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New 600V GaN Single-Stage Isolated Bidirectional 400V Input Three-Phase PFC Rectifier

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***Abstract*—This paper introduces a novel single-stage isolated bidirectional partly modular three-phase power-factor-correction (PFC) rectifier topology that requires half the blocking voltage rating of the primary-side transistors compared to conventional monolithic three-phase circuit arrangements. Specifically, interfacing a 400 V three-phase grid to a 400 V dc output is possible using modern high-performance 600 V GaN transistors in standard half-bridge configurations instead of 1200 V SiC devices or multilevel bridge-leg structures. The topology is also applicable for solid-state transformers connected to the medium-voltage grid, e.g., a 4.16 kV grid can be interfaced using 6.5 kV IGBTs. Further, emerging 600 V monolithic bidirectional GaN transistors (or, similarly, future bidirectional HV SiC devices) enable further variants of the proposed topology with only half the primary-side power transistor count.**

***Keywords*—Three-phase ac-dc converter, 600 V GaN, high-frequency isolation, single-stage power conversion, solid-state transformers.**

I. Introduction

Traditionally, isolated three-phase power-factor-correction (PFC) rectifiers generating a 400 V dc bus voltage from the European 400 V three-phase mains (565 V peak value of the line-to-line voltages) are two-stage systems that comprise a PFC ac-dc rectifier front-end and an isolated dc-dc converter with a high-frequency (HF) transformer; typical applications are, e.g., EV chargers [1] or datacenter power supplies [2]. Advantageously, three-phase ac-dc PFC rectifiers with *integrated* HF isolation allow to omit the isolated dc-dc converter and thus realize single-stage power conversion, which promises higher efficiency and/or more compact realizations. However, typically the primary-side switching stages require 900 V or 1200 V transistors because the line-to-line voltage defines the blocking voltage; this is, e.g., the case for the well-known three-phase (mains frequency) to single-phase (HF) matrix converters [3]–[6] and for the reduced-switch-count topology from [7], [8]. It also holds true for phase-modular (on the ac input side) topologies like [9] or those based on a Y-rectifier [10] ac input stage, where the dc offset needed to allow the use of standard half-bridge transistor configurations increases the blocking voltage requirement to about twice the phase voltage amplitude[1] [12], [13]. For example, the Y-rectifier-based single-stage isolated three-phase PFC rectifier recently presented in [13] requires at least 900 V SiC transistors for interfacing the 400 V mains; only the dc-side switching stage can employ modern high-performance 600 V GaN transistors [14].

In contrast, this paper proposes the novel single-stage isolated three-phase PFC rectifier topology depicted in **Fig. 1**, which results from combining three single-phase cycloconverters [15] with a three-phase HF transformer (or three individual single-phase HF transformers) and the dc-side switching stage from [13]. Advantageously, 600 V GaN transistors can be used for both switching stages (without resorting to multi-level bridge-leg arrangements) when interfacing a 400 V mains to a 400 V dc output.

II. Converter Concept

The basic function of the three primary-side single-phase ac (cycloconverter) stages [15] in **Fig. 1** is to generate a grid-voltage-amplitude-modulated HF differential-mode (DM) three-phase voltage system at the HF transformer's primary-side

[1]Alternative phase-modular variants like [11] limit the blocking voltage requirement to the phase voltage amplitude at the price of equipping each phase module with a low-frequency (LF) diode rectifier.

