-Source and Full-Bridge Boost DC-DC Converters

Roman Kosenko (PhD student, Tallinn University of Technology/Chernihiv Nat. University of Technology), Liisa Liivik (PhD student, Tallinn University of Technology), Andrii Chub (Junior Researcher, Tallinn University of Technology), Oleksandr Velihorskyi (Associate Professor, Chernihiv Nat. University of Technology)

Abstract – This paper compares semiconductor losses of the galvanically isolated quasi-Z-source converter and full-bridge boost DC-DC converter with active clamping circuit. Operation principle of both converters is described. Short design guidelines are provided as well. Results of steady state analysis are used to calculate semiconductor power losses for both converters. Analytical expressions are derived for all types of semiconductor power losses present in these converters. The theoretical results were verified by means of numerical simulation performed in the PSIM simulation software. Its add-on module “Thermal module” was used to estimate semiconductor power losses using the datasheet parameters of the selected semiconductor devices. Results of calculations and simulation study were obtained for four operating points with different input voltage and constant input current to compare performance of the converters in renewable applications, like photovoltaic, where input voltage and power can vary significantly. Power loss breakdown is detailed and its dependence on the converter output power is analyzed. Recommendations are given for the use of the converter topologies in applications with low input voltage and relatively high input current.

Keywords – DC-DC power converters; Energy efficiency; Pulse width modulation converters; Semiconductor device modeling.

I. INTRODUCTION

Isolated full-bridge boost (IFBB) DC-DC converters are a well known and proven topology [1]-[5]. Up to recently, its spread is limited due to the inherent drawbacks of the current-fed technology, such as high inrush current during start-up and high voltage stress of the transistors. Nevertheless, the IFBB converters can perform voltage step-up and maintain continuous input current in a wide operation range. At the same time, a new quasi-Z-Source (qZS) DC-DC converter topology has emerged that has all the benefits of the IFBB topology and does not suffer from the high inrush current, has even higher step-up factor and therefore potentially wider operation range [6]-[8], [22], [23]. Therefore, the topologies with an input stage that can work as a current-source could be preferable in such low-voltage applications as power conditioners for photovoltaic panels and fuel-cells.

Focus in this paper is on the comparison of these two topologies in terms of energy efficiency in low voltage applications. The generalized power circuit layouts of the qZS and IFBB DC-DC converters are presented in Figs. 1 and 2.

Both converters use the voltage doubler rectifier (VDR) to provide a higher voltage step-up factor and reduce the transformer turns ratio. The IFBB converter accommodates an active clamping circuit, which consists of a switch $S_{cl}$ and a capacitor $C_{cl}$ (Fig. 2). It is used to recycle the inductive energy when switching from the shoot-through to the active state, thus minimizing the turn-off losses and reducing the voltage stress of the switches.

II. OPERATION PRINCIPLE OF THE CONVERTERS

Fig. 3 shows the basic waveforms of the galvanically isolated qZS full-bridge DC-DC converter. The symmetric overlap of active states is used to control the converter in the continuous conduction mode (CCM). It requires generation of two control signals for the diagonal switches (one for $S_{cl}, S_{d}$ and the other for $S_{r}, S_{l}$). These signals are of equal duration and phase-shifted by 180 degrees. The switching period consists of four time intervals:

- a) and c) are the shoot-through state intervals. All four inverter switches are conducting, qZS network inductors are accumulating energy;
- b) is an active state interval when diagonal switches $S_{r}$ and $S_{l}$ are conducting and energy is transferred to the output filter capacitor $C_{2}$;
- d) is another active state when diagonal switches $S_{l}$ and $S_{r}$ are turned on and energy is transferred to the output filter capacitor $C_{1}$.

The operation principle of the qZS DC-DC converter is detailed in [8],[9].

The waveforms of the IFBB DC-DC converter are generalized in Fig. 4. The converter has an additional switch ($S_{cl}$), but in general the operation principle in the continuous conduction mode is similar to that of the qZS converter.
Fig. 2. Galvanically isolated full-bridge boost DC-DC converter.

Fig. 3. Generalized waveforms of the qZS full-bridge DC-DC converter.

