Efficient GaN Interface for emerging self-consumption scenarios in DC microgrids

Massimo Merenda
Department of Information Engineering, Infrastructures and Sustainable Energy (DIIES) and HWA s.r.l.-Spin Off of the University Mediterranea of Reggio Calabria
Reggio Calabria, Italy
massimo.merenda@unirc.it

Giovanna Adinolfi
ENEA C.R. Portici and Department of Industrial Engineering, University of Salerno
Piazzale Enrico Fermi 1
loc. Granatello Portici (NA), Italy
giovanna.adinolfi@enea.it

Demetrio Iero
Department of Information Engineering, Infrastructures and Sustainable Energy (DIIES) and HWA s.r.l.-Spin Off of the University Mediterranea of Reggio Calabria
Reggio Calabria, Italy
demetrio.iero@unirc.it

Angelo Merola
ENEA C.R. Portici
Piazzale Enrico Fermi 1
loc. Granatello Portici (NA), Italy
angelo.merola@enea.it

Giorgio Graditi
ENEA C.R. Portici
Piazzale Enrico Fermi 1
loc. Granatello Portici (NA), Italy
giorgio.graditi@enea.it

Francesco Giuseppe Della Corte
Department of Information Engineering, Infrastructures and Sustainable Energy (DIIES) and HWA s.r.l.-Spin Off of the University Mediterranea of Reggio Calabria
Reggio Calabria, Italy
francesco.dellacorte@unirc.it

Abstract—**Nowadays it is increasingly pressing the need of efficient and reliable DC-DC interfaces especially in emerging energetic scenarios. In fact, Distributed Energy Resources and recent smart DC grid paradigms require appropriate conversion systems toward DC bus. Silicon based circuits have represented main actors during last sixty years electronics exhibiting thermal and frequency limits only in recent applications. Advancements in Wide Band Gap technologies represent strengths to fulfill Distributed Energy Resources interfaces requirements both in terms of energetic and thermal improvements. This paper focuses on a GaN based DC-DC interface able to connect renewables, loads and storage systems in emergent DC microgrids. In fact, its modular structure matches wide input/output voltage and current specifications. The proposed GaN interface assures monitoring, diagnostics and communication features so permitting interoperation with DC microgrids controllers and energy self-consumption enhancement.**

Keywords—DC microgrids control, Data center, FC, GaN, RES integration, Self-consumption, V2H.

I. Introduction

Energetic scenario has been deeply changed both in terms of generation, storage and consumption units [1]. Distributed sources, (i.e. Photovoltaic, wind, etc) and microsources have been widespread installed initiating bidirectional power flows in traditional unidirectional AC grids. In this context network systems and equipment should be revised, rearranged or updated to match the current and prospective power flows characteristics [2]. It is worth noting Distributed Generation (DG) and their energy introduction in the AC national grid can cause criticality in terms of stability and power quality [3]. Suitable protection devices [4], control and power interfaces have begun mandatory.

Nowadays, everyone is usual and continuous user of DC loads and equipment. PCs, mobiles, Electric Vehicles, care and clean appliances represent only a few examples of recent DC consumption units.

Adequate interfaces are necessary for connecting each of them to the AC network or to the bus of DC microgrid [5], [6].

In addition, in these last years, Energy Storage Systems (ESS) have become more appealing in joined installations [7] “PV+ storage” and also in electric and hybrid mobility [8]–[12]. In this scenario, it is evident the increasing request of performant power interfaces. Published reviews and comparative analyses about different DC-DC systems underline the tight relationship among DC-DC interfaces performances and switching devices properties.

Advancement in Wide Band Gap (WBG) GaN technologies have permitted overcoming Silicon devices drawbacks so allowing the realization of performant solutions able to assure attracting energetic and thermal behavior.

