23rd International Conference on Renewable Energies and Power Quality (ICREPQ'25)
Tenerife (Spain), 25th to 27th June 20245
Renewable Energy and Power Quality Journal (RE&PQJ)
ISSN 2172-038 X, Volume No.23, September 2025

Dual-Purpose dc-dc/ac PWM Modular Power Converter as Dual-Output Hybrid Converter

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Abstract. Power electronic converters play a crucial role in integrating renewable energy sources into modern electrical systems and enabling the development of hybrid nanogrids and microgrids. These systems typically feature an architecture that combines both dc and ac buses. Within this framework, dual-purpose converters have emerged, capable of interfacing with both dc and ac grids, thereby enhancing modularity and standardization in converter configurations. This paper expands on this class of converters by introducing a novel topology with dual outputs, allowing it to simultaneously supply both ac and dc loads. The proposed converter is designed using a modular arrangement of basic buck-boost cells. Its effectiveness is demonstrated through simulations, successfully powering a three-phase ac load alongside a dc load.

Key words. renewable energies, hybrid nanogrids, dual-purpose converter, hybrid outputs.

1. Introduction

The European Union (EU) has outlined ambitious energy and environmental objectives aimed at transitioning to a low-carbon energy system. As part of its climate and energy framework, the EU has set targets for 2030, including a minimum 55% reduction in greenhouse gas emissions compared to 1990 levels, a 32% share of renewable electricity, and a 32.5% improvement in energy efficiency [1]. Achieving these goals requires advancing energy systems that support three key priorities: environmental protection, the development of cost-effective and market-driven energy solutions, and ensuring a secure, reliable, and resilient energy supply. The European Union's 2030 climate targets serve as a stepping stone toward achieving climate neutrality by 2050 [2]. The ongoing transition in the energy sector presents new opportunities for the integration and expansion of distributed energy resources (DERs). Additionally, it is reshaping the role of end users, transforming them from passive consumers into active participants who both generate and utilize energy. In this context, localized energy systems have the potential to play a crucial role in advancing the EU's energy and climate goals.

In this paradigm, Microgrids (µGs) and nanogrids (nGs) were planned a few decades ago as a compact electrical networks that integrate advanced power conversion technologies [3]. These systems leverage high-performance power converters (PCs) to efficiently manage energy from renewable sources and energy storage systems (ESSs) at a localized level. The increasing adoption of µGs/nGs is primarily driven by the previously mentioned urgent global need to incorporate DERs, such as solar power, into conventional energy frameworks. The energy transition not only helps curb CO_2 emissions but also lowers transmission losses and overall energy costs. Additionally, µGs and nGs can operate independently from the primary grid when necessary, functioning as self-sufficient and controllable energy entities [4]. Their effectiveness is further enhanced by integrating smart communication and information infrastructures, enabling a more sustainable and demand-responsive energy distribution.

Nowadays, the recent energy community (EC) planning enable local groups to collaborate and invest in renewable energy [5]. By functioning as a unified entity, these communities gain the ability to participate in energy markets on equal terms with other market players. According to EU law, energy communities can be organized as various types of legal entities, such as associations, cooperatives, partnerships, non-profit organizations, or limited liability companies. At the same time, EC foster collective, citizen-led initiatives that aid in the clean energy transition. They can help enhance public support for renewable energy projects and attract private investments to accelerate the shift toward clean energy. By empowering citizens, ECs offer an effective way to restructure energy systems, enabling local participation in the transition. This leads to benefits such as alleviated energy poverty, and the creation of more local green job opportunities [6]. Recognising the potential contribution of energy communities in achieving a more secure, affordable and cleaner energy system for Europe, the *REPowerEU* Plan [7] put forward the shared political objective of achieving one energy community per

