Isolated DC/DC Converters based on Quasi-Z-Source for Distributed Power Generation

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Abstract- **This paper presents a novel step-up dc/dc converter structure projected towards distributed power generation systems. The suggested topologies includes voltage fed quasi Z-source inverter having continuous input current on the primary side, a single-phase isolation transformer, and a Voltage Doubler Rectifier (VDR). To improve the power density of the converter, a three-phase auxiliary ac link (a three-phase inverter and a three-phase isolation transformer) and a three-phase VDR are required to be employed. This paper elaborates the principle of operation for the proposed topologies and analyzes the theoretical results.**

Index Terms- **DC/DC step up conversion, Z-Source invertersand pulse width-modulated power converters.**

I. INTRODUCTION

Distributed power generation can serve reliable, high-quality, and low-cost electric power. As a modular electric power generation close to the end user, it offers savings in the cost of grid expansion and line losses. If connected to the power grid, the bidirectional transactions between the grid and the local generation result in grid capacity enhancement, virtually uninterrupted power supply, and optimum energy cost due to the availability of use/purchase/sales options [1].

To interconnect a low-dc-voltage-producing FC (typically 40–80 Vdc) to residential loads (typically 230-Vac single phase or 3 × 400 Vac), a special voltage matching converter is required. A typical structure of a two-stage interface converter is shown in Fig. 1. Due to safety and dynamic performance requirements, the interface converter should be realized within the dc/dc/ac concept. This means that low voltage from the FC first passes through the front-end step-up dc/dc converter with the galvanic isolation; subsequently, the output dc voltage is inverted in the three-phase inverter and filtered to comply with the imposed standards and requirements (second dc/ac stage).

The design of the front-end isolated dc/dc converter is most challenging because this stage is the main contributor of interface converter efficiency, weight, and overall dimensions. The low voltage provided by the FC is always associated with high currents in the primary part of the dc/dc converter (switching transistors and primary winding of the isolation transformer). These high currents lead to high conduction and switching losses in the semiconductors and therefore reduce the efficiency. Moreover, the large voltage boost factor requirement presents a unique challenge to the dc/dc converter design [2]. This specific requirement could be fulfilled in different ways: by use of an auxiliary boost converter before the isolated dc/dc converter [3]–[7] or by use of an isolation transformer with a large turns ratio [8]–[14] for effective voltage step-up.

In the first case [Fig. 2(a)], the auxiliary boost converter steps up the varying FC voltage to a certain constant voltage level (80–100 Vdc) and supplies the input terminals of the isolated dc/dc converter. In that case, the primary inverter within the dc/dc converter operates with a near-constant duty cycle, thus ensuring better utilization of an isolation transformer. More-over, due to pre-boosted input voltage, the isolation transformer has the moderate turns ratio (1:7–1:8), which exerts a positive impact in terms of leakage inductance and efficiency. A very interesting solution is proposed in [5], where the conventional inductor in an auxiliary boost converter is replaced with a zero-ripple filter (ZRF). The ZRF comprises a coupled inductor-based filter for minimizing the high-frequency switching ripple and an active power filter for mitigating the low-frequency ripple. Despite evident advantages of the isolated dc/dc con-verter with an auxiliary boost converter, its main drawbacks are drawn from the multistage energy conversion structure, i.e., complicated control and protection algorithms and reduced reliability due to the increased number of switching devices.

A direct step-up dc/dc converter without input voltage pre-regulation [Fig. 2(b)] is simpler in control and protection. Due to the reduced number of switching devices, the converter tends to have better efficiency and reliability. The varying voltage from the FC passes through the high-frequency inverter to the step-up isolation transformer. The magnitude of the primary winding voltage is controlled by the duty cycle variation of inverter switches in accordance with the FC output voltage and converter load conditions.

