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A Novel Soft-Switched Three-Phase Three-Wire Isolated AC-DC Converter With Power Factor Correction

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***Abstract*— A novel isolated AC-DC converter for three-phase three-wire systems is proposed in this paper. The proposed rectifier has a phase modular design, and the input side of the three-phase modules are connected in a Wye (Y) shape creating a virtual ground that allows true three-phase systems to be connected to the proposed AC-DC converter. Moreover, the proposed rectifier is based on the single-stage LLC resonant converter modules and has almost no switching loss due to the zero voltage and current switching performance for all the switching devices. Furthermore, no bulky DC-link E-capacitor is needed in the proposed rectifier and the output capacitor is also small due to canceled low-frequency ripple at the output. Hence, the proposed AC-DC converter is suitable for applications that demand high power density with high efficiency. Principles of operation, analysis, and design considerations for two different output voltage levels are discussed in the paper. Simulation results for two different output voltage levels verified soft-switching, power factor correction, and output voltage regulation. Furthermore, the validity of the proposed three-phase three-wire AC-DC converter is verified through the experimental results of a scaled-down hardware prototype with a unity power factor performance (>0.99) and maximum efficiency of 96.8%.**

***Keywords*— AC-DC converter, Phase-modular rectifier, power factor correction (PFC), three-phase three-wire, single-stage LLC.**

I. Introduction

Three-phase rectification is demanding in any high-power application with DC voltage requirement. For example, in data center architecture a 400 V DC bus is created from a three-phase grid and is directly connected to the server motherboard where 400 V to 12 V DC-DC converters are utilized to power various chipset level loads. Another example of high power three-phase AC-DC rectification is in Electric Vehicle (EV) charging stations to provide high DC voltage for directly charging the 400 V battery pack [1], [2].

In both mentioned applications, a wide range of DC voltage is required for different reasons. In data centers, in case of grid failure, it is required to provide power to the IC for some short time (e.g. tens of milliseconds) until the data in memory can be saved [3]. In an EV charging application when the battery is depleted it is required to charge the battery from a much lower voltage than the rated voltage of the battery pack [4]. In addition to the wide output voltage range for high power rectification in the mentioned applications, high-power factor correction (PFC) is another important feature that is a utility grid requirement to utilize the full capacity of the grid lines. Electrical isolation for safety reasons, high conversion efficiency, and high power density are other main required specifications for high-power AC-to-DC power conversion.

To achieve all the above-mentioned features, the common practice in the industry is to use a direct three-phase two-stage approach using a three-phase AC-DC converter for PFC and an isolated DC-DC converter for output voltage regulation. Fig. 1 (a) illustrates the conventional approach for direct three-phase AC-to-DC conversion to achieve the required specifications. One of the mainstream three-phase PFC converters for high power applications is the 2-level six switch boost rectifier that can achieve a sinusoidal current shape [5]. Another boost type three-phase AC-DC converter is Vienna rectifier with a 3-level structure that requires smaller inductors and has less switching loss as compared with the 2-level six switch boost rectifier [6].

On the other hand, buck-type rectifiers are also beneficial when a lower DC-link voltage is needed. Swiss rectifier is an improved version of the Integrated Active Filter (IAF) PFC rectifier that can achieve sinusoidal currents and high efficiency while using SiC switches [7]. For the front-end isolation and voltage regulation stage, it is common to use phase-shifted full-bridge or resonant converters due to their soft-switching characteristics, which allow high power conversion efficiency [8], [9]. Nevertheless, adding a second DC-DC stage for isolation and voltage regulation reduces the total AC-to-DC conversion efficiency and adds to the system volume and cost.

Another interesting approach for three-phase AC-to-DC conversion is the phase-modular structure that is shown in Fig. 1 (b). In this method, all the knowledge applied to a single-phase AC-DC converter can be exploited to build a three-phase rectifier [10]-[13]. Hence, the analysis and modulation are simple, and since the total output power is distributed between the three phases the thermal stress on single components is less than a direct three-phase AC-DC converter. The downside of the conventional phase-modular method is that each module should filter double line frequency pulsating power meaning large electrolytic capacitors are needed at the DC-link, which reduces the power density and reliability. Further, as the three modules are working separately, power balancing is another obstacle.

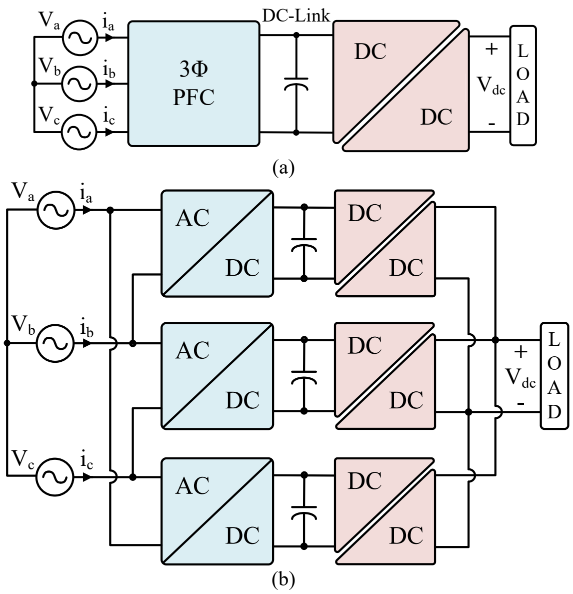


Fig. 1. Conventional three-phase two-stage AC-DC converters, (a) direct three-phase PFC rectifier, (b) phase-modular PFC rectifier.