- a) and c) are shoot-through intervals. All four inverter stage switches are conducting, the boost inductor $L_{IN}$ is accumulating energy, the clamping switch $S_{CL}$ is turned off;
- b) diagonal switches $S_1$ and $S_4$ are conducting, energy is transferred to the output filter capacitor $C_2$, the clamping switch $S_{CL}$ is turned on to protect inverter switches from the voltage overshoot during the transition from the shoot-through to the active state and back;
- d) diagonal switches $S_2$ and $S_3$ are conducting, energy is transferred to the output filter capacitor $C_1$, the clamping switch $S_{CL}$ is turned on to protect inverter switches from the voltage stress during the transition from the shoot-through to the active state and back.

Fig. 4. Generalized waveforms of the IFBB DC-DC converter.

The operation principle of the IFBB DC-DC converter is detailed in [10], [11].

Comparison carried out in this paper is limited to the semiconductor losses because of their strong influence on the performance of both of the converters. To ensure reliable results, the converters were analyzed in the same conditions. Passive elements parameters were calculated to ensure the same input current ripple for both topologies. $L_{IN}$, $L_{qz1}$ and $L_{qz2}$ were selected to achieve peak-to-peak input current ripple at the level of 10% of the nominal current.

As seen from Figs. 3 and 4, the current through the primary transformer winding ($I_{SP}$) is nearly the same for both topologies. Thus, the losses in the magnetic elements have to be nearly equal for both converter topologies. They were excluded from our analysis, since the main difference in the power losses is within semiconductor losses.

III. DESIGN CONSIDERATION

Both of the compared topologies are boost-enabled, and their switching period $T$ consists of the shoot-through and the active state. The duty cycles of the shoot-through and the active state are interdependent, as shown in (1):

$$\frac{I_A}{T} + \frac{I_S}{T} = D_A + D_S = 1,$$  (1)
where \( t_a \) and \( t_s \) are the duration of the active and the shoot-through state, correspondingly, \( D_a \) and \( D_s \) are the duty cycles of the active and the shoot-through state, correspondingly.

The output voltage of the qZS full-bridge converter can be expressed as

\[
V_{OUT} = 2n \cdot \frac{1}{1 - 2D_s} \cdot V_{IN} \tag{2}
\]

where \( n \) is the transformer turns ratio, \( V_{IN} \) is the input voltage of the converter, and \( V_{OUT} \) is the output voltage of the converter. For the IFBB converter, the output voltage can be calculated as

\[
V_{OUT} = 2n \cdot \frac{1}{1 - D_s} \cdot V_{IN} \tag{3}
\]

The main advantage of the discussed converters is the ability to operate with continuous input current. To maintain the CCM, the energy accumulating inductors must be selected based on the converter operation parameters.

For the IFBB converter, minimal inductance of the boost inductor required to limit the input current ripple on the level of \( \Delta I_{IN} \) can be calculated as [12]

\[
L_{IN} = \frac{V_{IN \min}^2 \cdot D_{max}}{f_{sw} \cdot P \cdot \Delta I_{IN}} \cdot 100 \tag{4}
\]

where \( f_{sw} \) is the switching frequency, \( \Delta I_{IN} \) is the selected peak-to-peak input current ripple, \( D_{max} \) is the maximum shoot-through duty cycle, \( P \) is the rated power of the converter, and \( V_{IN \min} \) is the minimum input voltage of the converter.

The inductance of the qZS network inductors required to limit the input current ripple on the level of \( \Delta I_{IN} \) from the nominal is expressed by [9]

\[
L_{q1} = L_{q2} = \frac{1 - D_{max}}{1 - 2D_{max}} \cdot \frac{V_{IN \min}^2 \cdot D_{max}}{f_{sw} \cdot P \cdot \Delta I_{IN}} \cdot 100 \tag{5}
\]

The capacitance of the capacitors in the qZS network required to limit the ripple of the DC-link voltage can be calculated as [13]:

\[
C_{q1} = C_{q2} = \frac{2n \cdot P \cdot D_{max}}{V_{OUT} \cdot \Delta V_{sc} \cdot V_{IN \min} \cdot f_{sw}} \cdot 100 \tag{6}
\]

where \( \Delta V_{sc} \) is the peak-to-peak voltage ripple of the capacitors.

