Grid-tied single source quasi-Z-source cascaded multilevel inverter for PV applications

R.A. Guisso[✉], A.M.S.S. Andrade, H.L. Hey and M.L. da S. Martins

A new cascaded multilevel topology is proposed in this study. It is denominated single DC source quasi-Z-source cascaded multilevel inverter (SS qZS-CMI). The SS qZS-CMI performs at maximum power point tracking of the photovoltaic (PV) array with a single inverter module and each of the inverter modules shares an equal amount of the power of the whole system. The SS qZS-CMI has the capacity to equally regulate the peak voltage on each inverter module by means of the dual control loop of the main inverter module and the shoot-trough state of the auxiliary inverter modules, ensuring the symmetry of the cascaded multilevel inverter. Experimental results verify the proposed topology.

Introduction: The combination of quasi-Z-source inverter modules and cascaded H-bridge (CHB) topologies in grid-tied photovoltaic (PV) applications [1] enables PV string voltage boosting. This may reduce the PV modules count per string and also may eliminate the voltage imbalance problem of DC-link that plagues conventional CHB inverters. This helps to stabilise the CHB voltage levels, reducing bus capacitance and output filter component requirements. Nevertheless, for many installation and safe operation guidelines and standards, PV system grounding is required, NEC690.41-64 Std [2]. This entails the employment of galvanic isolation for all CHB inverter modules. Fig. 1 shows two possible CHB configurations that permit system grounding. In Fig. 1*a* [3], the inverter comprises front-end isolated DC–DC half-bridges that ensure galvanic isolation for each grounded PV array. This additional power processing stage increases the conduction losses. On the other hand, Fig. 1*b* makes use of a single-switch isolated qZsource DC–DC stage followed by a standard H-bridge inverter [4]. In spite of reducing the power switch count, once again there is a double power processing that increases the losses.

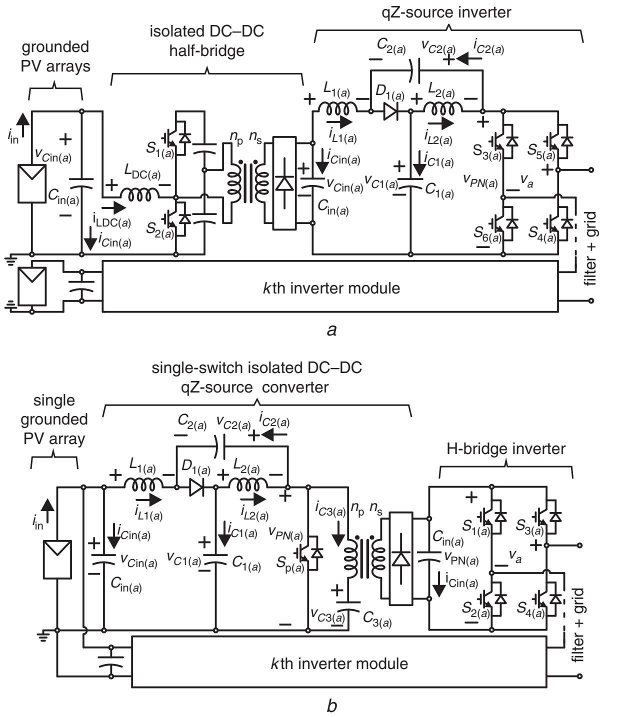

Fig. 1 *Diagram of*
a Cascaded qZ-source inverter with isolated DC–DC half-bridge stage
b CHB with single-switch isolated DC–DC qZ-source stage

