Design Guidelines of New Step-up DC/DC Converter for Fuel Cell Powered Distributed Generation Systems

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Abstract
This paper presents a new step-up DC/DC converter topology to be used for distributed energy systems. The topology contains a voltage-fed quasi-Z-source inverter with continuous input current, a high-frequency step-up isolation transformer and a voltage doubler rectifier. Main operating modes of the converter are explained and steady state analysis of the voltage-fed quasi-Z-source inverter is provided. Guidelines for selection of the converter’s components are discussed and design generalizations are provided in the final part of the paper.

Keywords
DC-DC power conversion, qZSI, voltage doubler rectifier, fuel cells, photovoltaic, PWM converters

Introduction
When distributed power generation is fully implemented, it can provide reliable, high quality and low cost electric power. Due to the costs of expansion of the electric grid and losses in the power lines, the shorter the way from the place of power generation to the consumer the cheaper are costs of electrical energy. There are several advantages when distributed power generation has a bi-directional connection with the power network: enhancement of power network capacity, uninterrupted power supply and optimal economic effect between suppliers and consumers [1].

The concept of distributed power comprises a wide spectrum of schemes that are used for local power generation from renewable and non-renewable energy sources in order to be environment friendly. Most often such schemes are based on fuel cells, solar energy, wind energy and micro turbines.

In terms of distributed power generation, the most promising and potentially most effective distributed power source is the fuel cell (FC). The efficiency of conversion based on the ratio of electrical output and the heat content of the fuel cell could be as high as 65-70% [1]. In theory electrical efficiency could be higher than 70%. Current technologies have only become capable of reaching efficiency around 45%. Combined cycles are intended to raise electrical efficiency up to 60% for plants based on high temperature cells [2].

Fig. 1 shows a typical variation of the output voltage of a fuel cell stack (NedStack P8.0-64 8 kW PEM fuel cell stack) in response to changes in the load current. Since the DC voltage generated by a fuel cell stack varies widely and is low in magnitude (<50 V for a 5 to 10 kW system, <350 V for a 300 kW system), a step-up DC/DC converter is essential to generate a regulated higher voltage DC (600 V typical for 3x400 AC output). The DC/DC converter is responsible for drawing power from the fuel cell, and therefore should be designed to match fuel cell ripple current specifications. Further, the DC/DC converter should not introduce any negative current into the fuel cell. Nowadays there are different DC/DC isolated converters that can be used for voltage stepping-up. They are, for example, highly efficient DSP-driven inverter based on a novel symmetrical flux forward converter with power up to 3kW [3], isolated DC/DC converters with zero-voltage turn-on switching (ZVS) of power switches and zero-current turn-off switching (ZCS) of diodes with power 270 W [4], step-up push-pull type isolated LLC series resonant DC/DC converters with power 600 W [5], isolated interleaved boost and buck converters with winding-cross-coupled inductors with power up to 650 W [6], high frequency transformer linked full-bridge type soft-switching phase-shift PWM control DC/DC power converters with power 1 kW [7], three-phase step-up DC/DC converters with a three-phase high frequency isolation transformer with power up to 6.8 kW [8, 9], isolated DC/DC power converter, which includes a stable and efficient zero voltage soft switching (ZVS) full bridge inverter in the high frequency planer transformer primary-side and a zero current soft switching rectifier in its secondary side with installed power of 2 kW [10].

Fig. 1. Operating waveforms of the fuel cell stack NedStack P8.0-64
1. New step-up DC/DC converter topology

This paper proposes a brand new step-up DC/DC converter topology for the distributed power generation systems with fuel cells with power ratings of 1...30 kW. The converter consists of a voltage-fed quasi-Z-source inverter (qZSI), a step-up isolation transformer and a voltage-doubler rectifier (Fig. 2).

The qZSI is derived from a traditional Z-source inverter (ZSI) [11] and has two distinctive advantages as compared to ZSI, such as continuous DC current drawn from the source and lower operating voltage of the capacitor C2 [12]. Practically, qZSI is a traditional PWM inverter coupled with a special quasi-Z-source network (qZS-network). As seen from Fig. 2, the qZS-network consists of two capacitors C1 and C2, two inductors L1 and L2 and a diode D1. The operation principle of the qZSI will be analyzed in detail in the next sections of the paper.