To limit the output voltage ripple on the level of \( \Delta V_{OUT} \), the capacitance of VDR capacitors should be at least [8]:

\[
C_1 = C_2 = \frac{P \cdot D_{max}}{\Delta V_{sc} \cdot f_{sw} \cdot V_{OUT}^2} \cdot 100 \tag{7}
\]

where \( V_{OUT} \) is the nominal output voltage of the converter.

The capacitance of the clamping capacitor \( (C_{CL}) \) is based on the \( LC \) circuit resonant frequency. The clamping capacitor \( (C_{CL}) \) can resonate with either the boost inductor \( (L_w) \) or with the transformer leakage inductor \( (L_{TX \_leak}) \). This resonant frequency should be lower than the doubled switching frequency \( f_{sw} \). Since the IFBB converter circuit has two inductors, the clamping capacitance is calculated as the maximum of two values, which is usually determined by \( L_{TX \_leak} \) [14]:

\[
C_{CL} = \frac{1}{16 \cdot L_{TX \_leak} \cdot f_{SW}^2 \cdot \pi^2} \tag{8}
\]

IV. COMPARATIVE ANALYSIS OF POWER LOSSES AND EFFICIENCY

The semiconductor losses of the converter can be categorized to a few major types. Analytical expressions of semiconductor losses in both topologies are well described in [9], [11], [15]-[17]. Here some of the resulting expressions adapted for the discussed converters and applications are presented.

A. Inverter Losses

The primary low-voltage MOSFET semiconductor losses are calculated based on the MOSFET on-state resistance, the average input current, and transformer primary winding current averaged over the half of the period. The use of average input current value instead of RMS value simplifies the analytical expressions for conduction losses during shoot-through state without significant impact on precision. For example, for the input current with ripple of 50% the difference between average and RMS values is around 1% only [17]. Conduction losses are different for the active and the shoot-through state as the different number of MOSFETs are conducting (Fig. 5). So the resulting equation consists of these two components. Total conduction losses in inverter MOSFETs of IFBB DC-DC converter are expressed by:

\[
P_{M_{s\_con}} = R_{DS(on)} \left( \frac{P}{V_{IN}} \right)^2 \cdot D_s + 2 \cdot R_{DS(on)} \cdot \left( \frac{4 \cdot n \cdot P}{\sqrt{3} \cdot V_{OUT}} \right)^2 \tag{9}
\]

where \( R_{DS(on)} \) is the on-state resistance of the MOSFET.

Total conduction losses in inverter MOSFETs of qZS DC-DC converter are expressed by:

\[
P_{M_{s\_con}} = R_{DS(on)} \left( \frac{2 \cdot P}{V_{IN}} \right)^2 \cdot D_s + 2 \cdot R_{DS(on)} \cdot \left( \frac{4 \cdot n \cdot P}{\sqrt{3} \cdot V_{OUT}} \right)^2 \tag{10}
\]

As seen from (9) and (10) component of the inverter MOSFETs conduction losses that corresponds to the active state is the same for both topologies as the difference in RMS values of the transformer primary winding current is compensated by difference in duty cycles of the active state. At constant input current \( (P/VIN) \), the MOSFET current during the shoot-through state interval is two times higher in qZS converter than in IFBB converter. However, the shoot-through duty cycle \( (D_s) \) for qZS converter is two times lower than for IFBB converter. Therefore component of the inverter
MOSFET’s conduction losses that corresponds to the shoot-through state is only two times higher than in IFBB converter. Impact of this component decreases as the shoot-through duty cycle decreases and thus inverter MOSFET’s conduction losses are equal for both converters at unity step-up factor.

Switching losses consist of turn-on and turn-off losses:

\[ P_{M_{\text{on}}+M_{\text{off}}} = 2 \left( P_{M_{\text{on}}} + P_{M_{\text{off}}} \right), \quad (11) \]

where \( P_{M_{\text{on}}} \) and \( P_{M_{\text{off}}} \) are the MOSFET turn-on and turn-off losses accordingly [19]:

\[ P_{M_{\text{on}}} = \frac{1}{2} \alpha \cdot (I_{IN} - I_{IN} \cdot \Delta I_{V_{DS}} / 200) \cdot V_{out} \cdot \frac{I_{SW}}{V_{drive}} \cdot (R_{g} + R_{drive}) \cdot f_{SW}, \quad (12) \]