To improve the overall conversion efficiency and power density of direct three-phase AC-DC converters, researchers have worked on several single-stage rectifiers in recent years [14]-[18]. In [14], a three-phase soft-switched boost-integrated bridge rectifier is proposed. Although soft-switching is achieved to reduce the power conversion loss, the PFC is achieved based on Discontinuous Conduction Mode (DCM) operation and hence the current ripple in switching devices is very high.

In [15], a single-stage three-phase AC-DC rectifier is proposed based on three primary bridges one for each phase and a single magnetic-integration transformer with a single output bridge for rectification. This converter achieves PFC without energy storage capacitors; however, the single magnetic-integration transformer is bulky and hard to manufacture. Another quad active bridge single-stage isolated three-phase AC-DC rectifier is proposed in [16]. This topology does not require any bipolar switches which makes it suitable for high power applications, however, it requires special modulation to achieve soft-switching and reduced circulation current. In [17], a nine switch single-stage three-phase rectifier is proposed that uses three relatively small size transformers and rectifier bridges at the DC side. This converter is the result of the integration of an Active Front End (AFE) three-phase boost rectifier and three half-bridge resonant converters. The mentioned topology remained unattractive until the advent of the wide-bandgap devices such as Silicon Carbide (SiC) MOSFETs that allow a high operating frequency to realize low THD for input current.

A three-phase bidirectional single-stage Dual Active Bridge (DAB-) based rectifier is proposed for EV application in [18]. In each phase, two switches are connected back-to-back to be able to block the line voltages and one transformer is utilized to connect to the output diode bridge. Although, the switching loss is eliminated in both the primary and secondary side switches that will allow increased switching frequency to improve power density, the RMS current and hence conduction loss, is increased resulting in reduced efficiency.

Phase-modular structure with a single-stage approach has been investigated during recent years by implementing various topologies and configurations [19]-[23]. An active clamp boost converter is used on each phase of a phase-modular three-phase AC-DC converter in [19]. This converter only uses two complementary switches on each phase that make the modulation and control simple. It can achieve unity power factor and soft-switching over a wide load range, however, the output is not isolated from the grid. In [20], a single-stage phase-modular three-phase isolated Cuk rectifier is proposed that uses a DCM inductor to realize PFC. Although a simple control is used, large power loss in active and passive components makes this converter unsuitable for applications that demand high power. In [21], a phase-modular three-phase AC-DC converter is proposed using a full-bridge boost PFC integrated with a half-bridge series-resonant converter. The AC side inductors exhibit DCM operation to achieve PFC and hence similar to other non-active PFC converters suffer from high ripple current.

An interesting phase-modular three-phase rectifier is proposed in [22] using interleaved bridgeless boost modules that eliminate the input bridge rectifier. This topology is compatible with both single-phase gird voltage and three-phase grid voltage, which makes it suitable for EV On-Board Charger (OBC) applications. A GaN-based phase-modular designed three-phase AC-DC converter using DAB converter modules is proposed in [23]. Dual-phase shift control alongside variable switching frequency is used to achieve soft-switching and PFC without too much compromising the RMS current. Although this converter seems interesting its modulation and control are complex and require multiple DQ transformations and online calculations to achieve soft-switching over the line cycle.

Resonant converters have been used as the front-end converter for various low to high DC voltage applications [24]-[26]. The advantage of these resonant converters is that soft-switching can be achieved for both the primary side bridge as well as the secondary side bridge. The disadvantage of the resonant converters is that they require wide frequency variation over diverse input and\or output operating voltage range that limits magnetics optimization. As compared to soft-switching PWM converters such as phase-shifted full-bridge or DAB converters it is usually easier to achieve high-efficiency and low circulating current at a high switching frequency. Different from the huge amount of research on LLC converter's application in DC-to-DC conversion, only in recent years a keen interest can be seen in the PFC operation of LLC converter [27]-[31].

In this paper, LLC resonant converter with PFC functionality is implemented in a phase-modular three-phase structure with a virtual neutral connection at the input that allows using 600V mainstream switching devices with a true three-phase system. All the switches operate with Zero Voltage Switching (ZVS) or Zero Current Switching (ZCS) conditions, hence the main power loss is conduction loss which makes the proposed AC-DC converter suitable for high frequency implementation. The structure and main characteristics of the proposed AC-DC converter are demonstrated in Section II. Section III shows the analysis and design guidelines of a single module for two different output voltage levels. Section IV shows the simulation and experimental results taken from a GaN-based laboratory prototype. Finally, the conclusion is provided in Section V.