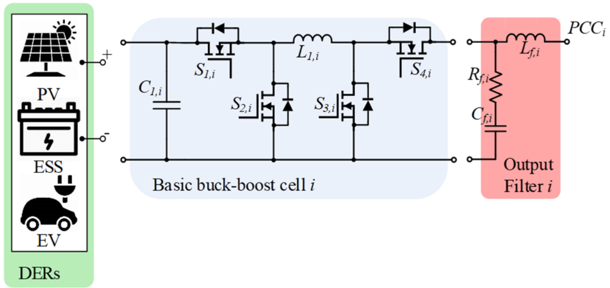

Fig. 1. Basic cell of the dual-purpose dc-dc/ac modular PC.

municipality with a population of more than 10.000 by 2025. Regardless of the architecture (µGs, nGs or ECs), it is evident that PCs will consistently have a significant presence, thereby leading these smaller systems to contribute to the concept previously coined as the power electronics-dominated systems [8].

Furthermore, since the majority of DERs generate dc power, additional equipment is required to interface with an ac grid, resulting in a reduction in conversion efficiency. These hybrid systems consist of multiple ac and dc network buses connected through an interlinking converter (IC), which manages power flow between the two sides. In order to contribute on this trend, the basic cell of the dual-purpose PWM power converter was designed to be used in dc grids and in ac grids [9], employing the same terminals (Fig. 1). This PC concept, supported by advanced control systems, will enhance the flexibility, versatility, modularity, resilience, and efficiency of the transition to a green electrical energy system, where both dc and ac infrastructures coexist into the explained µGs, nGs or ECs. Moreover, a dead-beat-type current control for the dual-purpose dc-dc/ac PWM modular PC was recently studied [10]. The proposed current controller is verified with successful results in four different applications: from dc to three-phase ac conversion with three-wire and with four-wire configurations, and from dc to unipolar dc and to bipolar dc conversion (see Fig. 2). A model-free deep reinforcement learning (DRL)-based current control methodology was proposed for that dual-purpose PC, from dc to three-phase ac (with three-wires) and from dc to unipolar dc [11].

Motivated by the modularity and simplicity of the basic cell of the dual-purpose PWM power converter, this paper explores the arrangement and connection of multiple basic cells to simultaneously provide both dc and ac outputs. This type of topology is known as single-stage dual-output hybrid converter [12]. It combines features such as dual-output capability, a compact design, high efficiency, and versatility, making it an attractive option for a wide range of PC applications in µGs, nGs or ECs.

The paper is organized as follows: the proposed converter circuit diagram and operation are described in Section II. The paper presents simulation results in Section III. Then, it concludes with a comprehensive summary and final remarks in Section IV.

2. Proposed Converter Arrangement as Dual-Output Hybrid Converter

Any subsystem of a µG or nG system may feature a single dc input and simultaneous dc and ac outputs. This task can be addressed by a dedicated power converter-based design or by a hybrid converter-based design, as depicted in Fig. 3. In here, Fig. 3 a) illustrates a conventional dual-output converter that utilizes renewable energy sources (such as PV, wind, fuel cells, or batteries) as the input dc source (v_{in}) to supply both dc (v_{dc}) and ac (v_{ac}) loads. The architecture of this converter relies on two separate converters (dc/dc and dc/ac) to meet the demands of dc and ac loads. In contrast, Fig. 3 b) features a single-stage PC that achieves the same functionality while offering improved voltage boost capability. As a result, the second converter in Fig. 3 b), referred to as a single-stage dual-output hybrid converter, provides higher power conversion density and enhanced reliability, among others.

The proposed single-stage dual-output hybrid converter is composed by several fundamental units or cells as