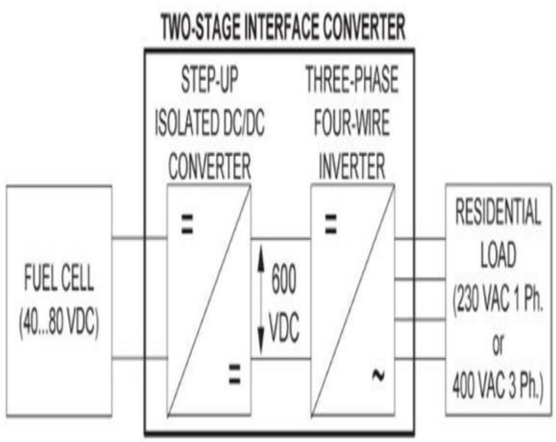

Figure 1.Typical structure of the interface converter for residential FC-powered systems

The isolation transformer should have an increased turns ratio (approximately 1 : 17) to provide effective voltage step-up in the whole range of input voltage and load variations. The choice of dc/dc converter topology in that case can be broadly categorized as a push–pull or a single-phase full-bridge topology. Because of the symmetrical transformer flux and minimized stress of primary inverter switches, the full-bridge topology has been found to be most useful in terms of cost and efficiency, particularly when implemented for power levels higher than 3 kW [8].

This paper is devoted to a new power circuit topology to be implemented in the front-end dc/dc converter for distributed power generation. The topology proposed (Fig. 3) contains a voltage-fed quasi-Z-source inverter (qZSI) with continuous input current at the converter input side, a high-frequency step-up isolation transformer, and a voltage doubler rectifier (VDR). In contrast to earlier presented topologies [3]–[14], the novel converter provides such advantages as increased reliability, isolation transformer with reduced turns ratio, and reduced impact on the FC due to continuous input current. To improve the power density of the converter, the topology with a three-phase intermediate ac link is discussed in the final section of this paper.

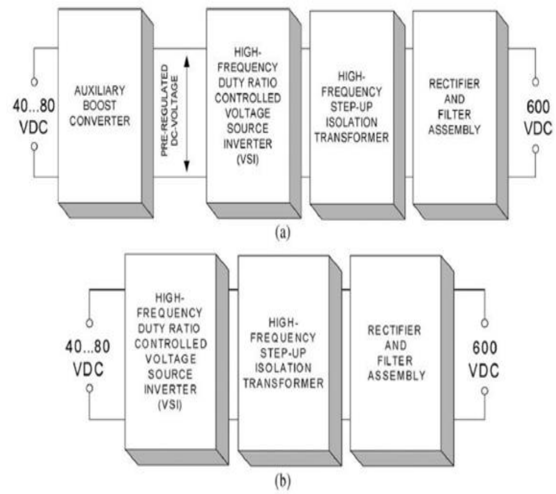

Figure 2. Generalized structures of most widespread front-end step-up isolated dc/dc converters for residential FC power systems

II.DESCRIPTION OF PROPOSED TOPOLOGY

The voltage-fed qZSI with continuous input current implemented at the converter input side (Fig. 3) has a unique feature:

It can boost the input voltage by utilizing extra switching state-the shoot-through state. The shoot-though state here is the simultaneous conduction of both switches of the same phase leg of the inverter. This operation state is forbidden for the traditional voltage source inverter (VSI) because it causes the short circuit of the dc-link capacitors. In the discussed qZSI, the shoot-through state is used to boost the magnetic energy stored in the dc-side inductors (L1 and L2 in Fig. 3) without short-circuiting the dc capacitors. This increase in inductive energy, in turn, provides the boost of voltage seen on the transformer primary winding during the traditional operating states (active states) of the inverter. Thus, the varying output voltage of the FC is first preregulated by adjusting the shoot-through duty cycle; afterward, the isolation transformer is being supplied with a voltage of constant amplitude value. Although the control principle of the qZSI is more complicated than that of a traditional VSI, it provides a potentially cheaper, more powerful, reliable, and efficient approach to be used for FC-powered systems.