II. The Proposed Three-Phase Three-Wire AC-DC Converter with Y Input

Fig. 2 illustrates the proposed isolated three-phase AC-DC converter for a true three-phase system with three AC lines. This structure is phase-modular and it comprises three LLC modules that are switched individually via a single microcontroller to achieve PFC in all three phases. Each module consists of an unfolding diode bridge at the input side to rectify the AC voltage that feeds a single-stage LLC converter that is designed for PFC operation [27]. In the proposed topology a virtual neutral is formed in Y connection via the input LC filter of each phase so the phase voltage (i.e. V_{aY}, V_{bY}, V_{cY}) will be applied to the semiconductors of each module instead of line-to-line voltages. The latter allows mainstream 600 V super-junction power MOSFETs or 650 V GaN HEMTs implementation, which can reduce the cost and improve performance. Overall, the fact that the same components of a single-phase design can be used in the proposed three-phase design suggests a lower component cost and failure rate

The LLC resonant converter is utilized in each phase module to benefit from ZVS and ZCS switching conditions for both active and passive switches. The latter suggests high switching frequency implementation leading to high power density. Furthermore, not using any bulky passive components such as boost inductor or electrolytic capacitor for DC-link improves power density over conventional AC-to-DC conversion approaches. The fact that the switching losses are minimized close to zero and the only main loss factor that remained in the semiconductors and passive components is the conduction loss promises a high AC-to-DC conversion efficiency. Moreover, the rectified output current of each module has a two-times line frequency pulsating nature that is 120º degrees apart from each other that get canceled out at the output so no low-frequency current will pass through the output capacitor. The latter allows small film or ceramic output capacitors implementation to improve reliability and power density.

Some assumptions are considered as follows to simplify the analysis of the proposed AC-DC converter:

1) Grid voltages are considered pure sinusoidal with equal amplitude and the same phase displacement of 120°.
2) The input impedance of each phase is ohmic as the LLC modules can achieve unity PF by operating in PFC mode.
3) All modules are lossless with 100% efficiency.
4) The input EMI filter does not affect the power circuit.

The phase voltages applied to each module are given by

$$v_{jY}(t) = \sqrt{2}\,\mathrm{V_s} \times \sin(\omega t + \phi_j) \quad (1)$$

where "j" is the phase indicator ($j = a, b, c$), "ϕ_j" is the displacement angle ($\phi_a = 0$, $\phi_b = -120$, $\phi_c = +120$), "V_s" is the RMS value of the source phase voltage and "ω" is the angular line frequency ($\omega = 2\pi f_{line}$).

The three-phase input current can be written as

$$i_j(t) = \sqrt{2}\,\mathrm{I_s} \times \sin(\omega t + \phi_j) \quad (2)$$

where "$\mathrm{I_s}$" is the RMS value of the source current entering each module.

Then the input power of each module can be written as follows

$$p_j(t) = \mathrm{V_s} \times \mathrm{I_s} \times 2 \times \sin(\omega t + \phi_j)^2 \quad (3)$$

Since the output of the three modules are connected in parallel the output voltage of each module is equal as

$$v_{oj}(t) = V_o \quad (4)$$

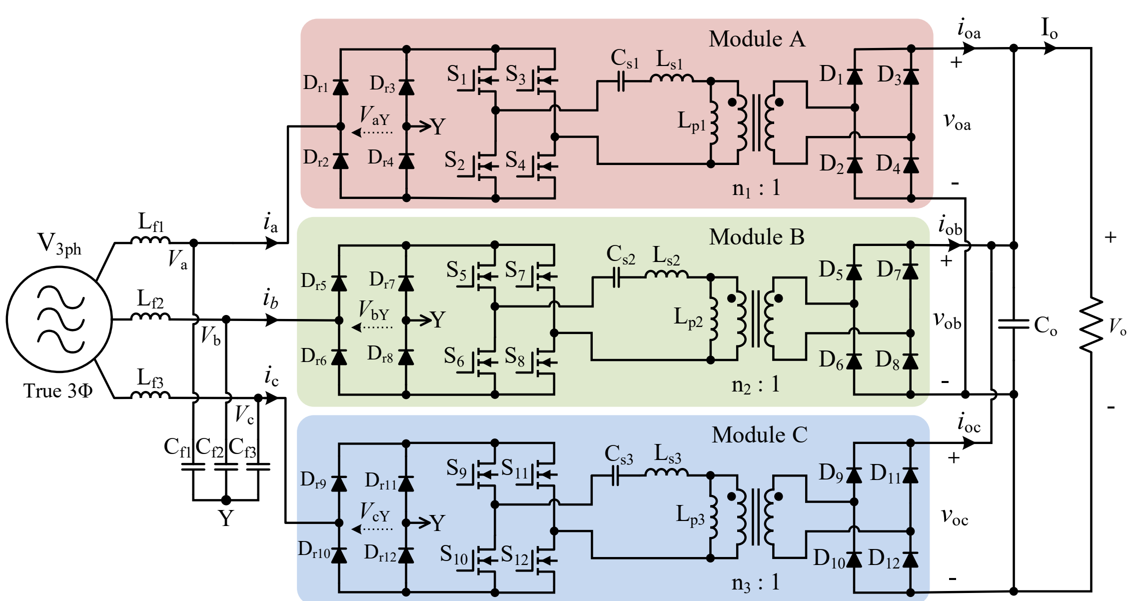


Fig. 2. The proposed isolated single-stage three-phase three-wire AC-DC converter with Y input connection.