In this work, the design and prototyping of a conversion interface with an "interleaved" topological structure is proposed both for reasons of reliability and for the optimization of the overall performance of the circuit. The converter interface is characterized by a peak power of 400-450W, an input current up to 10A and a maximum voltage of 70V [13]. This DC-DC regulator can be suitably matched to Renewable Energy Sources (RES), DC loads and storage units to adapt different systems voltage outputs to the common DC bus magnitude, also connecting different converter modules. The adoption of a custom microchip in FPGA technology ensures a configurable control section (*logic board*) with appropriate speed data processing. Due to the flexible embedded control system, the proposed solution represents a compatible interface also in self-consumption power systems.

In fact, in this energetic context, power loss minimization and dedicate control and resources schedule are necessary to the continuous energetic balance.

It is worth noting self-consumption communities represent a promising energetic paradigm. In fact, they assure RES integration, transmission and distribution losses decrease. They can also mitigate grid stability criticalities.

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In addition, the circuit features a Wi-Fi communication which enables real-time monitoring and remote diagnostics services.

This paper is organized as follows. Section II is dedicated to DC Microgrids interfaces description. In Section III details about GaN technologies and devices are reported. Results and experimental characterization are presented in Section IV. Conclusions are reported in Section V.

II. DC MICROGRIDS

Microgrids (MGs) are internationally defined as groups of interconnected loads and distributed energy resources within clearly limited electrical boundaries, which act as single controllable entities with respect to the main grid [12].

AC MGs architectures result still realized. In addition, last technological improvements and regulation also aim to DC MGs application and hybrid AC-DC power systems introduction in traditional AC networks. In this paper, the focus is on DC self-consumption MGs as emerging and promising energetic paradigm to favor RES and ESS integration reducing AC grid stability problems. A self-consumption MG configuration is schematically reported in Fig. 1.

In this context a huge requirement is the definition of power interfaces able to suitably connect the different generation, loads and storage units to the DC bus. In detail, in case of residential application, the proposed GaN regulator can be applied for each PV generator in order to maximize the produced power by the embedded Maximum Power Point Tracking (MPPT) algorithm. Some modules can be adopted to connect the ESS also allowing Vehicle-To-Home (V2H) charge and discharge operations for electric cars, scooters, bicycles, etc.

In this case, the embedded interface control implements the Battery Management algorithms. In addition, the DC bus, by means of one or more module of the proposed solution, can adequately supply LED lights and other appliances. These modules can reach satisfying performance taking advantages of emerging WBG technologies improvements and relative switching devices behavior.

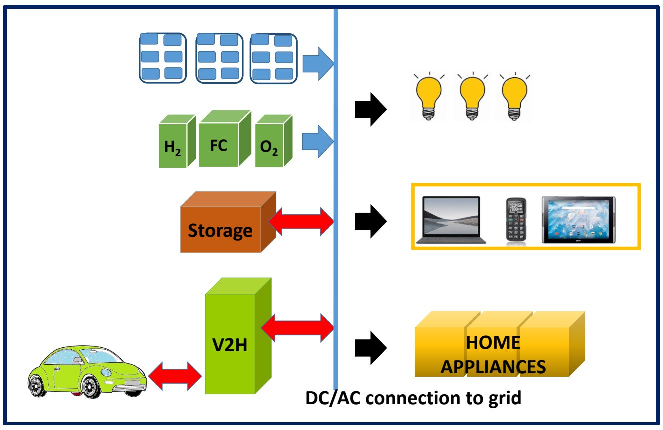

Fig. 1. Self-consumption DC MG example

III. GAN TECHNOLOGY AND DC INTERFACE

The unique material properties of GaN such as wide bandgap, high breakdown voltage, high thermal conductivity and electron mobility pave the way to the realization of devices as GaN High Electron Mobility Transistor (HEMT) which show interesting device properties as well as low parasitic capacitance, low turn on resistance and high cut off frequencies. GaN characteristics as high output power density and high operational voltage make GaN a game changer in medium and high power applications [14].