The voltage-fed qZSI with continuous input current was first presented in [15] as a modification of a currently popular voltage-fed Z-source inverter (ZSI) [16]–[18]. The drawback associated with the conventional ZSI is substantial—discontinuous input current during the boost mode that could have a negative influence on the FC. The discussed qZSI shown in Fig. 3 features continuous current drawn from the FC as well as lower operating voltage of the capacitor C2, as compared to the ZSI topology. The operating dc voltages of the capacitors C1 and C2 could be estimated as

$$V_{C1} = \frac{1-D_S}{1-2D_S} V_i \quad (1)$$

$$V_{C2} = \frac{D_S}{1-2D_S} V_i \quad (2)$$

Where D_s is the duty cycle of the shoot through state

$$D_s = \frac{t_S}{T} \quad (3)$$

Where t_s is the duration of the shoot through state and T is the operation period.

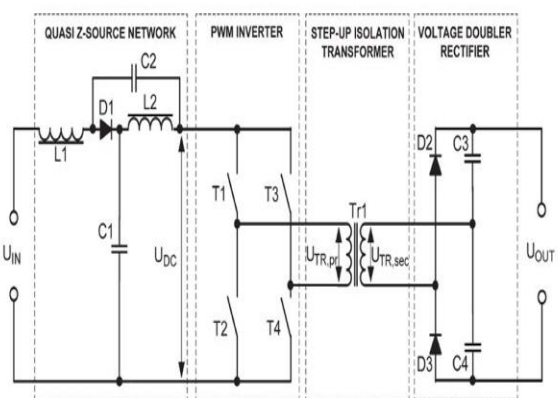

Figure 3. Simplified power circuit diagram of the proposed converter

When the input voltage is high enough, the shoot-through states are eliminated, and the qZSI starts to operate as a tradi-tional VSI, thus performing only the buck function of the input voltage. Thus, the qZSI could realize both the voltage boost and the buck functions without any additional switches using a special control algorithm only.

A. Voltage Boost Control Method of qZSI-Based Single-Phase DC/DC Converter –

Fig. 4 shows the control principle of the single-phase qZSI in the shoot-through (voltage boost) operating mode. Fig. 4(a) shows the switching pattern of the traditional single-phase VSI. These switching states are known as active states when one and only one switch in each phase leg conducts. To generate the shoot-through states, two reference signals (Vp and Vn) were introduced [Fig. 4(b)]. If the triangle waveform is greater than Vp or lower than Vn, the inverter switches turn into the shoot-through state [Fig. 4(b)]. During this operating mode, the current through the inverter switches reaches its maximum. Depending on the control algorithm, the shoot-through current could be distributed between one or both inverter legs. The dc-link voltage and the primary winding voltage waveforms of the isolation transformer during shoot-through are shown in Fig. 4(c) and (d), respectively.

According to the presented control methodology (Fig. 4), the shoot-through states are created during the zero states of the full-bridge inverter, where the primary winding of the isolation transformer is shorted through either the top (T 1 and T 3) orbottom (T 2 and T 4) inverter switches. To provide a sufficient regulation margin, the zero-state time tZ should always exceed the maximum duration of the shoot-through states tS,max per one switching period

$$t_Z > t_{S,max} \quad (4)$$

Thus, each operating period of the qZSI during the shoot-through always consists of an active state t_A, shoot-through state t_S , and zero state t_Z

$$T = t_A + t_s + t_Z \quad (5)$$

Equation (5) could also be represented as

$$\frac{t_A}{T} + \frac{t_S}{T} + \frac{t_Z}{T} = D_A + D_S + D_Z = 1 \quad (6)$$

whereDA is the duty cycle of an active state, DS is the duty cycle of a shoot-through state, and DZ is the duty cycle of a zero state. It should be noted that the duty cycle of the shoot-through state must never exceed 0.5. It should be noted here that, in the presented control scheme, the shoot-through time interval is evenly split into two intervals of half the duration. In that case, the operating frequency of the quasi-Z-source (qZS) network will be two times higher, and the resulting switching frequency of the power transistors will be up to three times higher [Fig. 8(a)] than the fundamental harmonic frequency of the isolation transformer. That fact is very relevant for proper component and operating frequency selection.