As we control the input current of each phase to be the same, considering balanced three-phase voltages result in a balanced distribution of the output current as

$$i_{oj}(t)=\frac{\mathrm{I_o}}{3} \tag{5}$$

Therefore, the power delivered by each module is equal to a third of the three-phase rectifier output power as

$$p_{oj}(t)=\frac{\mathrm{P_o}}{3} \tag{6}$$

Hence, the output power should be evenly distributed in order to have a balanced output current resulting in line frequency cancelation and output voltage ripple minimization.

Fig. 3 shows a simplified model of the proposed rectifier. In this model, there is no electrical connection between the rectifier virtual neutral (Y connection) and grid neutral. Fig. 4 illustrates the phasor diagram of the three-phase system by considering a balanced system, unbalanced rectifier impedances, and unbalanced input voltages. Using Kirchhoff's voltage and current laws, the potential difference between the grid neutral point (n) and the rectifier virtual neutral connection point (Y), which is known as neutral displacement voltage (V_{Yn}) can be calculated as in (7) [10].

$$V_{\mathrm{Yn}}=\frac{V_{\mathrm{a}}\mathrm{Y_A}+V_{\mathrm{b}}\mathrm{Y_B}+V_{\mathrm{c}}\mathrm{Y_C}}{\mathrm{Y_A}+\mathrm{Y_B}+\mathrm{Y_C}} \tag{7}$$

From (7) it can be understood that by balancing the input admittance of each module the neutral voltage displacement can be calculated from (8).

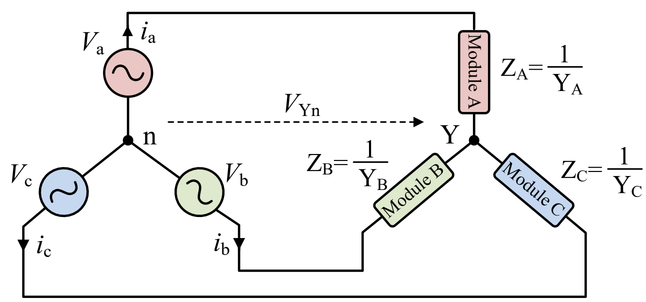


Fig. 3. Simplified equivalent input circuit model of the three-phase three-wire system connected to the phase-modular rectifier with Y-connected modules with a neutral connection.

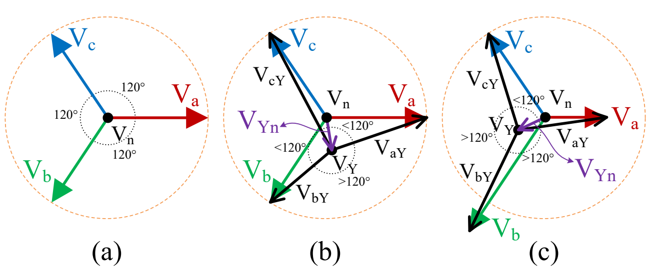


Fig. 4. (a) Phasor diagram of balanced input voltages, (b) unbalanced rectifier impedances, and (c) unbalanced voltages.

$$V_{\mathrm{Yn}}=\frac{V_{\mathrm{a}}+V_{\mathrm{b}}+V_{\mathrm{c}}}{3} \tag{8}$$

For balanced three-phase voltages, the neutral displacement voltage will be zero and hence the input voltage applied to each module will be equal to the grid voltages. This will ensure unity PFC performance and avoid over voltage / under voltage on each phase module. For unbalanced input voltage conditions and balanced input impedances, the neutral displacement voltage that is not zero anymore can be calculated as follows

$$V_{\mathrm{Yn}}=\sqrt{\left(\alpha-\frac{\beta}{2}-\frac{\gamma}{2}\right)^2+\left(\frac{\sqrt{3}}{2}\gamma-\frac{\sqrt{3}}{2}\beta\right)^2}\times \mathrm{V_s} \\ <\tan^{-1}\left(\frac{\frac{\sqrt{3}}{2}\gamma-\frac{\sqrt{3}}{2}\beta}{\alpha-\frac{\beta}{2}-\frac{\gamma}{2}}\right)^{\circ} \tag{9}$$

where α, β, γ are the proportional ratios of the phase voltages V_{a}, V_{b}, V_{c}, respectively (i.e., $V_{\mathrm{a}}=\alpha\mathrm{V_s}$, $V_{\mathrm{b}}=\beta\mathrm{V_s}$, $V_{\mathrm{c}}=\gamma\mathrm{V_s}$), and $\mathrm{V_s}$ is the RMS value of the phase voltage.

Both the unbalanced input impedance and input voltage conditions will make the power distribution between the phases unbalanced. The resulting unbalanced power on the phase modules will lead to an unbalanced output current and hence the total load current will be containing a low-frequency ripple component which is undesired for a single-stage AC-DC converter. Therefore, based on the requirement of the source and load, there should be a compromise in the proposed rectifier between keeping the neutral displacement voltage as small as possible for a unity PFC or keeping the output voltage ripple as small as possible. Accordingly, a proper control method should be implemented.