The high-frequency step-up isolation transformer provides the required voltage gain as well as the galvanic isolation of the input and output sides of the converter. Transformer’s primary winding is connected to the output terminals of qZSI, while the secondary side is connected to the voltage doubler rectifier (VDR). The VDR is derived from the full-bridge rectifier (B4U) by the replacement of diodes in one leg by the capacitors (C3 and C4) with equal capacity [13]. The resulting advantages of the VDR over the traditional B4U scheme are the doubling effect of the secondary winding voltage of the isolation transformer and reduced power dissipation due to smaller number of rectifying diodes and full elimination of the smoothing inductor. Moreover, the dynamic performance and stability of VDR could be increased.

2. Operating modes of the proposed converter

The central idea implemented in the proposed converter is to keep the DC-link voltage \(U_{DC}\) constant despite the variation of voltage of the fuel cell. By keeping the DC-link voltage constant the PWM inverter could be operated with a fixed duty cycle value, thus ensuring constant volt-second and flux swing of the isolation transformer.

The desired DC-link voltage level should be selected in accordance with the polarization curve of the FC implemented. The Fig. 1 shows that the idle (open cell) voltage of the studied FC stack is 64 V, but the voltage at maximum power drops to 32 V. The value for the DC-link voltage could be selected from the activation polarization region of the FC stack. Generally, it must correspond to the light-load operating voltage of the FC stack (e.g., point A in Fig. 1). In accordance with the input voltage (fuel cell voltage) the operating modes of the proposed DC/DC converter could be broadly categorized as non-shoot-through and shoot-through operating modes (Fig. 3).

2.1. Non-shoot-through operating mode

If the FC voltage is equal or higher than the desired DC-link voltage \(U_{DC}\) point A in Fig. 1), the converter starts to operate in the non-shoot-through mode. In this mode the qZSI operates as a traditional VSI performing only the buck function of the input voltage. The operating period of the qZSI in the non-shoot-through mode consists of the combination of active and zero states. During active (energy transfer) states the power switches of the inverter bridge are gated alternately in pairs (T1, T4 and T2, T3) and power is transferred from the DC-link to the isolation transformer (Fig. 4). During zero states the primary winding of the isolation transformer is shorted either through the upper switches (T1, T3) or the bottom switches (T2, T4) of the inverter bridge (Fig. 5) and the transformer sees no voltage from the inverter.

![Fig. 2. Simplified power circuit diagram of the proposed converter](image-url)
The operating period of the PWM inverter during the non-shoot-through mode consists of an active state $t_a$ and a zero state $t_z$:

$$T = t_a + t_z.$$  \hspace{1cm} (1)

Eq. (1) could also be represented as

$$\frac{t_a}{T} + \frac{t_z}{T} = D_a + D_z = 1,$$  \hspace{1cm} (2)

where $D_a$ and $D_z$ are the duty cycles of an active and zero states, correspondingly.

### 2.2. Shoot-through operating mode

If the FC voltage drops below the predefined DC-link voltage level ($U_{dc}$ point A in Fig. 1), the converter begins to operate in the shoot-through mode. The varying output voltage of the fuel cell is first preregulated to a desired DC-link voltage level by adjusting the shoot-through duty cycle. Afterwards the isolation transformer is being supplied from the inverter with a voltage of constant amplitude, as described in the previous section.

To boost the input voltage during the shoot-through operating mode the special switching state – shoot-through state - is implemented in the PWM inverter control. During the shoot-through states the primary winding of the isolation transformer is shorted through both the upper and lower switches of any one phase leg (i.e., both devices are gated on) or all two phase legs (Fig. 7). This shoot-through state (or vector) is forbidden in the traditional VSIs, because it would cause a short circuit of DC capacitors and destruction of power switches. The unique two-port network – the qZS-network (see Fig. 2) – makes the shoot-through states possible, effectively protecting the circuit from damage. Moreover, the shoot-through states are used to boost the magnetic energy stored in the DC side inductors L1 and L2 without short-circuiting the DC capacitors C1 and C2. This increase in the inductive energy in turn provides the boost of voltage seen on the inverter output during the active states of the inverter.