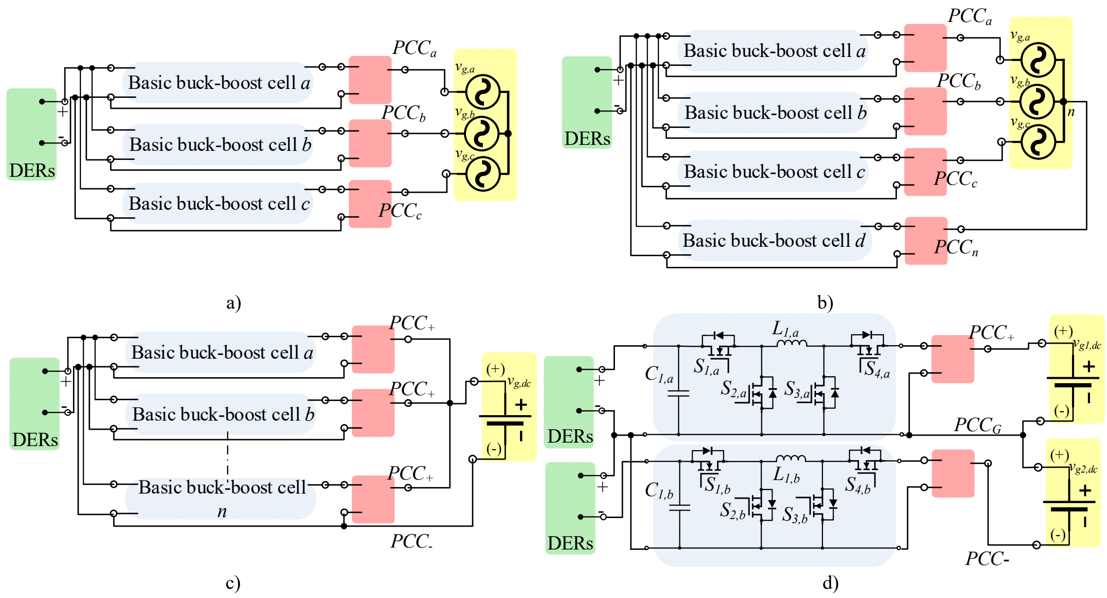

Fig. 2. Proposed configurations in [10]: a) three cells for dc-ac three-phase three-wire. b) Four cells for dc-ac three-phase four-wire. c) n cells for dc-dc (interleaved) and d) two cells for dc-dc bipolar.

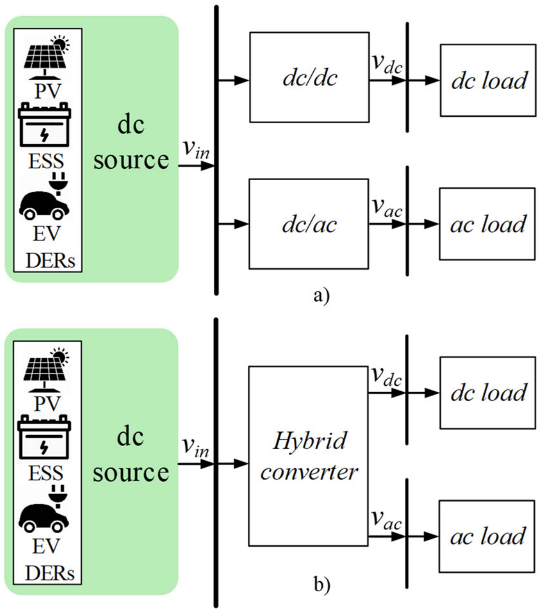

Fig. 3. nG system featuring a single dc input and simultaneous dc and ac outputs: a) a dedicated power converter-based design. (b) A hybrid converter-based design.

illustrated in Fig. 1. The fundamental unit comprises four power switches (denoted as $S_{1,i}$, $S_{2,i}$, $S_{3,i}$ and $S_{4,i}$, with i denoting each basic cell i), one capacitor ($C_{1,i}$), and an inductor ($L_{1,i}$). It is worth noting that a second-order LC filter ($C_{f,i}$ and $L_{f,i}$) with passive damping ($R_{f,i}$), highlighted in the red box in Fig. 1, is included to mitigate the propagation of higher harmonic components. To gain a comprehensive understanding of the operational principle of the basic cell, it is essential to recognize that this basic buck-boost cell operates in a unipolar manner, achieving a relatively high conversion ratio for both step-down and step-up applications.