III. Analysis and Design Guidelines of a Single Module

The proper design of the proposed three-phase AC-DC converter is about the design of a single module. Hence, in this section, only the design of one module will be discussed for two different output voltage levels. Fig. 5 illustrates one single module of the proposed rectifier with its main characteristics. As comprehensively discussed in the literature [27]-[31], in order to achieve proper PFC in the LLC converter, it is required to change the frequency of the primary bridge to control the voltage gain of the resonant tank over the half-line cycle. In this way, the input impedance will be ohmic and the input current can be sinusoidal at the input side of the LLC module. It is desired to keep the operating frequency range between the parallel-resonant frequency and series-resonant frequency (i.e, $f_p < f_{sw} < f_s$) to benefit from ZCS for the secondary side switches. To achieve a fixed output voltage (V_o), the required voltage gain for the LLC module over the line cycle can be calculated as follows

$$\mathrm{G_{req}}(\theta)=\frac{V_{\mathrm{o}}}{V_{\mathrm{in}(\theta)}}=\frac{V_{\mathrm{o}}}{\sqrt{2}\mathrm{V_S}}\times\frac{1}{\sin(\theta)}. \tag{10}$$

As in the proposed three-phase three-wire AC-DC converter, only phase voltages will be applied to the input rectifier bridge of each module, we need to consider phase voltage instead of line-to-line voltage for the design of the transformer turns ratio

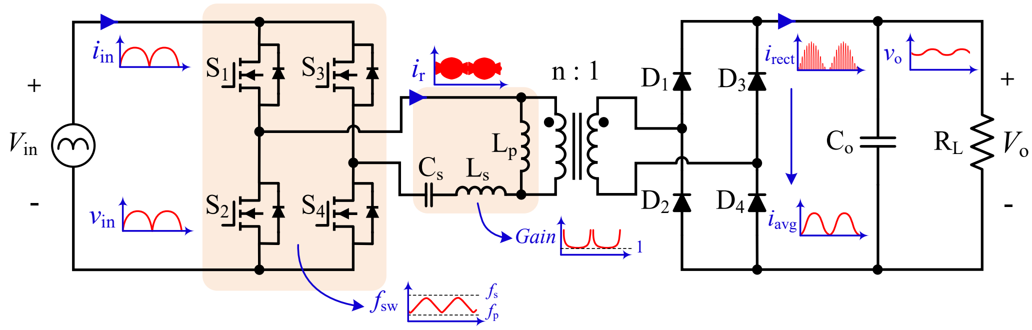


Fig. 5. Main characteristics of the single phase module of the proposed three-phase rectifier.

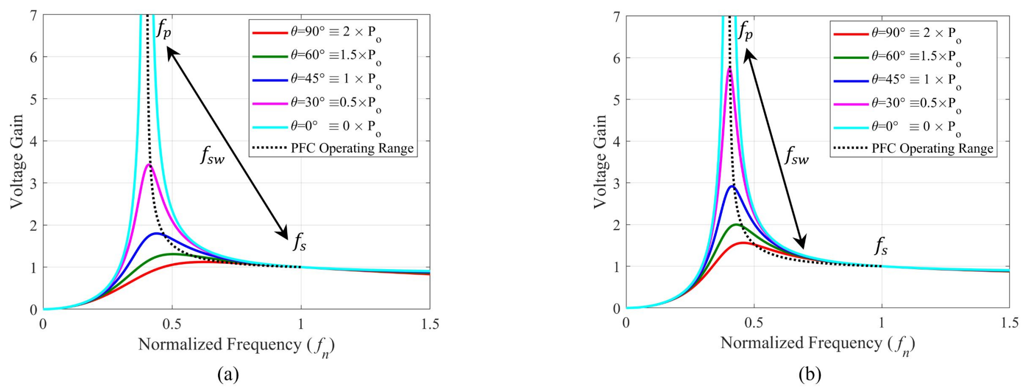


Fig. 6. The AC operation voltage gain curve of LLC tank at different phase angles, (a) for V_o=250 V, and (b) for V_o=400 V.

and resonant components of the LLC module for a wide output voltage range while considering input voltage fluctuations. Considering a line-to-line voltage of 380 V_{RMS}, the RMS value of input voltage for a single module is 220 V plus ±10% fluctuations. The output DC voltage range is here considered to be between 250 V to 400 V.

Finding the LLC transformer turns ratio (n) is the first step of the design that is realized based on the minimum gain requirement considering the minimum and maximum voltage range of input and output. The minimum voltage gain for the PFC converter ($\mathrm{G_{req}}^{\min}$) is required at the peak line input voltage ($\sqrt{2}\mathrm{V_s}$), which is corresponding to $\theta = 90^{\circ}$ of line angle. Note that the maximum input voltage fluctuation should be considered here. Hence, the minimum total input to the output voltage gain of the LLC converter which is set at f_s is designed to be equal to the minimum gain requirement for PFC operation.

$$\begin{gathered}\mathrm{G_{LLC(total)}}^{\min}(f_{sw}) = \mathrm{G_{req}}^{\min}(\theta)\\ \rightarrow \frac{1}{n} \times \mathrm{G_{LLC}}(f_s) = \mathrm{G_{req}}^{\min}(90)\\ \rightarrow n = \frac{\sqrt{2}\mathrm{V_s^{max}}}{\mathrm{V_o}^{\min}}\end{gathered} \tag{11}$$