### Table 1. PWM switching states sequence of the qZSI during the non-shoot-through operating mode

<table>
<thead>
<tr>
<th>State</th>
<th>T1</th>
<th>T2</th>
<th>T3</th>
<th>T4</th>
</tr>
</thead>
<tbody>
<tr>
<td>zero state</td>
<td>1</td>
<td>0</td>
<td>1</td>
<td>0</td>
</tr>
<tr>
<td>active state 1</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td>zero state</td>
<td>1</td>
<td>0</td>
<td>1</td>
<td>0</td>
</tr>
<tr>
<td>active state 2</td>
<td>0</td>
<td>1</td>
<td>1</td>
<td>0</td>
</tr>
</tbody>
</table>
through PWM control method, to reduce the current stress of the switches, the shoot-through states are created by simultaneous turning on of all inverter switches (Fig. 7). The shoot-through time is evenly split into two intervals of half the duration. During the shoot-through states the voltage across inverter bridge drops to zero.

\[ T = t_1 + t_2 + t_3. \]  

Eq. (3) could also be represented as

\[ \frac{t_1}{T} + \frac{t_2}{T} + \frac{t_3}{T} = D_1 + D_2 + D_3 = 1, \]  

where \( D_1, D_2, D_3 \) are the duty cycles of the active zero and the shoot-through state, correspondingly.

2.3 Operation of voltage-doubler rectifier

To reduce the turns ratio of the isolation transformer the voltage doubler rectifier (VDR) was implemented on the secondary side of the converter. In contrast to the traditional full-bridge rectifier, two diodes of one leg in the VDR topology are replaced by the capacitors. The operation principle of the VDR is explained in Figs. 9 and 10.

Fig. 8. Operation principle of the qZSI in the shoot-through mode

The PWM switching states sequence presented in Table 2 shows that the upper and lower switches operate with different switching frequencies. The switching frequency of the upper switches (T1 and T3) in the shoot-through mode is equal to the fundamental frequency of the isolation transformer, while the switching frequency of the lower switches (T2 and T4) is three times higher than that of T1 and T3.

<table>
<thead>
<tr>
<th>State</th>
<th>T1</th>
<th>T2</th>
<th>T3</th>
<th>T4</th>
</tr>
</thead>
<tbody>
<tr>
<td>zero state</td>
<td>1</td>
<td>0</td>
<td>1</td>
<td>0</td>
</tr>
<tr>
<td>shoot-through</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>zero state</td>
<td>1</td>
<td>0</td>
<td>1</td>
<td>0</td>
</tr>
<tr>
<td>active state 1</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td>zero state</td>
<td>1</td>
<td>0</td>
<td>1</td>
<td>0</td>
</tr>
<tr>
<td>shoot-through</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>zero state</td>
<td>1</td>
<td>0</td>
<td>1</td>
<td>0</td>
</tr>
<tr>
<td>active state 2</td>
<td>0</td>
<td>1</td>
<td>1</td>
<td>0</td>
</tr>
</tbody>
</table>

Fig. 9. Operation principle of VDR

Fig. 10. General waveforms of VDR
During the positive half cycle, the capacitor C3 is charged through the diode D2 to the peak secondary voltage of the isolation transformer (Fig. 9a). During the negative half cycle the capacitor C4 is charged through diode D3 (Fig. 9b). At every time instant the output voltage \( U_{OUT} \) from this circuit will be the sum of the two capacitor voltages (Fig. 10), or twice the peak voltage \( U_{TR,sec} \) of the secondary winding of the isolation transformer:

\[
U_{OUT} = 2U_{TR,sec}.
\]  

(5)

### 2. Operating principle of the qZSI during the shoot-through mode

As shown in Fig. 1, the voltage-fed qZSI with continuous input current is built in the converter input side and it has a unique property: it can boost the input voltage utilizing a special switching state - the shoot-through state (Fig. 7). The shoot-through state is a time interval when both switches of both inverter legs are conducting.

In the shoot-through operation mode there are two general power conversion states: shoot-through (voltage boost in primary side) and active (power transfer to secondary side) state. The equivalent schemes of the qZSI during the shoot-through and active state are presented in Fig. 11 [14]. All the polarities, voltages and currents are defined with arrows and polarity signs.

