Transient Response Analyze of Different Voltage-Fed qZS-family Inverters

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***Abstract*-In this paper a comparative overview of quasi-impedance source inverter topologies is given. The working principle, advantages and disadvantages of each topology as well as their possible fields of use are discussed and a comparison of the passive components, boost properties and dynamic behavior analysis of different quasi impedance source network topologies is carried out.**

I. INTRODUCTION

Distributed power is a concept that covers a wide spectrum of schemes used for local electric power generation from renewable and non-renewable sources of energy in an environmentally responsible way. Basic schemes are mainly based on solar energy, wind energy, fuel cells, and micro turbines offering reliable, high-quality and low-cost electric power and provide savings in the cost of grid expansion and line losses. To connect the renewable power generation systems to a grid a special converter is required [1].

In our application the grid interface inverter should fulfill the requirements presented in Table I and be EMI noise safe.

TABLE I
REQUIREMENTS FOR QZ-SOURCE NETWORK

Nominal power	12 kW
Input DC voltage	100 V
Output DC voltage	200 V
DC-link voltage ripple	25%
Input current ripple	5%

Although the traditional inverter topologies have proved themselves, they also have some drawbacks for these applications – for instance the current-source inverter (CSI), which is fed from a power source with relatively constant voltage that is generally supported with a relatively large inductor and with a three-phase full bridge used as an inverter, where the switches and diodes are in a series to provide unidirectional current flow and bidirectional voltage blocking. The CSI is susceptible to over-voltages of semiconductors, which can appear in error sequences. These error sequences can, for example, be caused by a faulty gate-driver control of the devices, which can lead to an interruption of the input current through the inductance. As a drawback the current source inverter is a boost converter. In other words the AC output voltage is greater than the DC-link voltage. For applications where AC output voltage should be lower than DC-link voltage an additional DC-DC buck converter is needed, which increases the system cost and reduces the converter's efficiency. The CSI is not well protected against EMI noise – it is not allowed to turn the upper and lower switch of the same phase-leg on simultaneously to avoid shoot-through. In other words, CSI does not fulfill the requirements and for that reason is not suitable for renewable power generation systems [2].

Another typical solution is the two-stage voltage source inverter (VSI). It is a widely used topology, where the front end DC-DC converter and VSI are connected in a series by a DC-link capacitor, which smoothes the DC-link voltage and ensures the decoupling of the grid side from the DC power source side.

The design of the front-end boost DC-DC converter is quite challenging since this stage is the main contributor to interface converter efficiency, weight and overall dimensions. High currents will lead to high conduction and switching losses in the semiconductors and therefore reduce efficiency. Moreover, the large voltage boost factor requirement presents a unique challenge to the DC-DC converter design [1].

However, the additional DC-DC boost converter increases cost and lowers efficiency. The required dead-time to avoid cross-conduction of the switching devices in the same phase leg (causing a short circuit of the DC-link capacitors) has to be provided in order to prevent a shoot-through, causing with it waveform distortion of the AC output voltage.

Three-level neutral-point-clamped (NPC) inverters are commonly used as a preferred topology for medium voltage AC drives. In recent years the inverter topology has been researched as a low-voltage grid-interfacing power converter. The three-level NPC inverter has many advantages over a two-level inverter, such as lower semiconductor voltage stress, lower required blocking voltage capability, decreased dv/dt, better harmonic performance, soft switching possibilities without additional components, higher switching frequency due to lower switching losses and balanced neutral-point voltage. Despite their good performance, three-level NPC inverters are only able to perform a voltage buck operation. Buck-boost energy conversion is usually achieved by connecting DC-DC boost converters in the DC-link. These two-stage solutions are usually more costly and harder to control, since they involve more active and passive components. The Z-source NPC inverter, qZ-source NPC inverter and DC-link cascaded inverter overcome these problems [25-29].