Fig. 6 illustrates AC operation voltage gain consideration of the LLC converter for two output voltage levels (i.e., 250 V and 400 V). In AC operation the instantaneous power at $\theta = 90^{\circ}$ is twice the average output power ($\mathrm{P_o}$) and at $\theta = 0^{\circ}$ it is zero. The maximum achievable voltage gain of the designed LLC tank for double output power is required at the higher output voltage level condition (i.e., 400 V), which is 1.6 (=400/250) in this case, as the unity gain that is achieved around the series resonant frequency (f_s) is set for the lower output voltage level (i.e., 250 V). At $\theta = 0^{\circ}$ the LLC tank can provide a high voltage gain around the parallel resonant frequency (f_p). It should be noted that as high voltage gains are required around the zero crossings line voltage using a small quality factor LLC tank design is preferred. In this way, when the bridge frequency of the LLC converter changes over the line cycle between f_p and a frequency lower than f_s corresponding to a specific output voltage, a high-power factor operation can be achieved.

IV. Simulation Results of the Proposed AC-DC Converter

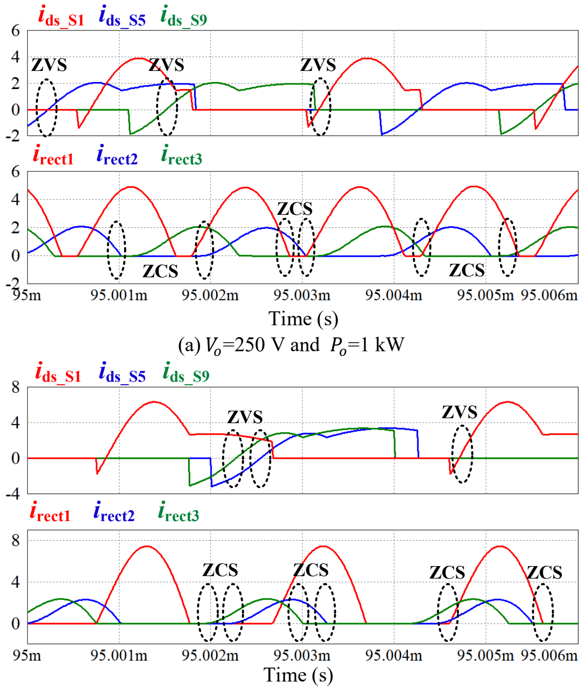
Computer simulation using PSIM software is used to verify the performance of the proposed three-phase three-wire AC-DC converter. Table I shows the parameters used for both simulation and experiment. Since only high switching frequency current flows into the output capacitor, in theory a negligible output capacitance is enough to obtain very small voltage ripples. Here, a total of 100 µF film capacitor is used at the output of a 1.5 kW designed AC-DC converter. Moreover, at the input of each phase, a small LC filter is used to filter the switching frequency ripples and form a virtual neutral point for the three phases.

Simulation results for peak power delivery of phase 1 (i.e., θ_1=90°) for both output voltage conditions are demonstrated in Fig. 7 to show the soft-switching performance of the primary bridges and secondary diode bridges. It can be observed that all primary switches can achieve ZVS at both boundary conditions and also all output rectifier diodes can achieve ZCS at both boundary conditions. The switching frequency of phase 1 in Fig. 7 (a) is around 400 kHz and the switching frequency of phase 1 in Fig. 7 (b) is around 260 kHz. It should be mentioned that phase 2 is operating around θ_2=150° of the half-line cycle and phase 3 is operating around θ_3=30°, so a similar switching frequency is expected for both phases.

The steady-state line cycle simulation results for two boundary output voltage levels are shown in Fig. 8. As can be observed from Fig. 8, due to the virtual neutral Y connection at the input, the applied maximum voltage on the drain-source of the input bridge switches is equal to the peak of phase voltage that is 311 V. Moreover, a low harmonic sinusoidal current with unity power factor correction performance is achieved for both