Therefore, these advanced devices result particularly suitable in MG interface converters. In fact, in DC MGs, such as data centers and telecommunication systems ones, high efficiency, small size, low weight and circuits hot spot avoidance represent stringent requirements. Furthermore, GaN HEMT output power can be increased about four times when compared with same transistor size GaAs devices [15]. Increased power density indicates more power per unit area and thus more functionality can be implemented in the same area. Also, the reduction of cooling systems, both active and passive, is allowed by the adoption of this technology so providing thermal performant solutions also in severe conditions, such as in high power applications or/and in high operating temperature [16].

The proposed GaN interface is designed by the Open-Source Hardware Platform for Smart Converters with Cloud Connectivity [13]. In detail, the power board has a buck-boost based architecture in order to satisfy appliances, storage and source voltage requirements toward the MG DC bus.

The GaN FETs selected for the power board are the Texas Instruments LMG5200. The device consists of two GaN HEMT [17], with an integrated high frequency driver. This integrated circuit support up to 80 V drain-source voltage and 10 A drain current. They are very suitable for use at very high switching frequencies (up to 10 MHz) and they results advantageous for their low power losses. In fact, they are characterized by small input charge and small on resistance. In addition, these devices can assure near zero reverse recovery, minimum parasitic elements and small size, so favoring converters performance improvement.

The developed Open-Source Hardware Platform [13] is also capable of codes validation, allowing tests of different current and voltage-controlled algorithms for RES and MG applications. The control board include the iCE40UP5K UltraPlusTM FPGA [18], a dsPIC33EPXXGS50X microcontroller [19], and a WGM110 Wi-Fi module [20]. The FPGA generates the PWM control signals and implements bootstrap and interleaved control logic. The microcontroller acquires currents and voltages from the power circuit running, in conjunction with the FPGA, the power conversion algorithms. Therefore, both the DC-DC regulator power and the control boards can be designed with particular attention on sources, loads and storage system specifications in terms of electro-thermal requirement and management and schedule firmware strategies.

IV. EXPERIMENTAL VALIDATION AND RESULTS

The Open-Source Hardware Platform [13] is employed to design an adaptable GaN converter able to fulfill different DC

MGs interface needs.

In detail, voltage, current and power range specifications are identified taking into account the single and multiple converters application.

DC MG bus voltage value and range are not still standardized. As shown in Fig. 2, the GaN interface can be employed to interface PV generators array or other RES sources to a (200-400) V bus.

Furthermore, the same GaN converter can be used in single or multiple combination to (48-60) V bus connection.

In Fig. 3, some possible applications are reported. Single GaN converter can be applied to fulfill Fuel Cells (FCs), computers and other portable devices, but also to charge Electric Vehicles (EVs) such as bicycles and scooters. Multiple GaN converter can be shunt to satisfy current requirements such as in Data Centers racks.

At the design step end, the GaN converter has been prototyped and then experimentally characterized at ENEA – National Agency for New Technologies, Energy and Sustainable Economic Development – labs. Its performances are measured, mainly in terms of conversion efficiency and ability to hook the control objectives. Experimental characterization are carried out on a single GaN converter module, at different power input to experimentally emulate the previous mentioned applications. The converter is also tested by Solar Array emulators [21] and with precision power measurement methods [22], [23],[24].

In any case, it should be noted that the extreme versatility of the designed circuit, both in terms of firmware and hardware components, makes it possible to experiment with a wide number of configurations, which could show performances even promising than those achieved in this first testing phase.