The single DC source quasi-Z-source cascaded multilevel inverter (SS qZS-CMI) is proposed with the aim of providing an alternative topology that offers the advantages of the qZS-CHB without the inclusion of an additional DC–DC stage, and also employs a single grounded PV string. Fig. 2 shows the diagram of the proposed inverter. The main bridge is fed by a PV array that characterises the topology as a single DC source inverter. The auxiliary bridge presents a capacitor that plays the role of input voltage source. This capacitor is charged exclusively by the secondary winding of a coupled-inductor or transformer whose primary winding is magnetised by the main H-bridge module during its shoot-trough (ST) state. This unique feature allows both active and reactive power to be processed by the auxiliary H-bridge cell. Furthermore, in spite of being presented as a replacement of the inductor L_2 (see Fig. 2*a*), the coupled inductor can also be used as the inductor L_1. The extended 7-level CHB inverter can be accomplished by replacing both L_1 and L_2 by coupled inductors. CHB inverters with nine levels or more require multi-winding coupled inductor solutions. The output voltage of the inverter is the sum of the voltages of the series-connected SS qZS-HBI modules according to Fig. 2*b*. The DC bus voltage of each inverter module is controlled independently, which ensures that the DC bus voltage ratio is kept constant. This characteristic is essential to enable the topology to work as a symmetric multilevel inverter, maintaining its advantages.

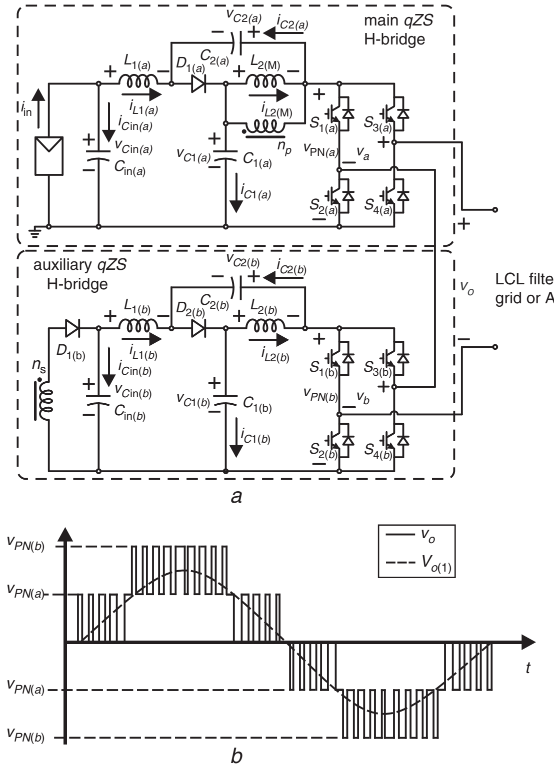

Fig. 2 *Proposed SS qZS-CMI topology*
a Circuit diagram of the SS qZS-CMI
b Multilevel output voltage waveform

Phase-shifted pulse width modulation [5, 6] is adopted as long as it facilitates voltage balancing among the inverter modules. However, phase-disposition PWM techniques can be adopted for asymmetrical cascaded qZS inverter applications. As a result, the SS qZS-CMI provides a five-level output voltage to feed the 60 Hz grid through the LCL filter.

SS qZS-CMI operating principle: Taking into account a single qZ-source H-bridge cell, it can be stated that its operation consists of two distinct operating states, the non-shoot-through (NST) and ST states. At the NST state, the power is transmitted from the DC side to the AC side for each qZ-source H-bridge cell. On the other hand, at the ST state, there is no power transmission from DC through AC in each bridge.

On the contrary, during the ST state, the main H-bridge coupled-inductor energy is transferred from its primary winding to its secondary winding, charging the input capacitor of the auxiliary qZS inverter module, where the input voltage is obtained from (1). The control goals adopted for the SS qZS-CMI grid-tie PV inverter are: (i) to use a single PV array with a maximum power point tracking (MPPT) algorithm to ensure maximum power extraction; (ii) provide active power to the grid at the unity power factor (PF) with low harmonic distortion; (iii) to ensure the same DC-link peak voltage for both main and auxiliary qZS-HBI modules

$$v_{Cin(b)} = \frac{n_s}{n_p} v_{C1(a)}, \quad (1)$$

where $\frac{n_s}{n_p}$ is the transformation ratio of the coupled inductor.