From Fig. 11a, which represents the shoot-through state of the qZSI with duration \( T_s \), we can obtain

\[
u_{l1} = U_{C2} + U_{in}, \quad u_{l2} = U_{C1}, \quad u_{dc} = 0.
\]  

(6)

\[
u_{dc} = U_{C1} + U_{C2}, \quad u_{di} = 0.
\]  

(7)

From Fig. 11b, which represents the active state of the qZSI with the duration of \((T-T_s)\), we can obtain

\[
u_{l1} = U_{in}, \quad u_{l2} = U_{C1} - U_{C2}, \quad u_{dc} = 0.
\]  

(8)

(9)

At the steady state the average voltage of the inductor over one switching period is zero. Thus, from Eqs. (6) and (8) we can obtain

\[
\begin{align*}
U_{C1} &= \frac{1}{T} \int_{0}^{T} u_{l1} dt = \frac{t_s}{T} (U_{C2} + U_{in}) + (T - t_s) \cdot (U_{in} - U_{C1}) = 0, \\
U_{C2} &= \frac{1}{T} \int_{0}^{T} u_{l2} dt = \frac{t_s}{T} (U_{C1}) + (T - t_s) \cdot (-U_{C2}) = 0.
\end{align*}
\]

Accordingly,

\[
U_{C1} = \frac{t_s}{1 - 2 \cdot \frac{t_s}{T}}, \quad U_{C2} = \frac{t_s}{T - 1 - 2 \cdot \frac{t_s}{T}} \cdot U_{in}.
\]  

(10)

The peak DC-link voltage across the inverter bridge is

\[
u_{dc,peak} = U_{C1} + U_{C2} = \frac{1}{1 - 2 \cdot \frac{t_s}{T}} \cdot U_{in} = B \cdot U_{in}.
\]  

(11)

where \( B \) is the boost factor of the qZSI:

\[
B = \frac{1}{1 - 2 \cdot \frac{t_s}{T}}.
\]  

(12)

Using the system power rating \( P \) we can obtain the average current of inductors \( L1 \) and \( L2 \):

\[
I_{L1,av} = I_{L2,av} = I_{in,av} = \frac{P}{U_{in}}.
\]  

(13)

where \( U_{in} \) is the input voltage of the converter. To obtain the necessary currents of the qZSI we can use Kirchhoff’s current law and Eq. (12):

\[
I_{C1,av} = I_{C2,av} = I_{dc,av} - I_{L1,av},
\]  

(14)

\[
I_{di,av} = 2I_{C1,av} - I_{pc,av}.
\]  

(15)

The operating voltages and average currents of the qZSI during active and shoot-through states are shown in Table 3. For the better appearance the shoot-through time interval \( t_s \) was replaced with the shoot-through duty cycle \( D_s = t_s/T \).
Table 3. Operating voltages and average currents of the qZSI

<table>
<thead>
<tr>
<th>State</th>
<th>Active</th>
<th>Shoot-through</th>
</tr>
</thead>
<tbody>
<tr>
<td>Inductor voltage (u_{L1}=u_{L2})</td>
<td>\frac{D_S}{1-2-D_S} \cdot U_{IN}</td>
<td>\frac{1-D_S}{1-2-D_S} \cdot U_{IN}</td>
</tr>
<tr>
<td>DC-link voltage (U_{DC})</td>
<td>\frac{1}{1-2-D_S} \cdot U_{IN}</td>
<td>0</td>
</tr>
<tr>
<td>DC-link current (I_{DC})</td>
<td>\frac{P \cdot (1-2-D_S)}{U_{IN} \cdot 2}</td>
<td>\frac{2 \cdot P}{U_{IN} \cdot D_S}</td>
</tr>
<tr>
<td>Diode D1 voltage (u_{D1})</td>
<td>0</td>
<td>\frac{1}{1-2-D_S} \cdot U_{IN}</td>
</tr>
<tr>
<td>Capacitor C1 voltage (U_{C1})</td>
<td>\frac{1-D_S}{1-2-D_S} \cdot U_{IN}</td>
<td></td>
</tr>
<tr>
<td>Capacitor C2 voltage (U_{C2})</td>
<td>\frac{D_S}{1-2-D_S} \cdot U_{IN}</td>
<td></td>
</tr>
<tr>
<td>Input current (I_{IN,av})</td>
<td>\frac{P}{U_{IN}}</td>
<td></td>
</tr>
<tr>
<td>Inductor current (I_{L,av} = I_{L2,av})</td>
<td>\frac{P}{U_{IN}}</td>
<td></td>
</tr>
<tr>
<td>Capacitor current (I_{C1,av} = I_{C2,av})</td>
<td>I_{DC,av} \cdot I_{L,av}</td>
<td></td>
</tr>
<tr>
<td>Diode current (I_{D1,av})</td>
<td>2 \cdot I_{L,av} \cdot I_{DC,av}</td>
<td></td>
</tr>
</tbody>
</table>