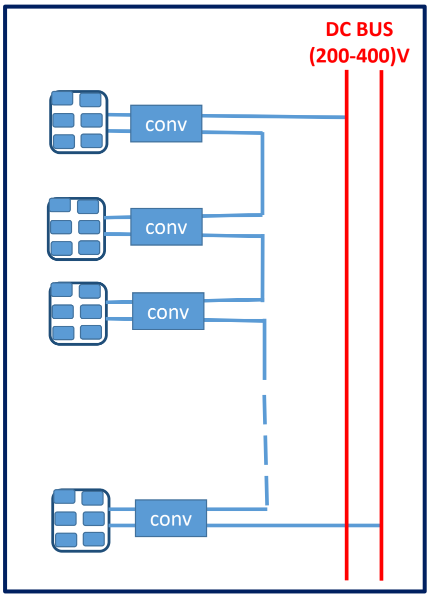

Fig. 2. DC (200-400)V bus interface example

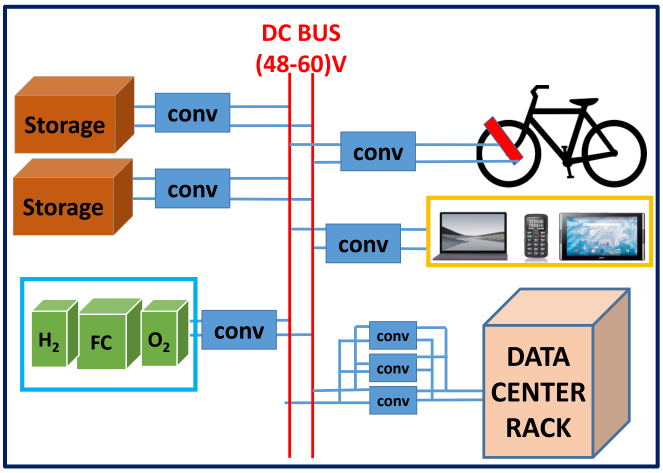

Fig. 3. DC (48-60) V bus interface example

A. Efficiency

Efficiency performance of a single GaN converter module are validated in different operating conditions, not only in terms of input power, but also for different dead-time and frequency values. The GaN FET power board shows overall good performances (Fig. 4). In fact, efficiency is always above 96% for all test conditions. Efficiency decreases almost linearly with increasing dead-time and switching frequency. In particular, the best values are obtained for a dead-time $D_t = 21$ ns and a switching frequency $f = 80$ kHz. The use of GaN devices assures higher efficiency than the silicon based prototype tested in [13]. In case of high current applications, as shown in Fig. 3, different GaN regulator modules can be paralleled so decreasing switches Drain-Source resistance and reducing the whole DC interface conduction losses. The realized converter also presents a by-pass mode to face first failure condition so providing a reliable behavior in case of critical operations. During bypass mode, the efficiency is between 98.3% and 99%.

B. MPPT performance

The control performances of the proposed DC converter are validated. As an example, the converter control performance is shown in Fig. 5 in case it is applied as Smart MPPT device to PV integration in DC MGs.

The implemented tracking technique consists in Perturbation and Observation (P&O) algorithm. The GaN converter is experimentally tested at different open circuit voltage and PV power values. A Solar Array Simulator equipment permits to validate converter performance when matched with different PV generators. Results are reported for PV generator power of 128 W. The MPP is reached at 99.9%, showing a good speed of convergence (from boot) and of response to a variation of the condition in the on state. The same algorithm and control firmware can be used to track FC Maximum Power Point. It is worth noting the embedded FPGA allows the implementation of accurate and complex codes to MG devices and systems control, schedule and monitoring. In detail, main circuits voltages and currents, the switching frequency and other parameters can be continuous monitored. MGs users can verify these parameters in real time by the relative web Server.