For any basic cell i in dc to ac operation, and assuming a three-phase ac system as generalization, the instantaneous reference voltage for each phase can be represented as $v_i^*(t) = V_{off} + \hat{V}\sin(\omega t + \varphi_i)$. Here, V_{off} is the dc bias, $\hat{V}$ is the peak voltage and ω and φ_i are the angular pulsation and phase respectively. Each phase is shifted by 2π/3 radians relative to the others, and the differential dc bias voltage across the load is zero. Depending on the v_{in}, only boost, only buck, or alternating buck and boost conversions are performed. Given the output voltage range of a photovoltaic string, typically between 250 V and 450 V, the converter will predominantly operate by transitioning between boost and buck modes.

In the buck mode, the duty cycle for $S_{1,a}$ ($D_{S1,a}$) is given as (note that phase a is used as example):

$$D_{S1,a} = \frac{v_a^*(t)}{V_{in}}, \tag{1}$$

meanwhile $S_{2,a}$ switches in a complementary way. Furthermore, $S_{3,a}$ and $S_{4,a}$ are turned OFF and ON respectively. During the voltage boost, the corresponding duty cycle for $S_{3,a}$ ($D_{S3,a}$) is expressed as:

$$D_{S3,a} = 1 - \frac{V_{in}}{v_a^*(t)}, \tag{2}$$

with S_4 operating in a complementary way, and S_1 and S_2 turned ON and OFF respectively.

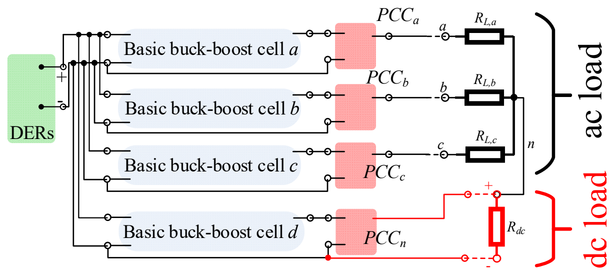

Fig. 4. Proposed converter topology of the dual-output hybrid converter based on the dual-purpose dc-dc/ac basic cell.

Similarly, considering that the fundamental cell operates in dc-dc mode, regardless of whether it functions as a boost or buck converter, the reference voltage will remain at a constant predetermined value.

The circuit diagram of the proposed single-stage dual-output hybrid converter based on the dual-purpose dc-dc/ac PWM Modular PC is represented in Fig. 4. In here, three basic buck-boost cells (a, b and c) operating from dc to ac, interface the DER with a three-phase four-wire ac load. Each cell generates a dc-biased sinusoidal PWM voltage waveform, with a sinusoidal component phase-shifted 2π radians relative to the other. Simultaneously, a dc load is connected between the output of a fourth cell (called d) and the negative pole. The neutral of the three-phase load is connected to the positive terminal of the dcload. The voltage value of this pole must match with the nominal dc voltage level [13].

3. Simulation Study and Discussion

To verify the theoretical claims presented earlier and assess the potential performance of the proposed single-stage dual-output hybrid converter based on the dual-purpose dc-dc/ac PWM Modular PC, the system was modelled and implemented using PLECS simulation software. An analysis in open loop operation was carried out across different scenarios, paying attention on the main waveforms in both steady and in transient states. The main simulation parameters and their values are listed in Table I.

Table I. – Main parameters and values.

	Parameter	Value
Basic cell	Input capacitor ($C_{1,i}$)	500 µF
	Cell inductor ($L_{1,i}$)	1.6 mH
	Cell resistance inductor	0.1 Ω
Filter	Filter capacitor ($C_{f,i}$)	10 µF
	Damping resistor ($R_{f,i}$)	0.3 Ω
	Filter inductor ($L_{f,i}$)	1.273 mH
	Filter resistance inductor	0.1 Ω
Switching frequency (f_s)		50 kHz
Input voltage (v_{in})		300 V
Peak ac voltage ($\hat{V}$), angular puls. (ω)		325 V, 314 rad./s
dc bias in ac reference voltage		350 V
dc reference voltage		350 V
ac loads	ac load 1	3000 W (52,9 Ω)
	ac load 2	2000 W (79,35 Ω)
dc loads	dc load 1	800 W (153,13 Ω)
	dc load 2	400 W (306,25 Ω)