3. Design issues of the proposed converter

3.1 qZS – network

The qZS-network consists of two inductors, two capacitors and one diode, which should be properly dimensioned to ensure the correct operation of the network during shoot-through states. As seen from Fig. 8, the shoot-through time is evenly split into two intervals of half the duration and the operating frequency of the qZS-network is twice the fundamental frequency of the isolation transformer.

- **Dimensioning of capacitors**
  The main purpose of capacitors C1 and C2 is to absorb the current ripple and limit the voltage ripple across the inverter bridge. The voltage ripple across the capacitor can be roughly calculated by

\[ \Delta U_C = \frac{I_{L,av} \cdot \Delta t}{C}, \]

where \( I_{L,av} \) is the average current through the inductor, \( C \) is the capacitance and \( \Delta t \) is the time interval of the shoot-through state. In the proposed shoot-through PWM control method the shoot-through time is evenly split into two intervals of half the duration. During active states both capacitors of the qZS-network are in series (Fig. 11b). Assuming that the capacitance should be the same for each capacitor, the capacitance needed to limit the peak to peak DC-link voltage ripple by \( r_{V,DC} \) could be calculated as

\[ C = \frac{2 \cdot P \cdot D_S}{U_{IN} \cdot U_C \cdot f \cdot r_{V,DC}} \cdot \frac{1}{2}, \]

where \( P \) is the power rating of the converter, \( U_{IN} \) is the input voltage, \( U_C \) is the capacitor’s voltage, \( D_S \) is the duty cycle of shoot-through states, \( f \) is the operation frequency of the qZSI and \( r_{V,DC} \) is the desired peak to peak voltage ripple across the DC-link (\( U_{pp}/U_{IN} \)).

- **Dimensioning of inductors**
  The inductor in the qZSI network will limit the current ripple through the switches during the shoot-through states. Choosing an acceptable peak to peak current ripple \( r_C \), the inductance can be calculated by

\[ L = \frac{U_{C1} \cdot D_S \cdot U_{IN} \cdot \frac{1}{2}}{P \cdot f \cdot r_C}, \]

where \( P \) is the power rating of the converter, \( U_{IN} \) is the input voltage, \( U_{C1} \) is the capacitor’s C1 voltage, \( D_S \) is the duty cycle of shoot-through states, \( f \) is the operation frequency of the qZSI and \( r_C \) is the desired peak to peak current ripple through the inductor (\( I_{pp}/I_{av} \)).

To minimize the size and weight of the inductors, the two inductors could be built together on one core, thus forming the coupled inductor [15] (Fig. 12). For a single coil on one core, the flux through core is

\[ \phi = E \cdot N \cdot i_C, \]

where \( E \) is a constant related to the core material and dimensions, \( N \) is the number of turns of the coil and \( i_C \) is the current through the coil.

![Coupled inductor](image)

**Fig. 12. Coupled inductor**

The inductance of the coil is

\[ L = \frac{N \cdot \phi}{i_C} = E \cdot N^2, \]

In the voltage-fed qZSI the currents through inductors L1 and L2 are always exactly the same in terms of waveform and magnitude. For two coils on one core with exactly the same current, \( i \), the flux through the core is

\[ \phi = 2 \cdot E \cdot N \cdot i_C. \]

The resulting inductance of each winding when supplying exactly the same current to the two windings is

\[ L = \frac{N \cdot \phi}{i_C} = 2 \cdot E \cdot N^2. \]
It is seen from Eq. (22) that the inductance of each winding is doubled. Therefore, for the same operating conditions we need to build two windings with twice smaller inductance than in the case of separate inductors.