\[ P_{M_{\text{off}}} = \frac{1}{2} \alpha \cdot (I_{IN} + I_{IN} \cdot \Delta I_{V_{DS}} / 200) \cdot V_{out} \cdot \frac{I_{SW}}{V_{drive}} \cdot (R_{g} + R_{drive}) \cdot f_{SW}, \quad (13) \]

where \( I_{IN} \) is the converter input current, \( Q_{SW} \) is the MOSFET switching charge, \( V_{drive} \) is the MOSFET driver logical “high” voltage (15 V), \( R_{g} \) is the MOSFET internal gate resistance, \( R_{drive} \) is the MOSFET driver current limiting resistor (2 \( \Omega \));

Equations (12)-(13) indicate that only conduction losses depend on the shoot-through duty cycle. So, at constant input current, the total losses of the clamping switch will be growing, moving toward the unity step-up factor (\( D_s = 0 \)).

\[ P_{DqZS_{\text{con}}} = V_{P_{V_{FV}} \cdot qZS} \cdot I_{IN} \cdot (15) \]

where \( V_{P_{V_{FV}} \cdot qZS} \) is the forward voltage drop of the qZS diode.

Conduction losses of the qZS diode depend on the shoot-through duty cycle. Taking into account the change of \( D_s \) in the range of \( 0 \ldots 0.25 \) (for the converter operating with the twofold input voltage range), the conduction losses will change roughly only by 6%.

D. Losses in Clamping MOSFET

Total power losses on the clamping switch consist of three components:

\[ P_{CL} = P_{CL_{\text{on}}} + P_{CL_{\text{off}}} + P_{CL_{\text{on}}}, \quad (16) \]

where \( P_{CL_{\text{on}}} \) is the clamping switch conduction losses, \( P_{CL_{\text{off}}} \) and \( P_{CL_{\text{on}}} \) are the clamping MOSFET turn-on and turn-off losses [11], [16]:

\[ P_{CL_{\text{on}}} = \frac{R_{DS(on)} \cdot V_{P_{IN}}}{2} \cdot (1 - D_s), \quad (17) \]

\[ P_{M_{\text{on}}} = \frac{1}{2} \alpha \cdot (I_{IN} - I_{IN} \cdot \Delta I_{V_{DS}} / 200) \cdot V_{out} \cdot \frac{I_{SW}}{V_{drive}} \cdot (R_{g} + R_{drive}) \cdot f_{SW}, \quad (18) \]

\[ P_{CL_{\text{off}}} = \frac{1}{2} \alpha \cdot (I_{IN} + I_{IN} \cdot \Delta I_{V_{DS}} / 200) \cdot V_{out} \cdot \frac{I_{SW}}{V_{drive}} \cdot (R_{g} + R_{drive}) \cdot f_{SW}. \quad (19) \]

Equations (17)-(19) indicate that only conduction losses depend on the shoot-through duty cycle. So, at constant input current, the total losses of the clamping switch will be growing, moving toward the unity step-up factor (\( D_s = 0 \)).

V. Simulation Results

The 300 W solar module-integrated converter (MIC) was selected as the case study for the modeling. Typically MICs working with a single PV-panel have the nominal output power in the range 240-275 W and maximum power point voltage near 30 V at standard test conditions. The converter parameters must be within that range. The simulation parameters of the converters are listed in Table I.

The power losses and efficiency of both converters were analyzed in four operating points, which cover the whole input voltage range (Table II). The operation parameters of each point were selected to achieve the maximum input current. As seen from Table II and (2), (3), the shoot-through duty cycle \( D_s \) needed to achieve the desired voltage boost factor is two times smaller for the qZS converter as compared to the IFBB converter counterpart. This has considerable influence on the distribution of the losses in the converters.

The power loss was analyzed by means of the PSIM simulation software with Thermal Module. It enables the calculation of the power loss in the semiconductor elements based on their datasheet parameters. The semiconductor...
elements selected for the simulation and their main parameters are presented in Table III.

To compare simulation and theoretical results, the losses calculated using (9)-(19) are shown in Tables IV and V for qZS and IFBB converters, respectively. The IFBB converter shows up to 4.7% higher calculated efficiency in boost mode.