As can be seen, the traditional solutions are not suitable for use as an interface inverter for renewable power generation. The inverter which fulfills all of the requirements – the quasi Z-source inverter (qZSI) – was proposed in [3]. The development of qZSI topologies has continued, and today we have several derivations of qZSI, whose classification is presented in Fig. 1.

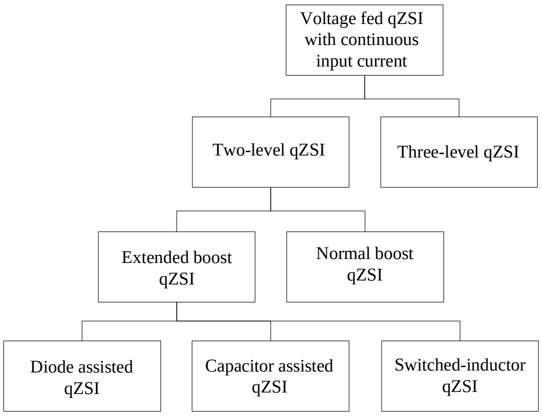

Fig. 1. Classification of qZSI topologies.

In this paper an overview of the qZSI topologies that are suitable for distributed power generation, their advantages and limitations as well as fields of use are introduced and the dynamic behavior of the qZSI topologies under the conditions which fulfill the above-mentioned requirements are compared in load changing situation.

A. Quasi Z-Source Inverter

The quasi impedance-source inverter (qZSI) shown in Fig. 2 (a) operates like a combination of the VSI and the CSI. This inverter topology obtains buck and boost functionality. The qZSI overcomes the limitations that traditional inverters face [4]. As can be seen from Fig. 2 (a), the qZSI consists of a quasi Z- (qZ) source network and a full-bridge inverter. The qZ-source network is a combination of two inductors (L_1, L_2), two capacitors (C_1, C_2), a diode D_1) and its energy storage and filtering element. The qZ-source network provides single-stage buck and boost capability as well as second-order filtering possibilities. The provided second-order filter is more effective in suppressing voltage ripples than the capacitor used in the traditional VSI. Due to the inductor in the qZ-source network, the in-rush current and harmonics are reduced [3-5].

The qZ-inverter can boost the input voltage by introducing a special shoot-through switching state, which is the simultaneous conduction (cross-conduction) of both switches of the same phase leg of the inverter. This switching state is forbidden for traditional voltage source inverters. Thus, the qZS inverter has excellent immunity against the cross-conduction of top and bottom inverter switches. The possibility of using shoot-through eliminates the need for dead-times without the risk of damaging the inverter circuit. The input voltage is regulated only by adjusting the shoot-through duty cycle.

If the fuel cell or photovoltaic module is used as the DC voltage source, the voltage varies widely. The task of the converter is to produce a desired AC voltage regardless of the level of the DC voltage source.

The DC-link voltage is boosted during the active state where the magnetic energy stored in the DC link inductors (L_1 and L_2) during the shoot-through state is released [1], [4-6]. The boost factor (B) of qZSI equals:

$$B = \frac{\hat{U}_{DC}}{U_{IN}} = \frac{1}{1 - 2 \cdot D_S}, \quad (1)$$

where D_S is the shoot-through duty cycle. Theoretically qZSI can produce infinite boost, like several boost converters, but due to the effects of parasitic components, where the voltage gain tends to drop drastically, this cannot be archived [3].

In other words, the AC output voltage is regulated according to the shoot-through duty cycle and modulation index, but there is a compromise between them in the case of a large shoot-through duty cycle. A small modulation index could be used and vice versa, but such an index does not only reduce the amplitude of the AC output voltage, but also degrades AC output performance [7]. Several PWM methods are presented in [8-9] to overcome this drawback.

As an advantage, qZSI has continuous input current and provides a cheaper and simpler single-stage approach [1], [3], [10].

The main drawback of the qZSI is its poor performance in the case of small loads and relatively low switching frequency. In these conditions the qZS inverter starts to work in discontinuous conduction mode, which causes an over-boost effect and leads to instability. Another typical characteristic is the relatively high ripple content of the input current and the resulting stress of the inductance and capacitors in the DC-link circuit [1], [5].