- **Dimensioning of diode**
  The diode D1 should be chosen taking into account the maximal voltage $u_{D1,max}$ and average current $I_{D1,av}$ through it. During the shoot-through states the diode D1 is reverse-biased (Fig. 11a) and neglecting transients the maximal blocking voltage is

$$u_{D1,max} = B \cdot U_{IN} = U_{IN} \cdot \frac{1}{1 - 2 \cdot D_S}.$$  

(23)

Average diode current could be found from Table 3:

$$I_{D1,av} = 2 \cdot I_{L1,av} - I_{DC,av} = 2 \cdot P \cdot \frac{P}{U_{IN}} = \frac{P}{U_{IN}}.$$  

(24)

where $P$ is the power rating of the converter, $U_{IN}$ is the input voltage, $U_{DC}$ is the DC-link voltage, $D_S$ is the shoot-through duty cycle. Maximal diode current could be found as

$$I_{D1,max} = I_{L1,max} + I_{L2,max} \approx I_{DC,av}.$$  

(25)

During the diode selection special attention should be paid to the switching properties of it, i.e. the fast recovery diodes should be preferred to ensure proper recovery times. The forward voltage drop $U_{FVD}$ is another important issue, because the high values of $U_{FVD}$ could cause high conduction losses during active states, which, in turn, could seriously affect the efficiency of the converter.

### 3.2 PWM inverter

In the PWM inverter, each switching device has to be selected according to the maximum voltage applied and the peak and average current going through it. The maximal voltage (neglecting transients) that should be taken as a basis for choosing power switches should be found as a multiplication of the input voltage $U_{IN}$ and the boost factor $B$:

$$u_{DC,max} = B \cdot U_{IN} = U_{IN} \cdot \frac{1}{1 - 2 \cdot D_S}.$$  

(26)

The current through the inverter switches consists of two elements, the current to the isolation transformer during active states $I_{SW,av}$ and the current through them when the circuit is in the shoot-through state $I_{SW,sh}$ (Fig. 13):

$$I_{SW,av} = I_{SW,av} + I_{SW,sh}.$$  

(27)

The current during shoot-through states in terms of average is evenly distributed between both inverter arms, as shown in Fig. 7. The average current value in the shoot-through period through each switch is

$$I_{SW,av} = I_{Lav} \cdot \frac{D_S}{2} = \frac{P \cdot D_S}{U_{IN}}.$$  

(28)

where $I_{Lav}$ is the average current through the inductors, $D_S$ is the shoot-through duty cycle, $U_{IN}$ is the input voltage of the converter and $P$ is the power rating of the inverter.

![Fig. 13. Operating current waveform of the inverter switch during one switching period](image)

While in active states the average current is the same as in a conventional PWM inverter:

$$I_{SW,av} = \frac{P}{2} \cdot \frac{U_{DC}}{U_{IN}}.$$  

(29)

where $I_{DC,av}$ is the average DC-link current, $U_{DC}$ is the DC-link voltage and $P$ is the power rating of the converter.

The overall average current through inverter switches is

$$I_{SW,av} = \frac{P}{2} \cdot \frac{D_S}{U_{IN}} = \frac{P}{2} \cdot \frac{U_{DC}}{U_{IN}}.$$  

(30)

The peak current through the switches occurs during shoot-through states:

$$I_{SW,sh} = I_{Lav} \cdot \left(1 + \frac{r_c}{2}\right) = P \cdot \frac{U_{IN}}{U_{IN}} \cdot \left(1 + \frac{r_c}{2}\right).$$  

(31)

where $I_{Lav}$ is the average current through the inductors and $r_c$ is the peak to peak current ripple through the inductors during maximum power operation ($I_{PEAK}/I_{IN})$.

### 3.3 Isolation transformer

The turns ratio $n$ of an isolation transformer is defined as a relation of primary and secondary winding voltages:

$$n = \frac{U_{TR,pr}}{U_{TR,sec}} = \frac{U_{DC}}{U_{OUT} / 2}.$$  

(32)

where $U_{TR,pr}$ is the primary winding voltage, $U_{TR,sec}$ is the secondary winding voltage, $U_{DC}$ is the DC-link voltage and $U_{OUT}$ is the average output voltage of the converter. Replacing the $U_{DC}$ value by that from Table 1 we can obtain:

$$n = \frac{U_{IN} \cdot B \cdot 2}{U_{OUT}} = \frac{2 \cdot U_{IN}}{(1 - 2 \cdot D_S) \cdot U_{OUT}},$$  