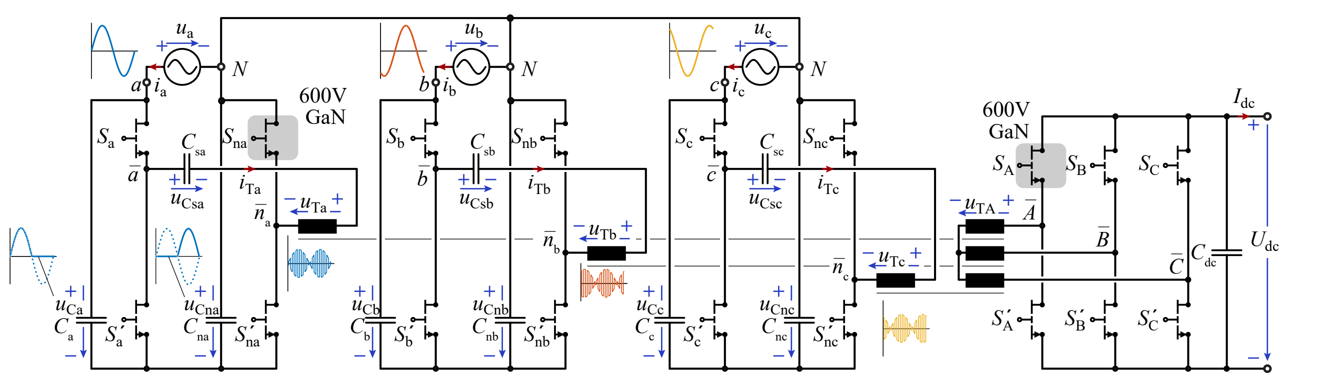

Fig. 1. Proposed single-stage isolated bidirectional three-phase PFC rectifier and conceptual key voltage waveforms. The system interfaces the European 400 V three-phase grid to a 400 V dc output voltage, and advantageously only employs modern 600 V GaN power transistors.

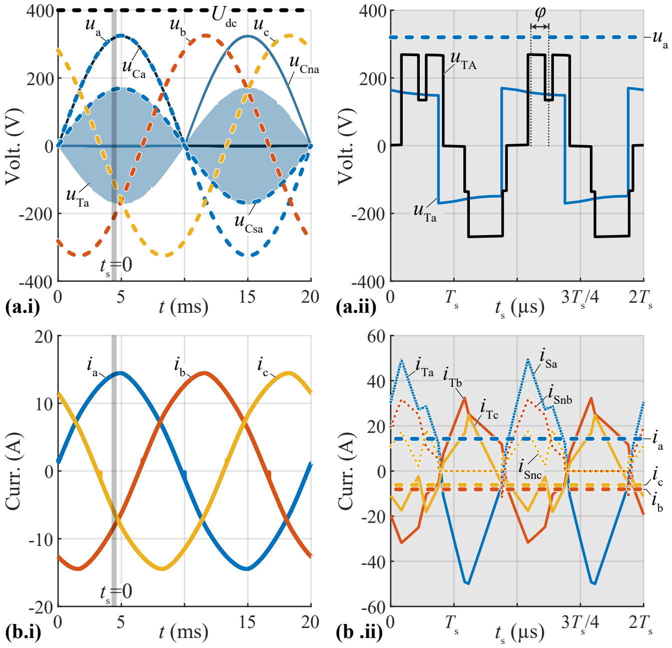

Fig. 2. Simulated voltage **(a)** and current **(b)** waveforms of the proposed topology (see **Fig. 1**) transferring a power of $P = 6.6\,\mathrm{kW}$ from the 400 V rms mains u_a, u_b, u_c to a $U_\mathrm{dc} = 400\,\mathrm{V}$ dc output (switching frequency $f_\mathrm{s} = 72\,\mathrm{kHz}$, transformer leakage inductance $L_\mathrm{s} = 9.9\,\mu\mathrm{H}$, DAB converter phase-shift $\varphi = \pi/4$). **(a.i)** Grid voltages u_a, u_b, u_c, module a input capacitor voltages u_Ca, u_Cna, and amplitude-modulated HF DM transformer primary-side voltage u_Ta; **(a.ii)** zoomed view of the HF transformer primary-side u_Ta and secondary-side voltage u_TA with the DAB converter phase-shift φ highlighted. **(b.i)** Sinusoidal LF grid currents i_a, i_b, i_c that are in phase with the respective grid phase voltages, and **(b.ii)** zoomed view of the HF transformer currents i_Ta, i_Tb, i_Tc and the currents of the currently active (i.e., operated with PWM) high-side switches i_Sa, i_Snb, i_Snc .

terminals. For brevity the modulation is detailed for phase module a only: The two half-bridges $S_\mathrm{a}/S'_\mathrm{a}$ and $S_\mathrm{na}/S'_\mathrm{na}$ are connected to the grid phase a and the neutral conductor terminal N, respectively. The half-bridge $S_\mathrm{a}/S'_\mathrm{a}$ operates with a duty cycle $d = 50\%$ for a positive grid voltage $u_\mathrm{a} \geq 0$, and both switches are turned on for a negative grid voltage $u_\mathrm{a} < 0$ such that the switch node $\bar{a}$ is clamped to the phase input terminal a. The second half-bridge $S_\mathrm{na}/S'_\mathrm{na}$ operates reciprocally to realize cycloconverter operation. This results in the unipolar voltage waveforms of the commutation capacitors u_Ca and u_Cna shown in **Fig. 1**. Thus, the line-to-neutral voltage amplitude (nominally 325 V for a 400 V mains) defines the transistor blocking voltage requirement and 600 V GaN transistors provide ample margin.

