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Operation and Control of a Quasi Z-source Converter in a Renewable Hybrid Microgrid

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Abstract. The power sharing need and operational reliability of a renewable hybrid microgrid are addressed in this study. A hybrid microgrid allows for the flexible incorporation of renewable energy sources, overcoming the limitations of AC and DC microgrids in terms of conversion losses and efficiency. To ensure optimal system performance, an interlinking converter (IC) is necessary for the seamless transmission of electric power between the two subgrids while keeping a stable DC bus voltage and appropriate AC sub-grid frequency. In this study, a Quasi Z-source converter (qZSC) with integrated boost capability is introduced as an IC in a PV-Wind based hybrid microgrid. Also, an adaptive dual loop based-PI (ADL-PI) control is proposed which maintains a constant peak DC-link voltage and supports maximum power point tracking while improving the system's overall stability. The proposed system and control approach are assessed using MATLAB/Simulink, and the results indicate its efficacy under various scenarios.

Keywords. Hybrid microgrid, quasi-Z-source, interlinking converter, renewable energy sources, photovoltaic, wind

1. Introduction

Power generation from traditional sources with the usage of fossil fuels is swiftly declining owing to the detrimental impacts on the environment from excessive carbon emissions[1]. The microgrid concept has become an efficient way to incorporate the penetration of clean (renewable) energy sources in the current power network for meeting the growing energy demand. It has provided other advantages such as enhanced power flow in distribution systems and decreased power loss in transmission lines [2]. The major purpose of the microgrid is to offer high quality and dependable electric energy to sensitive loads utilizing renewable energy sources (RES) like Wind Turbine Generators (WTG), Photovoltaic Systems (PV) and Energy storage systems (ESS) which are placed closer to the loads.

Microgrids are either created as an AC network or a DC network and because loads demand both AC and DC power, several steps of power conversion from AC to DC or vice versa are necessary to fulfill the load supply requirements. Using several power electronic converters is a pricey technique that also causes harmonic interactions in the system, as well as difficulties with efficiency and reliability [3].

AC microgrids are prominent because they can support a diverse set of loads and distributed generation (DG) units. The primary disadvantages of an AC microgrid are the need for DG unit synchronization and circulating reactive power [4]. Meanwhile, in DC microgrids no DG unit synchronization is required thus there is no reactive power. DC microgrids are also more appealing to grid operators due to the increasing development of DC loads with renewable energy sources [5]. Integration of DC microgrids into distribution networks necessitates significant changes to power networks, making it an expensive option [6]. As a result, hybrid microgrids appear to be an excellent alternative for integrating small-scale grids with unique DG and load types into traditional distribution systems while minimizing conversion losses [7]. An interlinking converter (IC) is used for coupling the AC and DC subgrids.

Typically, a regular voltage source inverter (VSI) is used, but an additional boost stage is necessary to provide the correct voltage corresponding to the network situation. As a result, this method raises the cost and volume of the converter while decreasing system reliability and efficiency [8]. To solve this issue, a quasi-Z-source converter (qZSC) is introduced in a renewable hybrid microgrid. The qZSC offers the benefits of low voltage stress, constant input currents, common grounding of the DC source, and is more appropriate for PV systems [9]. The qZSC is part of the non-magnetically coupled Z-source converter (ZSC) that was first introduced in [10] and its operation modes are explained. In addition, researchers have investigated the modelling and control of this inverter in [11].

Several studies have employed the use of a qZSC in renewable energy-based systems [12]–[14]. However, just a few studies have investigated its application in hybrid microgrid systems. Ref [15] provides an experimental study of a hybrid PV-wind standalone system based on qZSC. Also, in [16] a qZSC was used as an IC in a hybrid AC/DC microgrid but focused more on energy storage control. Considering the benefits of the qZSC and its control schemes, significant effort is still required to employ its use in renewable hybrid microgrids.