(33)

where $D_S$ is the shoot-through duty-cycle and $U_{IN}$ is the input voltage of the converter.
Taking into consideration Eq. (33), we can express the output voltage of the proposed converter for every operating point within the shoot-through operating mode:

\[ U_{OUT} = \frac{2 \cdot U_N}{(1 - 2 \cdot D_a) \cdot n} \]  \hspace{1cm} (34)

### 3.4 Voltage doubler rectifier

To provide correct operation of the VDR and ensure the voltage doubling effect the capacitors C3 and C4 (Fig. 2) should be properly dimensioned. To limit the peak to peak voltage ripple on these capacitors by \( r_{V,OUT} \), the capacitance should be

\[ C = \frac{P \cdot (1 - D_a)}{(U_{OUT})^2 \cdot f \cdot r_{V,OUT}} \]  \hspace{1cm} (35)

where \( P \) is the power rating of the converter, \( U_{OUT} \) is the output voltage, \( D_a \) is the duty cycle of active state, \( f \) is the operation frequency of the qZSI and \( r_{V,OUT} \) is the desired peak to peak voltage ripple in the output of the VDR (\( U_{p-p,OUT} \)).

When reverse-biased, the diodes D2 and D3 should block voltage twice the amplitude voltage of the secondary winding of the isolation transformer (neglecting transients):

\[ U_{D2,\text{max}} = U_{D3,\text{max}} = 2 \cdot U_{R,\text{max}} = U_{OUT} \]  \hspace{1cm} (36)

The peak current of the diodes is typically limited by the system parameters such as transformer leakage inductance, equivalent series resistance (ESR) of capacitors, active resistance of wires, etc. and cannot be directly calculated. However, the average current of diodes is equal to the output average current and could be found as:

\[ I_{D2,av} = I_{D3,av} = \frac{P}{U_{OUT}} \]  \hspace{1cm} (37)

As in the case of input diode D1, for ensuring higher efficiency of the converter the diodes for the VDR should be selected with special attention to the recovery times and forward voltage drop values.

### Conclusions

This paper presents a brand new step-up DC/DC converter topology for distributed power generation. The converter consists of a voltage-fed quasi-Z-source inverter with continuous input current, a high-frequency step-up isolation transformer and a voltage doubler rectifier. The converter is intended for applications with widely changing input voltage, e.g. fuel cells or photovoltaic.

The paper provides a detailed description of the proposed topology with an analysis of operation modes. The converter design issues are discussed. The most important generalizations for proper design of the proposed converter could be listed as follows:

- the converter performs the voltage step-up function and in some applications the input voltage could be gained more than ten times. It means that very high currents could circulate in the qZS-network and the PWM inverter. To minimize the undesired power dissipation special attention should be paid to component interconnections, especially to sizing of the wire cross-section. Implementation of laminated copper busbars is highly recommended.
- The diodes should be selected in accordance with the operating frequencies: twice and the same as the fundamental frequency of the isolation transformer for the qZS-network and VDR diodes, respectively. The Power Schottky diodes could be recommended for the D1 and fast recovery epitaxial diodes for D2 and D3 for the converter with the input voltage up to 200 V and output voltage up to 1.8 kV.
- Special attention should be paid to operating voltages and currents of the diodes. In the current paper the operating voltages and currents for diodes are shown for an ideal case. In real practice due to stray inductances and capacitances very high voltage overshoots and parasitic ringings can occur. Finally, it could destroy the diode or cause the undesired power dissipation and EMI. To cope with those problems the snubber circuits should be implemented.
- Power switches with high operation frequency and low voltage drop should be selected in order to reduce the losses of PWM inverter.
- A specific problem of the qZSI is the voltage overshoots across the inverter bridge caused by the stray inductance of the inverter supply circuit. To minimize the overshoots the multilayer copper busbars should be implemented. Furthermore, the DC-rail clamp circuits [15-17] should be used for the protection of power switches.
- Caused by transient processes the high voltage spikes could occur on the capacitors of the qZS-network. To increase the reliability and operation flexibility the polymer film capacitors could be recommended.
- To increase the power throughput the converter the single-phase auxiliary AC-link (PWM inverter-transformer-rectifier) could be replaced by the multiphase structure [18-19].
- To increase the power density of converter coupled inductors are highly recommended.
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References