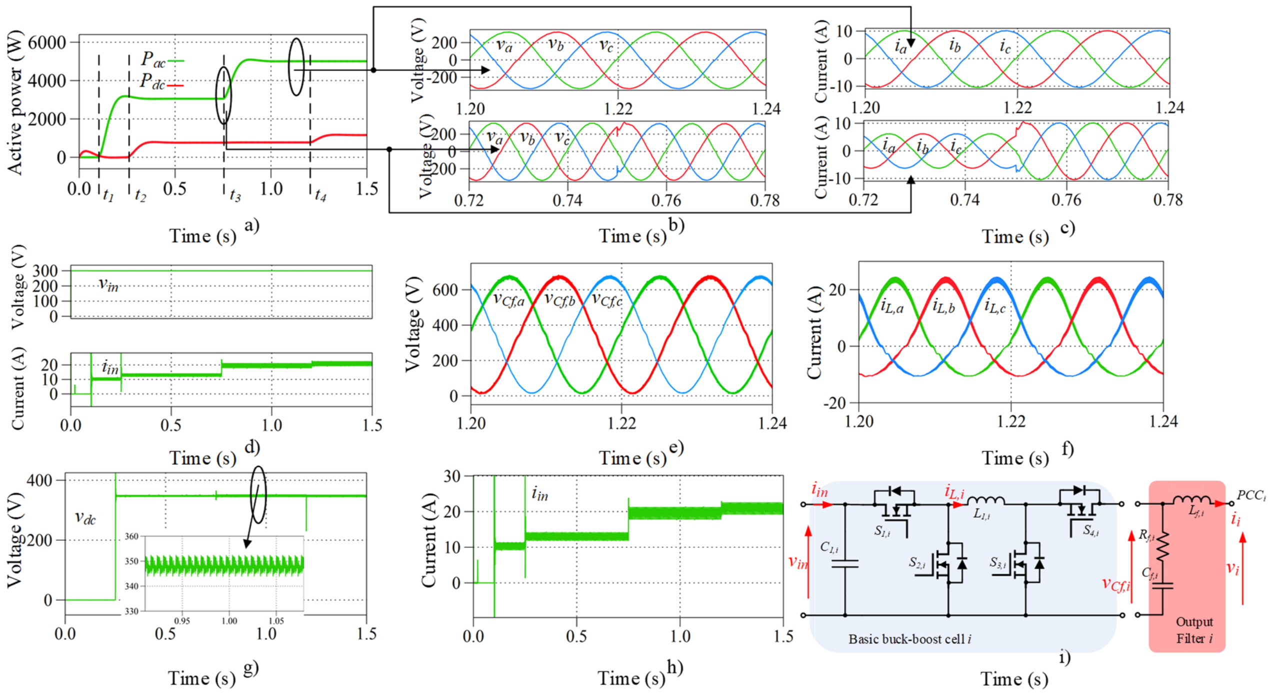

Fig. 5. Main waveforms of the simulation study: a) active power evolution in each output port, ac (P_{ac} in green line) and dc (P_{dc} in red line). b) ac load voltages v_i in steady state (top) and in transient state (bottom). c) ac load currents i_i in steady state (top) and in transient state (bottom). d) v_{in} and i_{in}. e) Capacitor voltages in the dc to ac port ($v_{Cf,i}$). f) Converter inductor ac currents ($i_{L1,i}$). g) Output voltage at the dc port (v_{dc}). h) Input current (i_{in}). i) Main electrical variables in the basic buck-boost cell.