II. Extended-Boost QZSI Topologies

To improve the boost properties of the traditional qZSI with a continuous input current, cascaded qZSI topologies could be used. By implementing the cascaded qZS network the duty cycle of the shoot-through state could be sufficiently decreased for the same voltage boost factor and component stresses compared to traditional qZSI. Due to the decreased shoot-through duty cycle the values of inductors and capacitors of the qZS network could also be decreased. On the other hand, for the same component ratings, voltage and current stresses, the qZSI with a cascaded qZS network ensures a higher voltage boost factor compared to the traditional solution [12-14].

The cascaded qZS network ensures the continuous input current of the converter during the shoot-through operating mode, thus featuring the reduced stress of the input voltage source, which is highly topical in demanding applications like fuel cells and solar panels [32].

Moreover, the voltage-fed qZSI with the cascaded qZS network features over 30% of shoot-through duty cycle reduction for the same voltage boost factor and component stresses as the conventional qZSI. The qZSI with the cascaded qZS network can be applied to almost all DC-AC, AC-DC, AC-AC and DC-DC power conversion schemes. To further decrease the shoot-through duty cycle for the same voltage boost factor, the number of stages of the qZS network could be increased. [31-32].

Thanks to its specific properties, the cascaded qZSI is well suited to applications that require a large range of voltage gain, such as motor controllers or power conditioners for renewable energy systems.

A. Diode-Assisted qZSI and Capacitor-Assisted qZSI

The topology of a diode-assisted extended boost qZSI (DAEB qZSI Fig. 2 (c)) is derived by adding one capacitor (C_3), one inductor (L_3) and two diodes (D_2 and D_3) to the traditional qZSI with continuous input current. The modified topology of a diode-assisted extended boost qZSI (MDAEB qZSI) is derived from the DAEB qZSI simply by changing the connection points of the capacitor C_3, as shown in Fig. 2 (d) [11].

The boost factor of a DAEB and MDAEB qZSI may be found as:

$$B = \frac{\hat{U}_{DC}}{U_{IN}} = \frac{1}{D_S^2 - 3 \cdot D_S + 1}. \tag{2}$$

The topology of a capacitor-assisted extended boost qZSI (CAEB qZSI, Fig. 2 (e)) is derived by adding one diode (D_2), one inductor (L_3) and two capacitors (C_3 and C_4) to the traditional qZSI with continuous input current [30-32].

The modified topology of a capacitor-assisted extended boost qZSI (MCAEB qZSI) is derived from the CAEB qZSI by changing the connection points of capacitors C_2 and C_3, as shown in Fig. 2 (f) [11].

The boost factor of CAEB and of a MCAEB qZSI is calculated as:

$$B = \frac{\hat{U}_{DC}}{U_{IN}} = \frac{1}{1 - 3 \cdot D_S}. \tag{3}$$

One advantage of all four topologies is continuous input current and the increased boost factor of the input voltage for the same value of the shoot-through duty cycle as per the traditional qZSI [3], [15-16]. All topologies have identical boost properties within the shoot-through duty cycle range of 0-0.15, which could be considered in proper topology selection for different applications. The topologies suffer from boost factor reduction, which is mostly caused by losses in the inductors and diodes of the qZS network as well as by voltage drops in interconnection wires. In order to achieve higher possible voltage gain and efficiency these problematic issues should be addressed during the design routine of extended boost qZS-converters [17].

B. Switched Inductor qZSI

The topology of switched inductor (SL) qZSI is derived by replacing the second inductor L_2 in the qZS-network with switched inductors, as shown in Fig 2 (d). The SL qZS network consists of three inductors (L_1-L_3), four diodes (D_1-D_4) and two capacitors (C_1 and C_2). Inductors L_2 and L_3 can be implemented as coupled inductors [18].