The simulation results are presented in Tables VI and VII for qZS and IFBB converters, respectively. Fig. 6 shows the graphical representation of the semiconductor losses for both topologies. The dependence of semiconductor losses on the

### Table I

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Symbol</th>
<th>Value</th>
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</thead>
<tbody>
<tr>
<td>Input voltage range, V</td>
<td>$V_{in}$</td>
<td>15…30</td>
</tr>
<tr>
<td>Maximum input current, A</td>
<td>$I_{in}$</td>
<td>10</td>
</tr>
<tr>
<td>Output voltage, V</td>
<td>$V_{ou t}$</td>
<td>300</td>
</tr>
<tr>
<td>Switching frequency, kHz</td>
<td>$f_{sw}$</td>
<td>100</td>
</tr>
<tr>
<td>Transformer turns ratio</td>
<td>$n$</td>
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<tr>
<td>Capacitance of output capacitors, uF</td>
<td>$C_1, C_2$</td>
<td>2.2</td>
</tr>
<tr>
<td>Converters power rating, W</td>
<td>$P$</td>
<td>300</td>
</tr>
<tr>
<td>Peak-to-peak input current ripple, %</td>
<td>$\Delta I_{in}$</td>
<td>10</td>
</tr>
<tr>
<td>Peak-to-peak voltages ripple, %</td>
<td>$\Delta V_{in}$</td>
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</tr>
<tr>
<td>Transformer magnetizing inductance, uH</td>
<td>$L_{m, m}$</td>
<td>60</td>
</tr>
<tr>
<td>Transformer primary leakage induc., uH</td>
<td>$L_{m, leak}$</td>
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<tr>
<td>qZS converter</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Capacitance of qZS capacitors, uF</td>
<td>$C_{qZS1, qZS2}$</td>
<td>33</td>
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<tr>
<td>Inductance of qZS inductors, µH</td>
<td>$L_{qZS1, qZS2}$</td>
<td>28</td>
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<tr>
<td>IFBB converter</td>
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<td></td>
</tr>
<tr>
<td>Inductance of boost inductor, µH</td>
<td>$L_{b}$</td>
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</tr>
<tr>
<td>Capacitance of clamping capacitor, uF</td>
<td>$C_b$</td>
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### Table II

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<td>$V_{in}$, V</td>
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<td>25</td>
<td>30</td>
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<tr>
<td>$P$, W</td>
<td>150</td>
<td>200</td>
<td>250</td>
<td>300</td>
</tr>
<tr>
<td>$D_1, qZS$</td>
<td>0.25</td>
<td>0.167</td>
<td>0.083</td>
<td>0</td>
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<tr>
<td>$D_2, IFBB$</td>
<td>0.5</td>
<td>0.333</td>
<td>0.167</td>
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### Table III

<table>
<thead>
<tr>
<th>Component</th>
<th>Type</th>
<th>Specifications</th>
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</thead>
<tbody>
<tr>
<td>$S_1, S_2, S_{ct}$</td>
<td>Vishay Si4190ADY</td>
<td>$V_{dss}=100$ V; $R_{on, @5A}=8.8$ mΩ; $I_{dSat}=18.4$ A; $C_{oss}=695$ pF; $R_s=1$ Ω; $Q_s=67$ nC</td>
</tr>
<tr>
<td>$D$</td>
<td>Vishay V60D100C</td>
<td>$V_{dss}=100$ V; $V_{f}=0.66$ V; $I_{d}=2x30$ A</td>
</tr>
<tr>
<td>$D_1, D_2$</td>
<td>CREE C3D02060E</td>
<td>$V_{dss}=600$ V; $I_{d}=1.8$ A; $V_{f}=4$ A</td>
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### Table IV