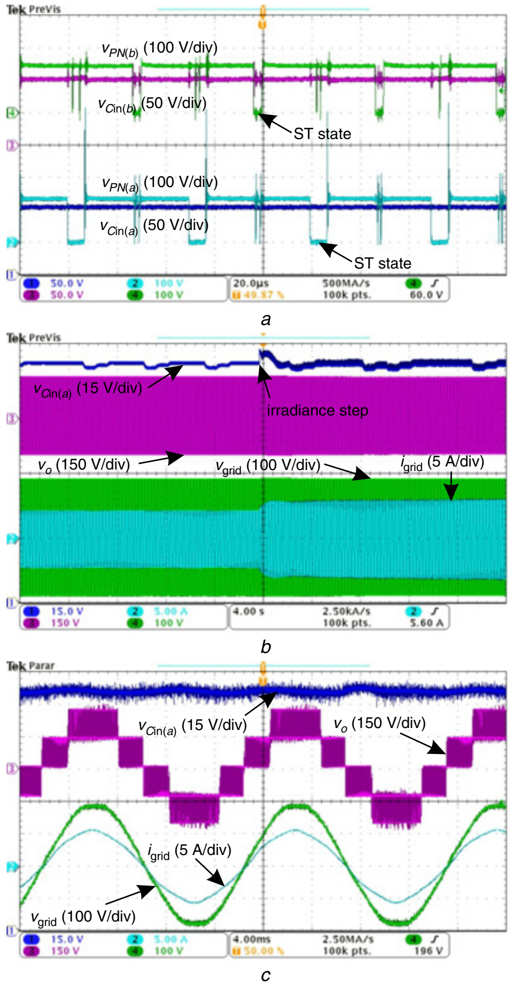

Fig. 3 *Experimental results of SS qZS-CMI*

a Voltage waveforms $v_{PN(b)}$, $v_{Cin(b)}$, $v_{PN(a)}$ and $v_{Cin(a)}$
b Voltage waveforms $v_{Cin(a)}$, v_o, v_{grid} and current i_{grid}
c Voltage waveforms $v_{Cin(a)}$, v_o, v_{grid} and current i_{grid}

Experimental results: A prototype of a grid-tied single-phase five-level SS qZS-CMI has been built. To emulate the PV array, an Agilent E4360A programmable power supply was used. The proposed control structure for the prototype was constructed using the TMS320F28335 digital signal processor model, which integrates an interface for power supply, A/D conversion, serial communication and so on. The prototype was assembled according to the following parameters: $L_{1(a)} = L_{1(b)} = L_{2(a)} = L_{2(b)} = 2.568\,\text{mH}$, inductors' series damping resistance of the DC side of the converter ($rL_1 = rL_2 = 0.5\ \Omega$), $C_{in(a)} = C_{in(b)} = 470\,\mu\text{F}$, $C_{1(a)} = C_{1(b)} = C_{2(a)} = C_{2(b)} = 4.7\,\text{mF}$, capacitors' intrinsic damping resistor on the DC side of the converter ($RC_1 = RC_2 = 0.0389\,\Omega$), components of the LCL filter, converter side inductor ($L_{cf} = 1.750$ mH), grid side inductor ($L_{gf} = 0.860\,\text{mH}$), capacitor ($C_f = 4.242\,\mu\text{F}$), filter damping resistance ($R_f = 16.5\,\Omega$), maximum power voltage (*VMP*) of the PV array for $1000\,\text{W/m}^2$ ($VMP = 102.6\,\text{V}$), grid voltage ($v_{grid} = 127\,\text{V}$), grid frequency ($f_g = 60\,\text{Hz}$), switching frequency ($f_s = 10.02\,\text{kHz}$), and the maximum power injected into the grid ($P_{out} = 483\,\text{W}$). Fig. 3*a* shows some key experimental results, where the voltage of the PV array in the input of the main module $v_{Cin(a)}$ is controlled at $\sim$ 102 V, with a ST value of around 0.24. The input voltage of the auxiliary module $v_{Cin(b)}$ is about 105 V, for a ST value of around 0.17. Peak voltages on both DC buses, $v_{PN(a)}$ and $v_{PN(b)}$, are set to ~150 V. According to Fig. 3*b*, an irradiance step was imposed on the PV array of the main module input, from 750 to $1000\,\text{W/m}^2$, where it can be seen that the peak voltages of both DC buses were controlled during and after the step, since the voltage v_o remained constant. The current i_{grid} increased after the step, demonstrating the effectiveness of the implemented cascade control structure. In Fig. 3*c*, it is clearer by zooming in v_o that both DC buses have very similar voltage values because the voltage levels have almost equal amplitudes. Additionally, the i_{grid} current is in phase with the v_{grid} voltage, yielding a PF close to unit. Regarding total harmonic distortion of the i_{grid}, the obtained value was 2.85% based on the IEEE 1547 Standard with respect to the total harmonic content of the injected current. By performing an individual analysis with respect to the order of the even and odd harmonics, it is concluded that i_{grid} also met the standard. It was also observed that the phase-shift modulation was effective in the power distribution in both cascaded H-bridge modules, in which, at the maximum power point, $P_{out} = 483\,\text{W}$, the main qZS H-bridge processed 247.2 W and the auxiliary qZS H-bridge processed 247.1 W. The experimental results confirm the effectiveness of the MPPT algorithm, of the peak voltage control structure of both DC buses and the current injected into the grid.