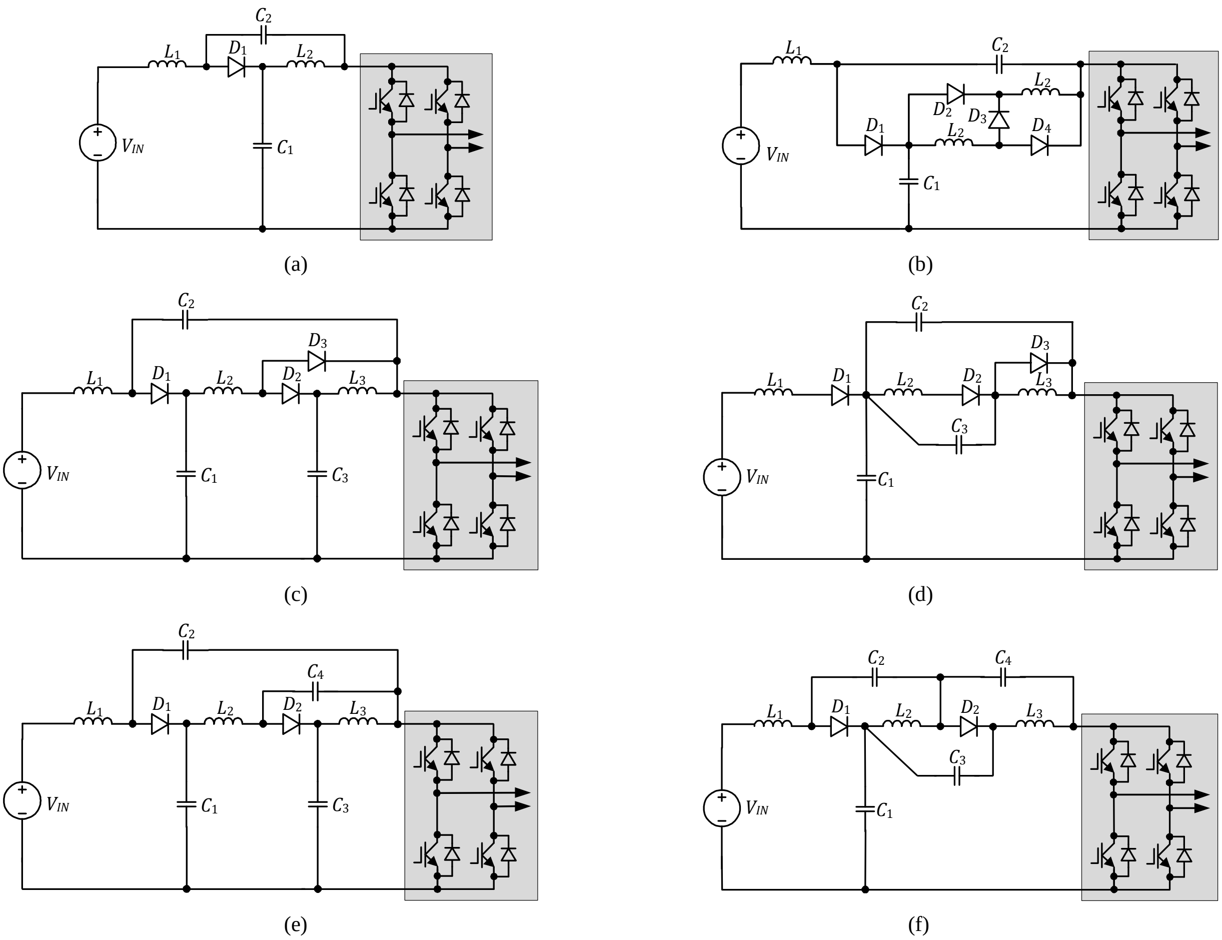

Fig. 2. Simplified schematic of qZSI (a), SL qZSI (b), DAEB (c), MDAEB (d), CAEB (e) and MCAEB (f).