<table>
<thead>
<tr>
<th>Output power, W</th>
<th>150</th>
<th>200</th>
<th>250</th>
<th>300</th>
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<tbody>
<tr>
<td>qZS diode (cond.), W</td>
<td>6.60</td>
<td>6.60</td>
<td>6.60</td>
<td>6.60</td>
</tr>
<tr>
<td>MOSFETs (cond.), W</td>
<td>1.47</td>
<td>1.63</td>
<td>1.92</td>
<td>2.35</td>
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<tr>
<td>MOSFETs (switch), W</td>
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<td>1.10</td>
<td>1.10</td>
<td>1.10</td>
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<tr>
<td>Rectifier diodes (cond.), W</td>
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<td>2.40</td>
<td>3.00</td>
<td>3.60</td>
</tr>
<tr>
<td>Total losses, W</td>
<td>16.97</td>
<td>11.73</td>
<td>12.62</td>
<td>13.65</td>
</tr>
<tr>
<td>Efficiency, %</td>
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<td>94.1</td>
<td>95.0</td>
<td>95.5</td>
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### Table V

<table>
<thead>
<tr>
<th>Output power, W</th>
<th>150</th>
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<th>250</th>
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<tbody>
<tr>
<td>Clamping MOSFET, W</td>
<td>0.50</td>
<td>0.57</td>
<td>0.64</td>
<td>0.72</td>
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<tr>
<td>MOSFETs (cond.), W</td>
<td>1.03</td>
<td>1.34</td>
<td>1.78</td>
<td>2.35</td>
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<tr>
<td>MOSFETs (switch), W</td>
<td>0.55</td>
<td>0.55</td>
<td>0.55</td>
<td>0.55</td>
</tr>
<tr>
<td>Rectifier diodes (cond.), W</td>
<td>1.80</td>
<td>2.40</td>
<td>3.00</td>
<td>3.60</td>
</tr>
<tr>
<td>Total losses, W</td>
<td>8.87</td>
<td>4.86</td>
<td>5.97</td>
<td>7.21</td>
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<tr>
<td>Efficiency, %</td>
<td>97.4</td>
<td>97.6</td>
<td>97.6</td>
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### Table VI

<table>
<thead>
<tr>
<th>Output power, W</th>
<th>150</th>
<th>200</th>
<th>250</th>
<th>300</th>
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<tbody>
<tr>
<td>qZS diode (cond.), W</td>
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<td>6.31</td>
<td>6.28</td>
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<tr>
<td>MOSFETs (cond.), W</td>
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<td>2.07</td>
<td>2.37</td>
<td>2.50</td>
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<td>MOSFETs (switch), W</td>
<td>0.39</td>
<td>0.39</td>
<td>0.37</td>
<td>0.49</td>
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<tr>
<td>Rectifier diodes (cond.), W</td>
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<td>1.99</td>
<td>2.60</td>
<td>3.30</td>
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<tr>
<td>Total losses, W</td>
<td>10.21</td>
<td>10.76</td>
<td>11.62</td>
<td>12.53</td>
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<tr>
<td>Efficiency, %</td>
<td>93.2</td>
<td>94.6</td>
<td>95.4</td>
<td>95.8</td>
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### Table VII

<table>
<thead>
<tr>
<th>Output power, W</th>
<th>150</th>
<th>200</th>
<th>250</th>
<th>300</th>
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<tr>
<td>Clamping MOSFET, W</td>
<td>0.41</td>
<td>0.44</td>
<td>0.48</td>
<td>0.52</td>
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<tr>
<td>MOSFETs (cond.), W</td>
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<td>1.94</td>
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<td>MOSFETs (switch), W</td>
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<td>0.20</td>
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<td>Rectifier diodes (cond.), W</td>
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<td>2.24</td>
<td>2.78</td>
<td>3.34</td>
</tr>
<tr>
<td>Total losses, W</td>
<td>4.09</td>
<td>4.87</td>
<td>5.69</td>
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</tr>
<tr>
<td>Efficiency, %</td>
<td>97.3</td>
<td>97.6</td>
<td>97.7</td>
<td>97.8</td>
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</table>
Fig. 6. Semiconductor power losses breakdown of the qZS and IFBB converters.

and duty cycle. At the same time, in other operating modes the VDR losses in the qZS topology are lower than in the IFBB topology. The reason is that to provide the same average output current with a lower active state duty cycle, the VDR diode peak current in the IFBB converter must be higher.

In the IFBB converter, the $D_t$ increases with the output power growing. Therefore, the losses in the clamping MOSFET are rising, since it is conducting only during the active state. In general, the direct impact of the clamping MOSFET losses on the converter efficiency is insignificant.