In this study, the power sharing need and operational reliability of a renewable hybrid microgrid are addressed in which a qZSC is adopted for coupling a DC and AC subgrid with renewable energy sources. The hybrid microgrid is operated in grid-connected mode. In the DC subgrid, a photovoltaic (PV) array is employed as DG combined with DC loads while in the AC subgrid, a wind turbine generator is employed as DG combined with AC loads. Also, an adaptive dual loop based - PI (ADL-PI) control is designed as DC side controller to maintain a constant peak DC-link voltage and support maximum power point tracking while improving the system's overall stability. A PQ control in dq frame is also applied to control power exchange between AC and DC subgrids. The hybrid microgrid with the suggested IC is simulated in Matlab/Simulink and the results validate the function of the IC and the efficacy of its control system.

The paper is organised as follows: Section 2 outlines the system configuration. Section 3 provides the operating principle of the qZSC based hybrid microgrid. The control approach is described in section 4. Section 5 discusses the simulation findings and finally, conclusions are made in section 6.

2. System Configuration

The general structure of the proposed renewable hybrid microgrid with a qZSC is depicted in **Fig. 1**. A WTG is linked to the AC bus together with several AC loads. With the help of an isolation switch, the AC bus is linked to the utility grid. Hence if any failure arises, the utility grid is isolated from the microgrid by an isolation switch and operates in an islanded (autonomous) mode. Similarly, a PV array is linked to the DC bus together with several DC loads.

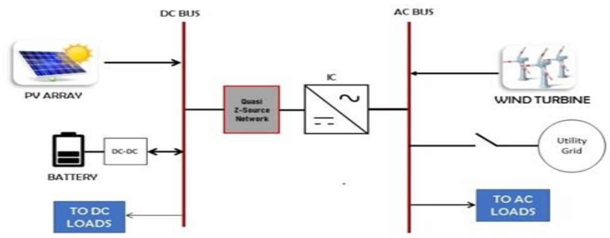

Fig 1: Hybrid Microgrid Configuration

3. Operating Principle of qZSC based Hybrid Microgrid

The qZSC-based hybrid microgrid can be operated in two modes: the non-shoot-through(nST) and the shoot-through (ST) mode. **Fig. 2** depicts the effective equivalent circuit of a qZSC in the shoot-through and non-shoot-through states. In **Fig. 2(b),** the non-shoot-through state inverter switch resembles a current source, whereas in **Fig 2(c)** the inverter switches in the shoot-through state are shorted with V_{PN}=0[17]. During a switching cycle with period T, the shoot-through interval is T Sh, hence the ST duty ratio D is given as;

$$D = \frac{T_{sh}}{T} \tag{1}$$

Similarly, the non-shoot-through interval is;

$$T_{nSh} = T - T_{Sh} \tag{2}$$

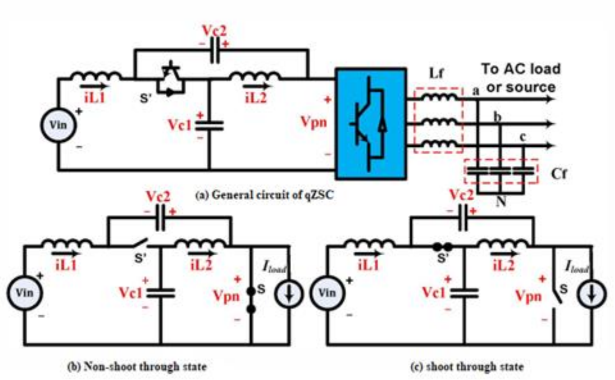

Fig 2: Equivalent circuit of qZSC

According to the inductor volt-second balance and capacitor charge balance principles, the average voltage of an inductor and the average current of a capacitor over one switching cycle T are both zero in steady-state [18]. As a result, the peak DC link voltage V_{PN} across the inverter bridge/switches can be determined as follows:

$$V_{PN} = V_{C1} + V_{C2} = \frac{T_{nsh}}{T_{nsh}-T_{sh}} V_{in} = \frac{1}{1-2\left(\frac{T_{sh}}{T}\right)} V_{in} = BV_{in} \tag{3}$$

Where B is the boost factor of the qZSC.