Conclusion: The proposed cascaded multilevel qZS inverter topology (SS qZS-CMI), enabling all H-bridge qZS to process equally the same active power, provides benefits of power sharing, such as modules derating and better heat management due to the increased loss distribution. The topology control system performs at MPPT for the PV array and controls the peak voltage of the independent DC bus for each cascaded qZS module. A unity PF has been achieved and the injected current complies with the IEEE 1547 Standard. The closed-loop control of the DC bus voltage of the auxiliary module ensures that all cells of the SS qZS-CMI have voltage balance, thus providing a precise symmetry to the output voltage levels, increasing the injected current quality. The operating principles and the control strategies were confirmed by experimental results.

Acknowledgments: The present study was carried out with the support of the Coordenação de Aperfeiçoamento de Pessoal de Nível Superior – Brasil (CAPES/PROEX) – Finance Code 001 and the Instituto Nacional de Ciência e Tecnologia em Gerção Distribuída (INCT-GD) – CNPq process no. 465640/2014-1, CAPES 23038.000776/2017-54 and FAPERGS 17/2551-0000517-1.

Submitted: *7 December 2018* E-first: *4 February 2019*
doi: 10.1049/el.2018.8013
One or more of the Figures in this Letter are available in colour online.

R.A. Guisso, A.M.S.S. Andrade, H.L. Hey and M.L. da S. Martins (*Power Electronics and Control Research Group (GEPOC), Federal University of Santa Maria, Santa Maria 97105-900, Brazil*)

✉ E-mail: ronaldo.guisso@gmail.com

References

1 Liu, Y., Ge, B., Abu-Rub, H., *et al.*: 'An effective control method for quasi-Z-source cascade multilevel inverter-based grid-tie single-phase photovoltaic power system', *Trans. on Industrial Informatics*, 2014, **10**, (1), pp. 399–407
2 Bower, W.I., and Wiles, J.C.: 'Analysis of grounded and ungrounded photovoltaic system'. Proc. of IEEE World Conf. on Photovoltaic Energy Conversion, Waikoloa, HI, USA, December 1994, vol. 1, pp. 809–812
3 Liu, Y., Ge, B., and Abu-Rub, H.: 'Front-end isolated quasi-Z-source DC-DC converter modules in series for photovoltaic high-voltage DC applications'. IEEE Applied Power Electronics Conf. (APEC), Long Beach, CA, USA, March 2016, pp. 1214–1219
4 Liivik, L., Chub, A., and Vinnikov, D.: 'Input-parallel output-series cascading possibilities of single-switch galvanically isolated quasi-Z-source DC-DC converters'. 2016 2nd Int. Conf. on Intelligent Energy Power Systems (IEPS), Kyiv, Ukraine, June 2016, pp. 1–6
5 Sun, D., Ge, B., Peng, F.Z., *et al.*: 'A new grid-connected PV system based on cascaded H-bridge quasi-Z-source inverter'. Proc. IEEE Int. Symp. Industrial Electronics, Hangzhou, China, May 2012, pp. 951–956
6 Liu, Y., Ge, B., Abu-Rub, H., *et al.*: 'Phase-shifted pulse-width-amplitude modulation for quasi-Z-source cascade multilevel inverter-based photovoltaic power system', *IET Power Electron.*, 2014, **7**, (6), pp. 1444–1456