![Fig. 7. Semiconductor power losses versus output power in the qZS converter.](image)

Nevertheless, the clamping network has substantial impact on the inverter MOSFET switching losses [10], [15].

The switching losses of the inverter MOSFETs in qZS converter are higher than that in the IFBB converter. It is a result of the higher switching current in boost mode for qZS, as predicted by (12)-(13), and soft-switching possibilities of the IFBB converter with active clamping [24]. This soft-switching performs better at higher load and leads to lower switching losses of the inverter MOSFETs.

The last component in the power losses is the MOSFET conduction losses. They are increasing with the output power increase due to the higher power losses during active state, which depend on the load. In the active state, two MOSFETs are connected in series with the transformer primary winding and conducting output current reflected to the primary winding of the isolation transformer. With given test conditions for both converter topologies the RMS current of the inverter MOSFETs during active state interval differs in boost mode. However they feature equal conduction losses in active state, since different in RMS currents is compensated by the difference of active state duty cycles. The difference in total conduction losses of the inverter MOSFETs for these two converters is determined by the losses during shoot-through state. As shown in Fig. 5, in the shoot-through state the input current is flowing though the parallel connection of two branches with two conducting MOSFETs connected in series [7]. For the IFBB converter in the shoot-through state, the RMS current through each inverter MOSFET is equal to half of the average input current. In the qZS converter the RMS MOSFET current equals to the average input current. Consequently, the conduction losses during shoot-through state in the inverter MOSFETs of the qZS converter are two times higher than that of the IFBB converter, taking into account two times higher duty cycle required for IFBB converter to achieve the same voltage step-up as in the qZS converter. In both converters the conduction losses during the shoot-through state are proportional to its duty cycle. Therefore their impact growing as the step-up factor increases, i.e. the converter input voltage decreases. Since the difference in the conduction losses between two converters is determined only by the component caused from the shoot-through state, the inverter MOSFETs conduction losses are equal for both converters.

![Fig. 8. Semiconductor power losses versus output power in the IFBB converter.](image)

![Fig. 9. Efficiency of qZS and IFBB converters versus output power.](image)
topologies in the operating point with the unity step-up factor, which was confirmed by the simulation.

The dependences of the efficiency on the output power for both converters are summarized in Fig. 9. As can be seen, the efficiency curve of the IFBB converter is flat over the whole operation range, while the qZS converter efficiency drops significantly with the decrease of the output power. This efficiency drop is caused mainly by the nearly constant qZS diode conduction losses. They have a crucial impact on the efficiency at light loads.

In general, the distribution of the losses and their dependence on the output power corresponds to the analytical expressions in section III of this paper.

VI. CONCLUSIONS

In this paper the semiconductor losses in the isolated qZS and IFBB converters were analyzed and compared. The comparison shows that the IFBB DC–DC converter topology could be more preferable in low-voltage applications than the conventional qZS full-bridge converter topology with a diode in the qZS network. At the same time, the IFBB converter topology has a number of drawbacks that limit its use. Major drawbacks are the high inrush current and higher voltage stresses under hard-switching as compared to the qZS and conventional voltage fed topologies. Additional active clamping circuit is commonly used in the IFBB converters to improve their switching performance.

Nevertheless, both topologies can be significantly improved in terms of efficiency. For example, by accommodating synchronous qZS-network and synchronous rectification it is possible to increase the maximum efficiency of the qZS converter by up to 3% [7]. This eliminates the main drawback of the qZS converter in low voltage applications. By accommodating separated commutation and four quadrant active switches to the IFBB converter, it is possible to limit voltage stress by achieving full soft-switching and to minimize rectifier stage conduction losses by the use of synchronous rectification [4],[20].

Efficiency is not a single factor in topology selection for low voltage applications. The following additional points for consideration have resulted from our comparison of the discussed topologies in terms of practical applications:

1) qZS converters need fewer MOSFETs, which provides cost savings on MOSFETs themselves, driver circuits, and control system.

2) IFBB converters have only one energy-accumulating inductor as compared to two inductors in the qZS topology. At the same time, the inductance of the IFBB converter inductor is higher than the inductance of the qZS inductors. Moreover, the qZS network inductors can be magnetically coupled, which allows the required inductance value to be reduced two times in the same operating conditions [13],[21]. It means that the qZS can be implemented with a single magnetic component like the IFBB converter.