TABLE I. THE DESIGN PARAMETERS

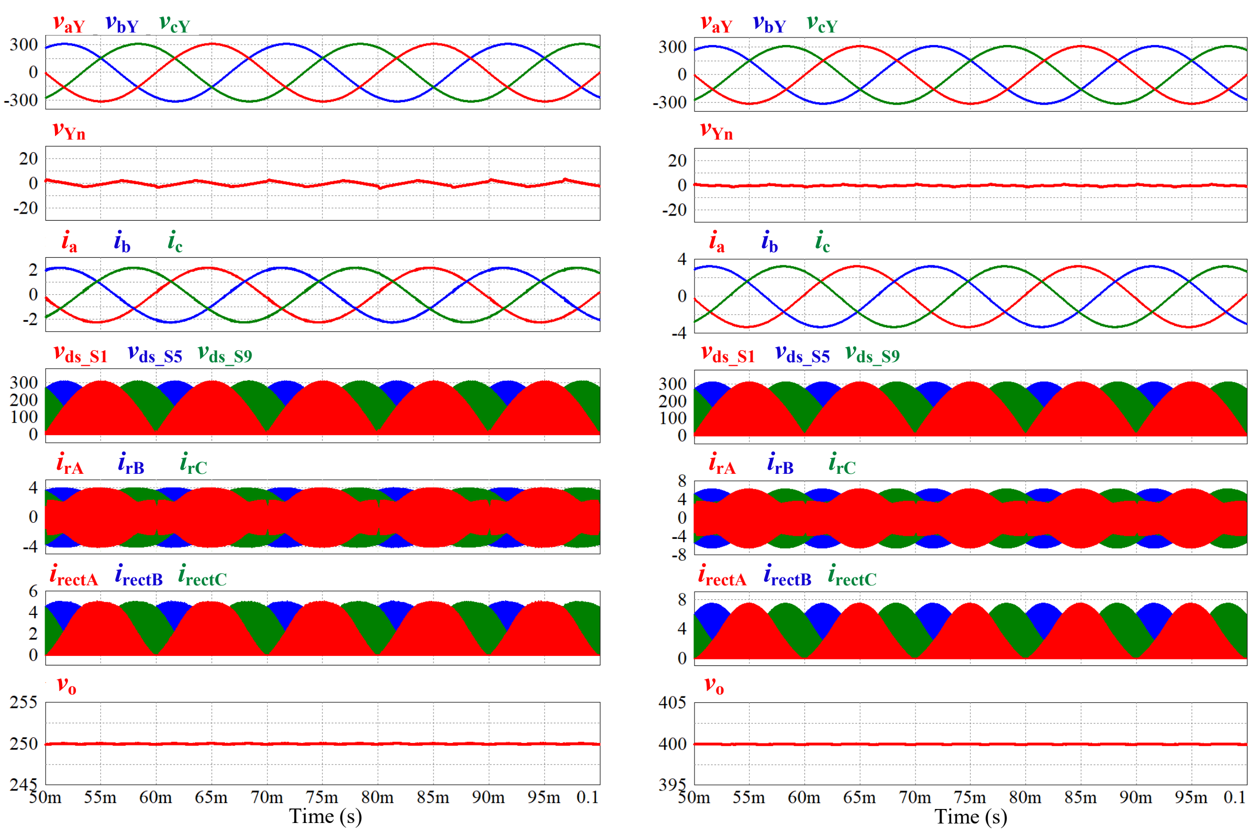
Parameters/Descriptions		Values
Rated Output Power (P_o)		1.5 kW
Line-to-Line Voltage (V_{ab}, V_{bc}, V_{ca})		380 V_{RMS}
Output Voltage Range (V_o)		250V - 400V
Switching Frequency Range ($f_{sw[1,2,3]}$)		200 kHz-400 kHz
Parallel Resonant Inductor ($L_{p[1,2,3]}$)		118 µH
Series Resonant Inductor ($L_{s[1,2,3]}$)		22.5 µH
Series Resonant Capacitor ($C_{s[1,2,3]}$)		4.8 nF
Transformer Turns Ratio ($n_{[1,2,3]}$: 1)		1.3
Transformer Leakage Inductacne ($L_{k[1,2,3]}$)		1.5 µH
Input LC Filter	Inductor ($L_{f[1,2,3]}$)	80 µH
	Capacitor ($C_{f[1,2,3]}$)	2 µF
Output Capacitor (C_o)		100 µF



(a) V_o=250 V and P_o=1 kW

(b) V_o=400 V and P_o=1.5 kW

Fig. 7. Zoomed-in simulation results around the peak power delivery of phase 1 to show soft-switching performance.



(a) V_o=250 V and P_o=1 kW

(b) V_o=400 V and P_o=1.5 kW

Fig. 8. The steady state line frequency simulation results for the proposed three-phase three-wire AC-DC converter.

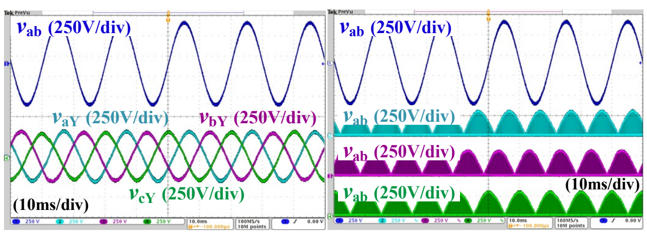
output voltage levels (PF > 0.999). Furthermore, the peak-to-peak output voltage ripple is less than 100 mV and it mainly consists of high-frequency switching ripples. It should be mentioned that a balanced system is considered in the simulation, hence the potential of the input virtual neutral Y connection (V_{Yn}) is stable and close to zero referenced to the three-phase source neutral for both boundary conditions. It should be mentioned that due to imperfection of the applied voltages and achievable sinusoidal currents at the input of the proposed rectifier, a small sixth times line frequency ripple cannot be avoided in practice.

V. Experimental Results of the Proposed AC-DC Converter with Y Input

A GaN-based three-phase prototype is built in the laboratory to take advantage of high switching frequency while verifying the feasibility of the proposed three-phase three-wire AC-DC converter. Fig. 9 (a) shows the input line-to-line voltage and the phase voltages with respect to the virtual neutral point for each module. Moreover, Fig. 9 (b) shows that the maximum applied voltage on the GaN bridges is equal to 311 V.