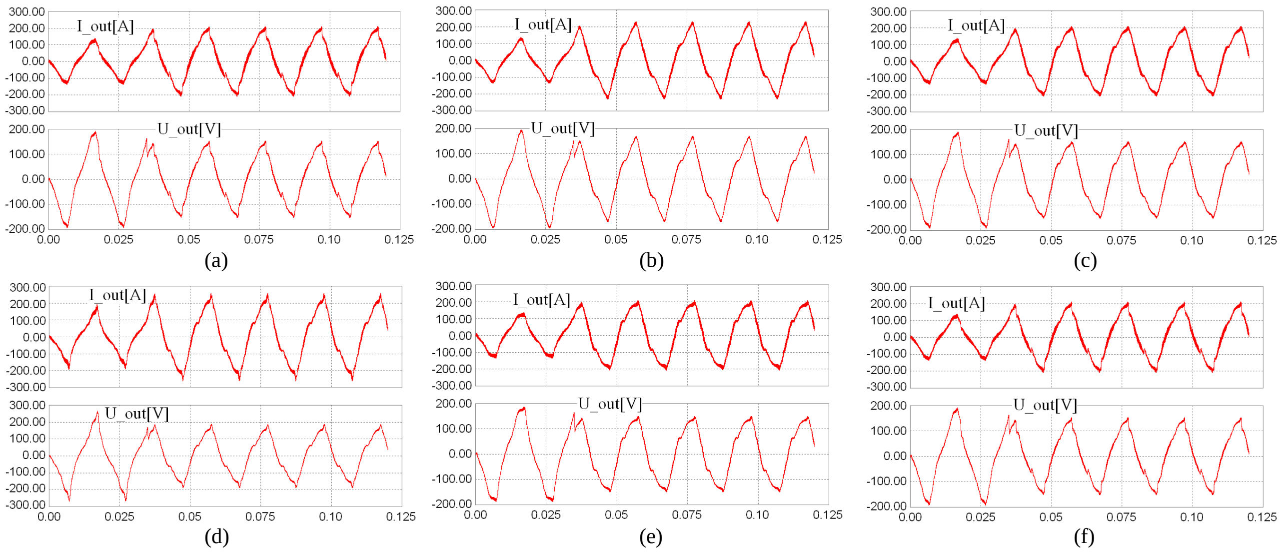

Fig. 3. Dynamic behavior to the load step of qZSI (a), -DAEB qZSI (b), MDAEB qZSI (c), CAEB qZSI (d), MCAEB qZSI (e) and SL qZSI.

The operation principles of the SL network are similar to those of the classic qZ-source network [19]. SL qZSI can provide a strong boost inversion ability to overcome the limitations of the traditional qZ-source inverter.

The boost factor of SL qZSI equals to:

$$B = \frac{\hat{U}_{DC}}{U_{IN}} = \frac{1 + D_S}{1 - 3 \cdot D_S}. \quad (4)$$

III. Simulation Results

As defined in the Table I the inverters should work with constant boost factor, this means the dynamic simulations have been carried on in order to evaluate the performances and the responses of the inverters in load changing situation.

The tests were carried out under the overload situation. This means the inverter worked with nominal power and the inverters' load was raised according to step function 13 %. Simulation results demonstrate the ability of inverters to response fast enough to the large demand in active and reactive power without compromising the inverter performance, mainly waveform quality and voltage balancing.

The settling times of the inverters under the changing load condition is presented in Table II.

TABLE II
Voltage Settling Times Under Changing Load Situation

	Settling time
qZSI	1.2 ms
DAEB qZSI	2.1 ms
MDAEB qZSI	2.5 ms
CAEB qZSI	2.5 ms
MCAEB qZSI	2.7 ms
SL qZSI	2.1 ms

Conclusion

An overview of the qZSI topologies that are suitable for distributed power generation, their advantages and limitations as well as fields of use are introduced and the dynamic behavior of the qZSI topologies under the unexpected load changing situation was given. All the qZS-family inverters respond enough fast to the load change.

Acknowledgment

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