3) qZS DC-DC converters can work in both the shoot-through and the open state of the inverter, while the IFBB converter needs special circuits and more complex control algorithms to protect the inverter from the voltage overshoot caused by the boost inductor if the open state occurs in the inverter bridge.

4) qZS DC-DC converters have comparatively low efficiency in low voltage applications but can additionally operate in the buck mode (without any additional switches), providing a wider operation range without any need for clamping circuits to protect switches from the voltage stress.

5) qZS DC-DC converters have higher step-up factor (up to 3 with an acceptable level of MOSFET conduction losses), which extends the operating range as compared to that of the IFBB converter [7].

By adopting modern control algorithms and semiconductor devices, current fed topologies have all chances to become widespread in low voltage applications, especially those requiring continuous input current. The choice of a particular topology is determined by the specific application and the additional requirements to the converter.

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REFERENCES


Oleksandr Veligorskyi received the B.Sc. and M.Sc. degrees in electronic systems from Chernihiv State University of Technology, Chernihiv, Ukraine, in 2001 and 2002, respectively. He received doctoral degree in semiconductor power converters from National Academy of Sciences, Institute of Electro dynamics, Kiev, Ukraine in 2007. He is currently Head of Biomedical Radioelectronic Apparatus and Systems Department, Chernihiv National University of Technology. He has authored more than 20 published papers on power converters and is the holder of several Utility Models. His research interests include semiconductor power converters, photovoltaic, biomedical electronics.
Postal address: Chernihiv National University of Technology, Biomedical Radioelectronic Apparatus and Systems Department, Address: Shevchenko Str., 95, 14027, Chernihiv, Ukraine, oleksandr.veligorskyi@mst.stu.cn.ua

Roman Kosenko received Dipl.-Eng and M.Sc. in Electronics from the Department of Industrial Electronics, Chernihiv State University of Technology, Chernihiv, Ukraine, in 2011 and 2013, respectively. He is currently working toward the Ph.D. degree at the Department of Electrical Engineering of Tallinn University of Technology and at the Biomedical Radioelectronic Apparatus and Systems Department of Chernihiv National University of Technology. His fields of interest include research, design and simulation of switch mode converters for distributed power generation systems. He is the holder of one Utility Model.
Postal address: Department of Electrical Engineering, Tallinn University of Technology, Ehitajate tee 5, 19086 Tallinn, Estonia, mr.roman.kosenko@ieee.org

Liisa Liivik received Dipl.-Eng, M.Sc. in Electrical Engineering degrees from the Department of Electrical Drives and Power Electronics, Tallinn University of Technology, Tallinn, Estonia, in 1998 and 2000, respectively. She is currently working toward her Ph.D. degree at the Department of Electrical Engineering.
From 2002 to 2007, she was a lecturer in the Department of Electrical Drives and Power Electronics, Tallinn University of Technology. Her teaching areas included basics of measurement engineering and numerical calculations in electrical engineering. Her fields of interest are: research, design and simulation of switch mode converters for distributed power generation systems.
She received an award (2nd place) for her master thesis “Numerical Calculations of Electrotechnics” from Estonian Academy of Sciences and is author or co-author of more than 15 scientific papers and 1 book.
Postal address: Department of Electrical Engineering, Tallinn University of Technology, Ehitajate tee 5, 19086 Tallinn, Estonia, liisa.liivik@gmail.com

Andrii Chub received the B.Sc. degree in Electronics and M.Sc. degree in Electronic Systems from Chernihiv State University of Technology, Chernihiv, Ukraine, in 2008 and 2009 respectively. He is currently pursuing the Ph.D. degree in the Power Electronics Research Group, Tallinn University of Technology. He is employed as a Junior Researcher at the Department of Electrical Engineering, Tallinn University of Technology. He has co-authored more than 15 papers on power electronics and applications. His research interests include dc-dc converters, dc-ac inverters, impedance source electric energy conversion technology, implementation of the new wide bandgap semiconductors in power converters, and control of the renewable energy conversion systems.
Postal address: Department of Electrical Engineering, Tallinn University of Technology, Ehitajate tee 5, 19086 Tallinn, Estonia, andrii.chub@ieee.org