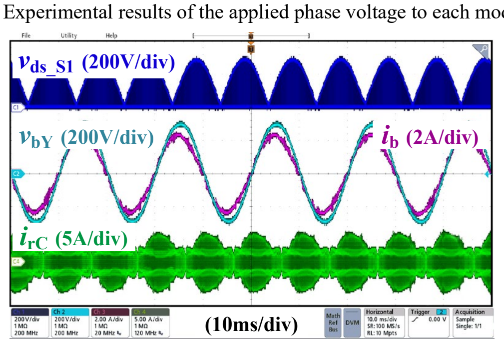
Fig. 10 (a) shows steady-state line frequency experimental results demonstrating the drain-source voltage of S_1 from module A, input voltage and current of module B, and the resonant current of module C for 250 V output voltage condition at 1 kW total output power. Fig. 10 (b) demonstrates the same waveforms for the 400 V output voltage condition at 1.5 kW total output power. It can be observed from Fig. 10 that more than 0.99 power factor is achieved in both boundary output voltage conditions. Fig. 11 (a) demonstrates applied input voltage on phase 3 (V_{cY}) along with the three-phase AC currents for 400 V output voltage level at rated power. It can be observed that a proper PFC is achieved in all three phases. Fig. 11 (b) shows the output voltage alongside the three-phase AC input current for rated power. It is clear that the output voltage of the proposed single-stage AC-DC converter does not have any low-frequency harmonics.

The efficiency of the proposed three-phase rectifier is measured with a Zimmer precision power analyzer LMG671 to be 96.8% for 250 V output voltage condition and the measured efficiency for 400 V output voltage condition was 96.5%. The estimated loss breakdown for 250 V and 400 V output voltage conditions is shown in Fig. 12. Moreover, the estimated peak efficiency is 97.1%, which is close to what was achieved in practice. It should be mentioned that based on the power loss estimation the efficiency can be enhanced to close to 98% by using MOSFETs instead of diode rectifiers.

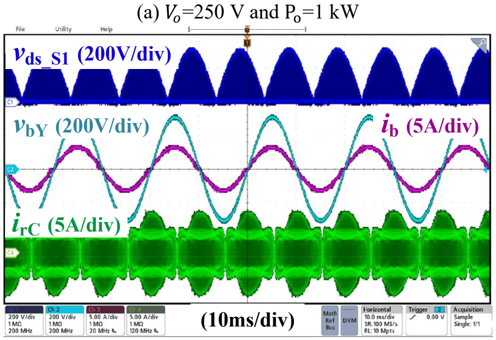


(a) (b)

Fig. 9. Experimental results of the applied phase voltage to each module.

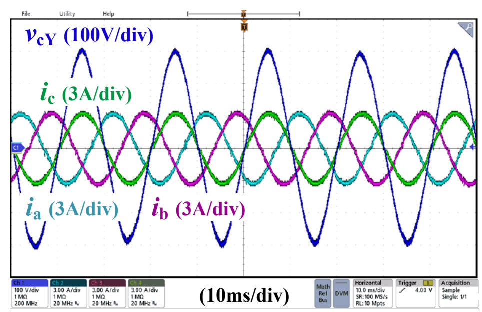


(a) V_o=250 V and P_o=1 kW



(b) V_o=400 V and P_o=1.5 kW

Fig. 10. Line frequency experimental results for two output conditions.



(a) V_{cY}=220 V_{RMS}, i_c=2.3 I_{RMS}

(b) V_o=400 V and P_o=1.5 kW

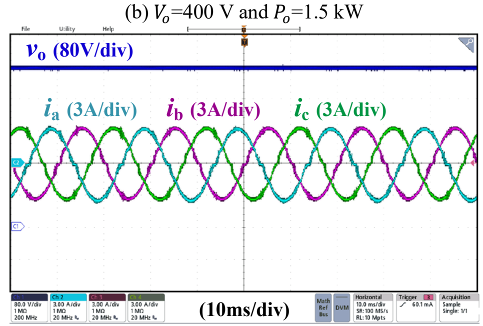
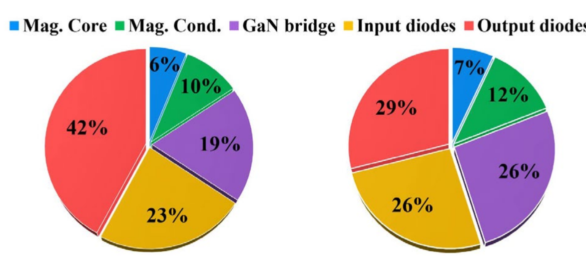


Fig. 11. Experimental results showing three-phase PFC performance.



(a) V_o=250 V and P_o=1 kW (b) V_o=400 V and P_o=1.5 kW

Fig. 12. Estimated power loss breakdown of the proposed rectifier.

VI. Conclusion

This paper has presented a novel soft-switching three-phase three-wire rectifier. The proposed topology has a single-stage phase-modular structure that uses LLC resonant converters in each module. The presented AC-DC converter outperforms conventional two-stage rectifiers in terms of achievable efficiency and power density. Due to the input Y connection, only a 311 V peak voltage was applied to the semiconductors while using a three-phase three-wire source. The paper describes the operation of the proposed AC-DC converter for two different output voltage conditions. Simulation and experimental results verified unity power factor operation (>0.99) for both output voltage levels. Moreover, the soft-switching performance of high switching frequency devices has been validated. The proposed rectifier achieved 96.8% efficiency in the implemented GaN-based prototype, which was close to the estimation. Hence, the proposed topology is a good candidate for high-power AC-to-DC conversion.

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