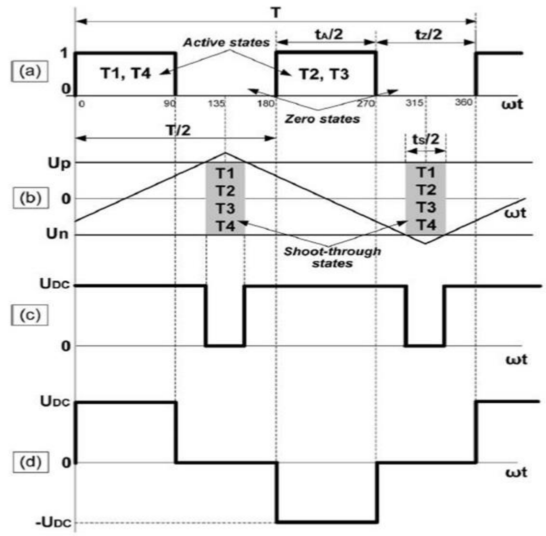

Figure 2. Proposed operating principle and resulting voltages of the single-phase qZSI in the shoot-through (voltage boost) mode

In the operating points, when the input voltage is high enough, the shoot-through states are eliminated, and the qZSI operates as a traditional VSI. Thus, the qZSI discussed could provide both the voltage boost and buck functions by the single-stage energy conversion.

B. Power Circuit Design Considerations –

This section provides an overview of the design process of the proposed dc/dc converter. In the given application, the desired value selected for the dc-link voltage UDC was 80 V. It is assumed that the converter is always operating with the rated load and between two boundary operating points, which correspond to the minimal VIN,min and maximal VIN,max input voltages. In the first case, the shoot-through states should be used to boost the input voltage to the predefined dc-link voltage level. In the second case, when the input voltage is equal to the desired dc-link voltage, no shoot-through is applied, and the qZSI operates as a traditio-nal VSI.

The design of the power converter should be performed for the operating point with a minimal possible input voltage and at rated power, when the shoot-through duty cycle reaches its maximum. As a consequence, the boost ratio of the input voltage is also maximal

$$B_{max} = \frac{V_{DC}}{V_{IN,min}} \quad (7)$$

To achieve proper efficiency of the converter and better transformer utilization, in real designs, proper balance between the boost ratio and the transformer turns ratio should be found.In the current application, the maximal duty cycle of the shoot-through state is

$$D_{S,max} = \frac{1-(B_{max})^{-1}}{2} \quad (8)$$

During the active states, the transformer primary winding is being supplied from the inverter by a voltage with an amplitude value VTR,pr = VDC = 80 V. To reduce the turns ratio n of the isolation transformer, a 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. Since each capacitor charges to the peak secondary voltage VTR,sec, the output voltage from this circuit will be the sum of the two capacitor voltages or twice the peak voltage of the secondary winding. This circuit then produces an output voltage that is twice the transformer secondary voltage. Due to the voltage doubling effect, the VDR enables the use of the isolation transformer with a reduced secondary turns ratio, i.e., 1 : 3.75 for the application discussed. Furthermore, the VDR improves the rectification efficiency due to minimized voltage drops in the components (twice reduced number of rectifying diodes and full elimination of a smoothing inductor).

For every operating point within the predefined boundaries [VIN,min; VIN,max], the output voltage of the converter could be estimated as

$$V_{OUT} = \frac{2\, V_{IN}\, B}{n} \quad (9)$$

where$n$ is the turns ratio of the isolation transformer. To limit the voltage ripple on the output half-bridge capacitors ($C3$ and $C4$), e.g., by 1% (6 V) at peak power P, the capacitance should be

$$C_3 = C_4 = \frac{P(1-D_A)}{(0.01)\, f_{TR}\,(V_{OUT})^2} \quad (10)$$

Inductors and capacitors of the qZS network should also be selected in compliance with the desired current and voltage rip-ples on the elements during the shoot-through and active states. The design guidelines are described in detail in [19] and [20].