4. Control Scheme of Proposed qZSC based Hybrid Microgrid

The hybrid microgrid in this work operates in grid-tied mode, but it can also function in island mode using a wind turbine generator as an AC source. On the DC side, an adaptive dual-loop PI-based (ADL-PI) control technique is used to achieve maximum point tracking and keep the DC-link voltage constant. A bidirectional DC-DC converter is linked to a battery on the DC side. The role of an energy storage system is less crucial in grid-tied mode since the utility system balances power demand, but it is vital in islanded mode. Both the AC and DC subgrids are connected with resistive loads. A three-phase bidirectional qZSC interconnects both subgrids.

A. DC Subgrid Voltage Control

On the DC side, the qZSC capacitors and DC source charge the inductors during the shoot-through state while in the non-shoot-through state, the qZSC inductors and DC source charge the capacitors. An adaptive dual loop PI-based control is used here which maintains a constant peak DC- link voltage and ensures maximum point extraction while improving the overall stability via the inner current loop as depicted in **Fig. 3**.

By adjusting the inductor current (i_L) and the voltage across the capacitor (V_{c1}), the control generates the shoot-through duty ratio D. The desired DC-link peak voltage V^*_{PN} is compared with the actual DC-link voltage V_{PN}. Because of the pulsed dc-link voltage of the qZSC induced by the shoot-through condition, V_{PN} is computed using the qZSC capacitor voltage and shoot-through duty cycle according to (eq. 1). The error between V^*_{PN} and V_{PN} passes via a PI regulator, which provides the inner loop's inductor current reference, i^*_L. The shoot-through duty cycle D is then generated by a proportional regulator from the error between i^*_L and the actual qZSC inductor current i_L.

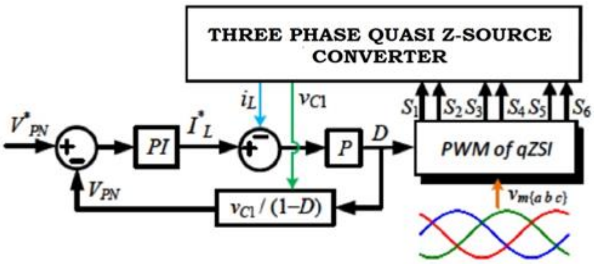

Fig 3: DC side voltage control

B. AC Subgrid Power Control

The AC sub-microgrid power control is shown in **Fig. 4.** The voltages and currents on the three-phase AC bus are monitored and converted to d-q components. In addition, three-phase AC bus voltages are routed through a phase-locked loop (PLL) to get three-phase voltage phases.

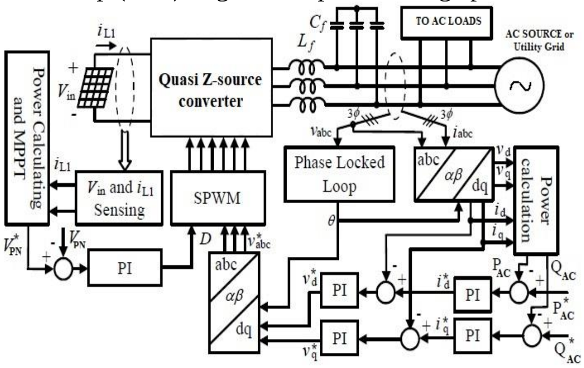

Fig 4: Control scheme of the system

PQ control technique in dq frame is employed in this control scheme to get references of d-axis and q-axis components of the current injected into the AC sub microgrid[19].