Fig. 5 a) to h) presents the key waveforms observed under both steady-state and transient conditions. For an easier understanding, the different electrical magnitudes are specified in the basic buck boost cell (see Fig. 5 i) that constitutes the proposed circuit shown in Fig. 4. Fig 5 a) displays the active power evolution in each output port, ac (P_{ac} in green line) and dc (P_{dc} in red line), respectively. In particular, and considering the main specifications listed in Table I, the ac load 1 demands 3000 W. The dc to ac output starts switching at t_1 = 0.1 s. At t_3 = 0.75 s. the ac load 2, with a nominal power equal to 2000 W is connected at the same output port. Similarly, the dc load 1 demands 800 W in its corresponding dc port. This power conversion is performed by the cell d (see Fig. 4), which has implemented a PWM enable at t_2 = 0.25 s. At t_4 = 1.2 s. the dc load 2, with a nominal power equal to 400 W is also connected.

Fig 5 b) represents the ac output voltages (v_i). The peak reference voltage is set at 325 V between the phase and the neutral wires. It is worth noting that, despite exhibiting proper performance, a slight voltage drop can be observed in the zoomed-in view (bottom) after t_3 = 0.75 s. This phenomenon occurs because an increase in power demand leads to a greater voltage drop. It is important to emphasize that the system operates in an open-loop configuration; therefore, this issue can be effectively mitigated using a closed-loop voltage control mechanism. The ac output currents (i_i) and a zoom-in view are shown in Fig. 5 c). The system performance is correct. The total current harmonic distortion (THD_I) was measured and its value was below 3 %.

As illustrated in Fig. 5 d), the applied input voltage v_{in} was equal to 300 V. This implies that alternating buck and boost conversions are performed at the dc-to-ac port, while only boost conversion occurs at the dc-to-dc port. The filter capacitor voltage ($v_{Cf,i}$) is illustrated in Fig. 5 e). The measured output voltage in the capacitors includes the dc V_{off} along with the sinusoidal component, resulting in the expected peak voltage value ($\hat{V}$) around 675 V. Thus, the unipolar operation of the basic cell is verified. Fig. 5 f) shows the converter inductor current ($i_{L,i}$). This waveform is characterized by the 50 Hz pulsation during the buck mode and 100 Hz pulsation in the boost mode [10].

In Fig. 5 g) the dc output voltage (v_{dc}) synthetized by the cell d is displayed. The dc reference voltage is set at 350 V according to the standards, which is properly tracked by the system. It is worth noting that, despite exhibiting proper performance, a voltage ripple can be observed in the zoomed-in view (bottom) after t_3 = 0.75 s. This phenomenon is expected to be improved by selecting a better output filter value. Finally, the total input current (i_{in}) demanded by the two ports of the proposed single-stage dual-output hybrid converter based on the dual-purpose dc-dc/ac PWM Modular PC is represented in Fig. 5 h). The different port connections (ac port and dc port at t_1 = 0.1 s and at t_2 = 0.25 s respectively) and load connections (ac load 2 and dc load 2 at t_3 = 0.75 s and at t_4 = 1.2 s respectively) can be observed with their corresponding step responses.

4. Conclusion

This study presents a new configuration of the basic cell designed for a dual-purpose dc-dc/ac PWM modular power converter. Specifically, it introduces a novel single-stage, dual-output hybrid converter capable of simultaneously supplying three-phase four-wire ac loads and dc loads. This converter is particularly useful as an interlinking device in hybrid nG applications.

The core concept is based on connecting the ac neutral point to the positive dc terminal. The system is evaluated through open-loop simulations, confirming the feasibility of the approach and its proper operation. While the initial results are promising, overall performance is expected to improve under closed-loop control. Future work will further investigate grounding interactions between ac and dc systems, as well as power quality challenges when supplying nonlinear loads.

Acknowledgements

This work was supported by the Grant PID2022-137345OA-I00 funded by MCIN/AEI/10.13039/501100011033 and “ERDF A way of making Europe”, and by Grant FPU22/01376 funded by MCIN/AEI /10.13039/501100011033 and by “ESF Investing in your future”. It was also supported by the project GR24040 (Government of Extremadura and “ERDF A way of making Europe”), and in part by the Estonian Research Council grant (PUTJD1209).

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