III.QZSI-BASED DC/DC CONVERTER WITHTHREE-PHASE INTERMEDIATE AC LINK AND VDR

Modern trends in residential power systems are directed to increased efficiency and power density of electronic converters to enhance the feasibility of the whole system. For the discussed application, an increase in power density (more power for the same volumetric space of the converter) could be achieved by the implementation of the three-phase intermediate ac link instead of the single-phase one. The hardware modifications are shown in Fig. 18. In contrast to the single-phase topology, the three-phase configuration has an additional inverter leg, two extra isolation transformers, and an additional rectifier diode leg. For every operating point within the predefined boundaries [VIN,min; VIN,max], the output voltage of the converter could be estimated by (9).

Although the control principle of the three-phase qZSI in the shoot-through (voltage boost) operating mode is more complicated, the resulting advantages of the three-phase intermediate ac link over the single-phase one are obvious:

1. lower rms current through the inverter and rectifier switches (higher power transfer through the switch with the same level of switch current and voltage stresses);
2. reduced isolated transformer's volume (and weight) due to reduced overall yoke volume and reduced voltage and magnetic stresses;
3. reduced ratings of passive components of the qZS net-work due to an increase by a factor of three of its operating frequency;
4. windings of isolation transformers in the three-phase isolation transformer stack, which could be connected in different configurations to obtain the desired output voltage.

It is noticeable that, during the shoot-through, the inverter output voltage drops to zero, thus splitting the primary winding voltage waveform and reducing the operating duty cycle of the isolation transformer

$$D_A = 1 - D_S \quad (11)$$

whereD_A and D_S are the duty cycles of the active and shoot-through states, respectively.

IV.CONCLUSION

This paper has presented two new isolated step-up dc/dc converter topologies with qZSIs. The topologies are intended for applications with widely varying input voltage and stabilized output voltage and when the galvanic separation of the input and output sides is required. The high-frequency transformer stack is responsible for providing the input/output galvanic isolation demanded in many applications. This paper has focused on an example of the step-up dc/dc converter with high-frequency isolation for the distributed power generation systems. The operating principle, converter design methodology, simulation, and experimental results have been presented and analyzed. Moreover, to improve the power density and reliability, the updated converter topology with the three-phaseauxiliary ac link and the three-phase VDR was proposed and verified.

The proposed converters have the following key features in comparison to traditional topologies.

1. The qZSI implemented on the primary side of the converter could provide both the voltage boost and buckfunctions with no additional switches, only by use of a special control algorithm.
2. The qZSI has an excellent immunity against the cross conduction of the top- and bottom-side inverter switches. Moreover, the qZSI implemented can boost the input voltage by introducing a shoot-through operation mode, which is forbidden in traditional VSIs. The qZSI implemented has the continuous input current (input current never drops to zero) during the shoot-through (voltage boost) mode.
3. The high-frequency step-up isolation transformer pro-vides the required voltage gain as well as input–output galvanic isolation demanded in several applications.
4. The VDR implemented on the converter secondary side has the improved rectification efficiency due to the re-duced voltage drop (twice reduced number of rectifying diodes and full elimination of the smoothing inductor).
5. The turns number of the secondary winding of the isolation transformer could be reduced by 62% (turns ratio of 1: 3.75 in the case of VDR instead of 1: 10 of traditional full-bridge rectifiers) due to the voltage doubling effect available with the VDR.

Finally, it could be stated that the proposed qZSI-based dc/dc converters with a high-frequency step-up transformer and a VDR could be positioned as a new alternative for the front-end dc/dc converter for residential power systems with the operating power up to 10 kW. Moreover, with several modifications, the proposed converters could be extended to photovoltaic and regenerative FC applications as well as to telecom, marine, and aerospace applications.

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