$$i_q^* = \frac{2}{3}\frac{Q_{ac}^*}{v_d} \qquad (4)$$

$$i_d^* = \frac{2}{3}\frac{P_{ac}^*}{v_d} \qquad (5)$$

Furthermore, two feedback controls are employed to control i_d and i_q respectively. Both controls employ PI regulators to track their current references. Output variables of these controllers are voltage references v^*_d and v^*_q. Using dq/abc transformation, the IC output voltage references V*a, V*b, and V*c can be obtained and used to generate gate signals for SPWM. More details about the PQ control scheme is given in[20]. The real and reactive power flow is given by:

$$P_{AC} = \frac{3}{2}(v_d i_d + v_q i_q) \qquad (6)$$

$$Q_{AC} = \frac{3}{2}(v_q i_d + v_d i_q) \qquad (7)$$

Where v_{dq}, i_{dq} is the output voltage and current of qZSC. When an abrupt load reduction occurs on the DC side, there will be surplus power on DC side of the hybrid microgrid and therefore the qZSC is regulated to transfer the excessive power from DC side to AC side. This is achieved by controlling the voltage across C_1. When there is excessive power on the DC side, it leads to a greater value of the active current reference id*. As a result, the active component of the current increases and hence the surplus power is exported to the electrical grid. Similarly, if there is excessive demand on the DC side, it creates a negative value of active current reference. Hence, the active part of the current decreases and the power is transferred from the utility grid to the DC side of the hybrid microgrid. **Fig. 4** shows the control design of the system.

5. Results and Discussion

The operation and control of the proposed qZSC based renewable hybrid microgrid is simulated using MATLAB. Different irradiation levels and load conditions are considered for simulation. The obtained results are shown in this section. An 85 kW PV system and 20 kW WTG is taken as DC and AC source respectively and the parameters are given in Table I.

TABLE I: Component Parameters of Hybrid Microgrid

	Symbol	Description	Value
DC Sub-microgrid	C_{pv}	Capacitor across the PV Panel	100 µF
	Vdc	Dc bus voltage	600V
	C_d	Dc link Capacitor	2000 µF
AC Sub-microgrid	f	AC grid frequency	50 Hz
	R_2	AC line resistance	$2\text{x}10^{-3}\,\Omega$
	L_f	Filtering Inductor on AC grid	1 mH
	C_f	Filtering Capacitor on AC grid	110 µF
Quasi Z-source Converter	L_1, L_2	Inductor for Quasi Z-source converter	700 µH
	C_1, C_2	Capacitor for Quasi Zsource converter	470 µF
	f_s	Switching frequency of converter	5 kHz

The solar irradiation level applied to the system is shown in **Fig 5**. From 0s to 0.5s, the irradiation level is set to 1000 W/m2, then drops linearly to 250 W/m2 from 0.5s to l.5s, and then increases linearly to 1000 W/m2. **Figure 6** depicts the Power output from PV array. The MPPT algorithm can be seen allocating new terminal voltages to detect the maximum power point. **Figure 7** depicts the voltage across the DC-link capacitor. the controller as designed keeps the dc link voltage constant. The ideal power transfer from DC side to AC side is shown in **Fig.8.**