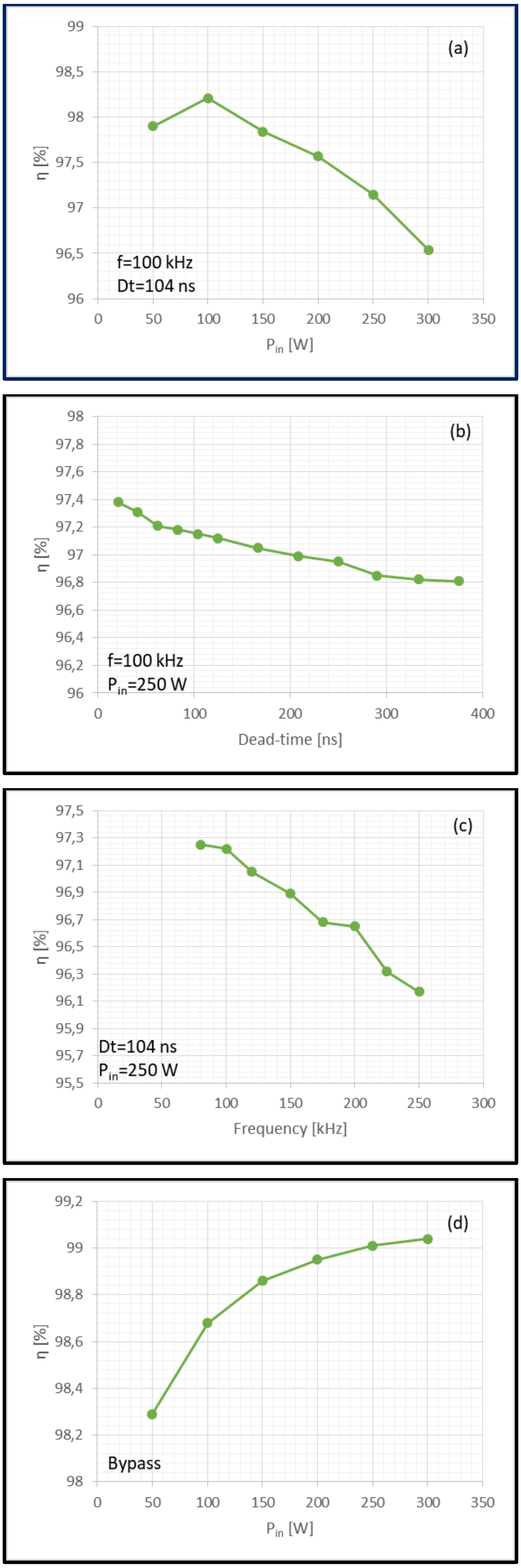

Fig. 4. Efficiency measurements with the variation of the input power (a), the dead-time (b), the switching frequency (c) and the bypass condition (d).

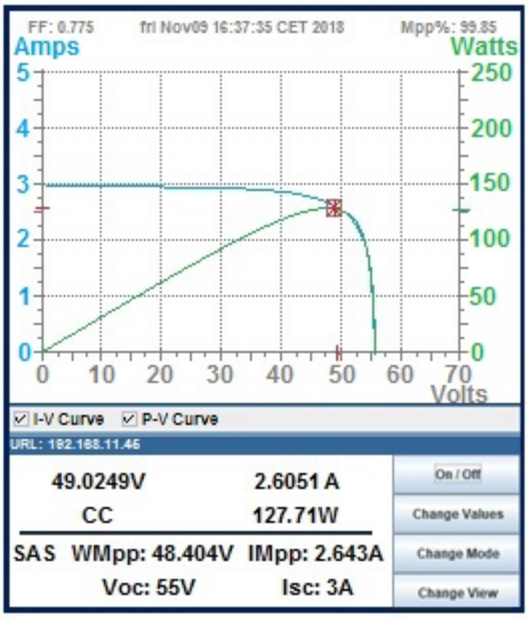

Fig. 5. SMPPT with FET in GaN, convergence to the Maximum Power Point for P_{in} of 128 W.

V. Conclusion

In this paper a DC-DC regulator is proposed for DC MG applications. The DC-DC interface is realized employing GaN HEMT switching devices to reach high performance solution able to adequately match generation, load and storage systems. The GaN interface is designed by the Open-Source Hardware Platforms and it is prototyped and tested at the ENEA Research Center (Portici, Italy). Obtained results show the GaN interface adequacy to the analyzed applications assuring efficient energetic behavior and control features, with a conversion efficiency above the 96% in all test conditions, and above 98% for a properly selected combinations of operational parameters suitable for normal operations.

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