Further, the described modulation results in the depicted grid-voltage-amplitude-modulated HF DM transformer voltage u_Ta, while the series capacitor C_sa carries a low-frequency voltage $u_\mathrm{Csa} = 0.5u_\mathrm{a}$ (note that C_sa is sized such that it's impedance at the switching frequency f_s is small compared to the impedance of the transformer leakage inductance L_s). As the transformer primary-side voltages are identical to those from [7], [8], [13], dual-active-bridge (DAB) converter operation resulting in quasi-sinusoidal grid currents can be achieved by operating the secondary-side three-phase PWM rectifier with

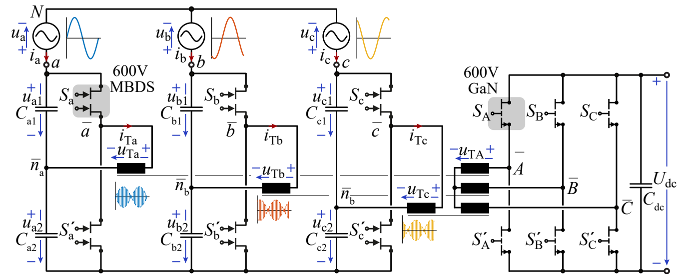

Fig. 3. Alternative realization of the single-stage isolated three-phase PFC rectifier (cf. **Fig. 1**), employing monolithic bidirectional switches (MBDSs); here shown interfacing a 400 V mains to a 400 V dc output using 600 V GaN MBDSs in the primary-side switching stage.

the space vector modulation (SVM) scheme from [7], [8].

Fig. 2 presents simulated (PLECS) voltage **(a.i)** and current **(b.i)** waveforms during one grid period of 20 ms, where the discussed cycloconverter operation of the ac stage of phase a and quasi-sinusoidal grid currents can be observed. **Figs. 2a.ii,b.ii** further detail the HF converter waveforms during two switching periods $T_\mathrm{s} = 1/f_\mathrm{s}$ for a grid angle of $80\,°$, highlighting the trapezoidal DAB-converter-type transformer currents. Note how the secondary-side transformer voltage u_TA balances the primary-side voltage u_Ta by means of a quarter-wave-symmetric SVM [7], [8]. As in any DAB converter, the phase shift φ between the primary-side and secondary-side HF transformer voltages controls the (bidirectional) power flow.

III. Topology Variants

Similar to the 400 V mains case, where the proposed topology allows to employ 600 V transistors, it is also advantageous for solid-state transformers (SSTs) interfacing the medium-voltage (MV) grid: scaling the voltages by roughly a factor of ten, a typical U.S. 4.16 kV MV grid could be interfaced using 6.5 kV IGBTs or SiC MOSFETs [16], whereas alternative topologies require 10 kV devices [17].

Further, emerging monolithic bidirectional switches (MBDSs) enable the topology variation shown in **Fig. 3** with reduced realization effort (half the number of active devices on the ac input side, no LF-blocking series capacitors). Whereas 600 V GaN MBDSs [18]–[21] are already available as engineering samples, SiC MBDSs are researched for MV applications, e.g., 15 kV bidirectional SiC IGBTs in [22].

IV. Conclusion

This paper introduces a novel bidirectional PFC rectifier topology providing single-stage HF-isolated power conversion between a three-phase mains and a dc output. Advantageously, the required transistor blocking voltage rating is cut in half compared to alternative circuits. For example, a 400 V three-phase mains can be interfaced using modern high-performance 600 V GaN transistors in two-level arrangements instead of 1200V SiC MOSFETs or multilevel bridge-legs. Similarly, an SST connected to the 4.16 kV MV grid could be realized with 6.5 kV IGBTs or SiC MOSFETs instead of 10 kV devices. For both cases, emerging monolithic bidirectional switches allow a further simplification of the topology.

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