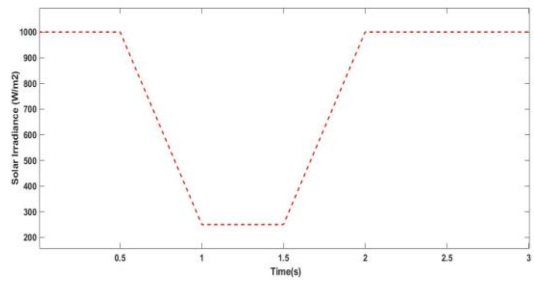

Fig. 5: Solar irradiation level

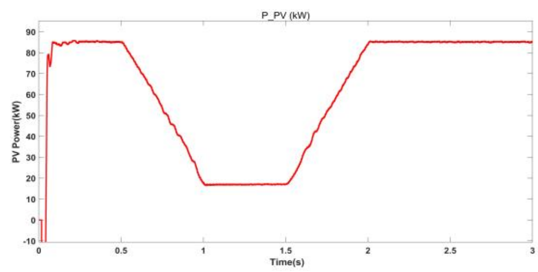

Fig. 6: Power output from PV System

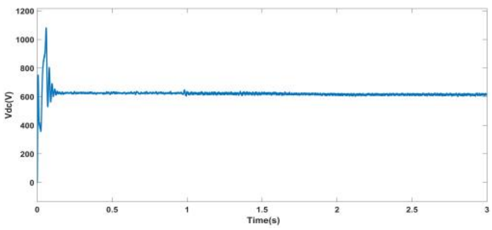

Fig. 7: DC-link voltage

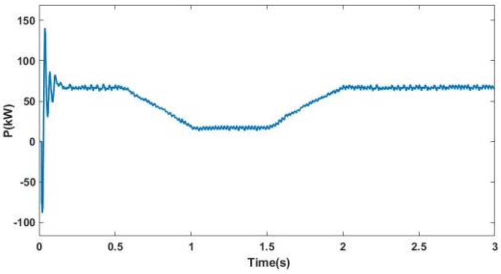

Fig. 8: Power exchange from DC side to AC side in ideal case

Figure 9 shows the output power of the WTG linked to the AC side as illustrated in Fig. 1 under constant wind speed. The system's behavior under various load situations is examined, and the results are discussed below.

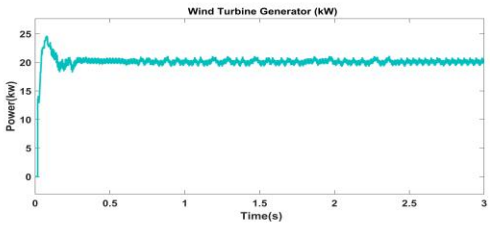

Fig. 9: Wind turbine generator power output

5.1 CASE I: AC/DC loading

When a light load of 12kW and 14kW is applied to the AC and DC subgrids respectively, the excess power on the DC side of the microgrid is transmitted to the utility grid, as seen in **Fig. 8**. On the AC side, the corresponding voltage and current waveforms are depicted in **Fig. 10.** The active current reference (id*) is shown in **Fig.11**. It can be seen that id* is positive and so the available power on the DC side gets transmitted to the AC side.

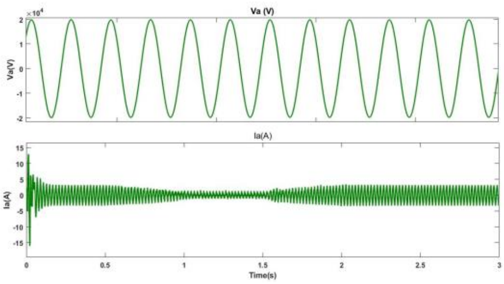

Fig. 10: Voltage and current waveform on AC side

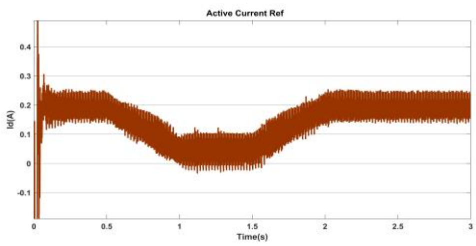

Fig. 11: Active current reference during light load

5.2 Case II: AC loading

When a 60kW load is put on the AC side, a deficiency of power is noticed which has to be supplied by the PV system. The suggested control enables the power generated from the PV array to be transferred to the AC side. The AC side grid power is given in **Fig. 8**. The voltage and current waveforms on the AC grid are illustrated in **Fig. 12.** The active current reference for this scenario is illustrated in **Fig. 13**.

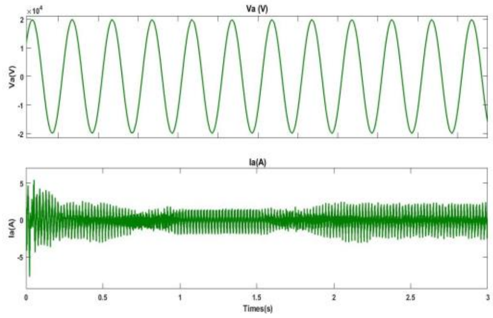

Fig. 12: Voltage and current waveform on AC side

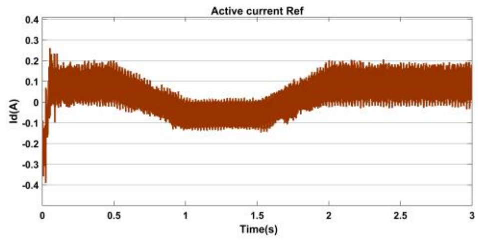

Fig. 13: Active current reference during heavy load

5.3 CASE III: DC loading

When the DC subgrid is heavily loaded (55kW), there will be a noticeable deficit of power at lower irradiation levels between 1s and 1.5s. This deficiency has to be supplied either by the utility grid or by the WTG. The compensating power from AC side is displayed in **Fig. 14**. The power is transferred from the AC side to compensate for the heavy loads on the DC side during lower irradiation levels. The voltage and current waveforms on the AC grid are illustrated in **Fig. 15**. The active current reference during heavy load on the DC subgrid is depicted in **Fig. 16.**

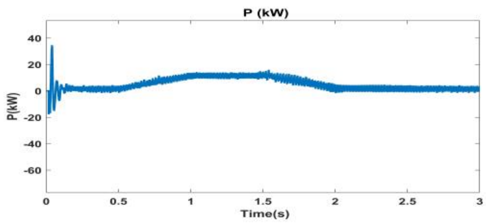

Fig. 14: Power transferred from AC side to DC side

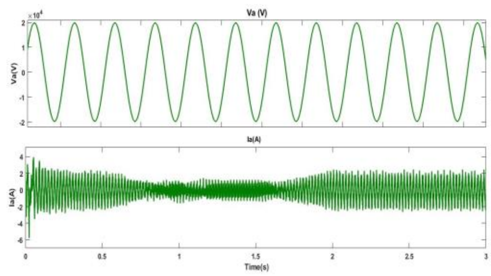

Fig. 15: Voltage and current waveform on AC side

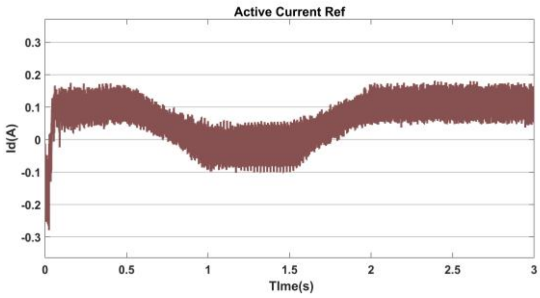

Fig. 16: Active current reference during heavy load on DC Subgrid

5.4 Comparison with related work

To check the accuracy of the proposed model, the qZSC power results is compared with a VSC model [21]. Table II shows the results of the comparison of the qZSC's power sharing capacity and the efficacy of the incremental conductance (IC) tracking technique with a voltage source converter-based model at a certain time.

TABLE II: Power Sharing Capacity comparison of qZSC and VSC based Microgrid

Converter Type with tracking Algorithm	*Maximum Power Extracted (kW)*	*Power on the AC grid (kW)*
qZSC (IC)	52.7	9.22
VSC (P&O) [21]	49.3	7.71

The perturb and observe (P&O) tracking technique is employed in the VSC-based model to track the PV system's maximum power point. The system is then simulated when the AC side is heavily loaded. When compared to the VSC-based hybrid microgrid, the findings reveal that the qZSC-based hybrid microgrid can provide improved power sharing capabilities according to the power demand. In addition, as compared to the P&O technique, the incremental conductance tracking algorithm is capable of extracting more power when used with the qZSC.

6. Conclusion

The operation and control of a qZSC-based renewable hybrid microgrid with AC and DC sub-grids is examined and verified using Matlab/Simulink. The proposed microgrid uses PV and WTG as power sources. The findings demonstrate the efficacy of the MPPT tracking algorithm in extracting maximum power from the PV system, as well as the PQ control scheme for flexible power flow between the AC and DC sides of the microgrid under various irradiation levels and loading situations.

This work serves as an increment for further development on the operation and control of multiple renewable energy sources in a hybrid microgrid structure.

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