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Two-Channel Bridgeless Power Factor Corrector

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This paper discusses the analysis and design details of a bridgeless power factor corrector. The circuit topology of the proposed power converter is based on the combination of two DC/DC converters forming a two-channel structure of the power processing path. To meet the safety requirements, the converter circuit is equipped with a common ground link between the AC input voltage source and the DC output. The two-channel bridgeless power factor corrector operates under a power factor close to one and is robust to a short circuit fault. The resonance mode of the converter circuit prevents unpredictable overvoltage across the converter semiconductors. The device was modelled and simulated using MATLAB/Simulink software environment under varying load conditions. The results of numerical investigations have confirmed predicted device performance parameters and operational characteristics. The paper content will attract the attention of researchers and engineers working in the areas of electrical power engineering and power supplies.

Key words: *rectifier, power factor corrector, DC/DC converter, inverting converter, power supply ground, total harmonic distortion*

The vast majority of power supplies used for domestic and industrial applications to energise various electronic devices, circuits and systems are based on AC/DC converter topology. Following the standards for electricity quality and electromagnetic compatibility, the AC/DC converters are required operation with power factor correctors (PFC) to reduce higher harmonic pollution of the voltage source. The installation of a boost DC/DC circuit between bridge rectifier and filtering capacitor of a power supply is a conventional way to integrate PFC feature into AC/DC converter. This approach provides appropriate shaping of the input current to mitigate higher harmonic spectrum and to improve power factor. Despite relatively greater power loss due to a higher number of semiconductors involved in the power processing, the bridge-based boost PFC converters are commonly recognised as simple circuitry, low-cost and easy control solutions widely used in power supplies for both home appliances and industrial installations.

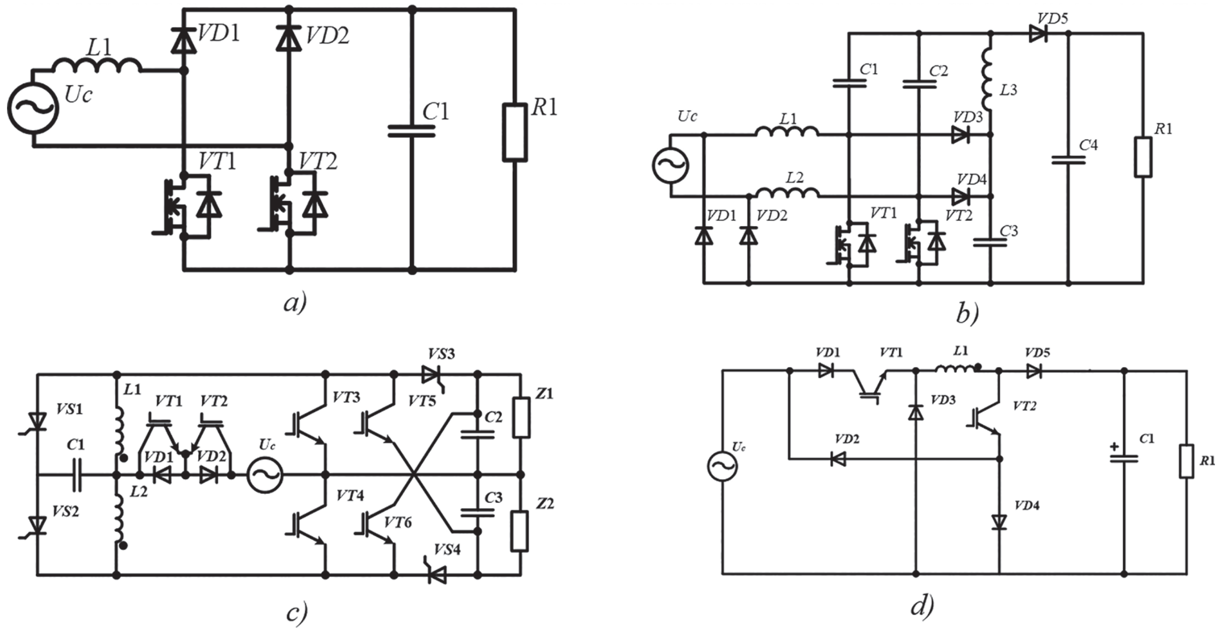
A very important requirement of the safety standards is the installation of common ground between a power grid and installed electrical equipment. The implementation of the common ground link between AC input voltage source and DC output of the power supply in the converters improves electromagnetic compatibility and the safe operation of the power supplied equipment [1–3]. Most of the rectifier-based converters are not designed to have a common ground. In order to install the common ground link in an AC/DC converter having a bridge rectifier at the front-end terminals, an output/input isolating transformer has to be included in the power supply circuit topology. However, further increase in the number of the semiconductors and inductive components in the power processing path significantly reduces the power supply efficiency.

The family of bridgeless PFC converters has been introduced as a solution to the mentioned above issues. The bridgeless PFC converters have a reduced number of semiconductors in the power processing path, higher efficiency, and are operating under almost unity power factor to avoid reactive power circulation [4]. The bridgeless converters can be also used as the basis to design power supplies having a common ground link between input and output terminals.

Analysis of existing circuit topologies. There is a large variety of power supplies and converters providing bridgeless AC/DC voltage rectification with the PFC function [1–25]. The typical solutions and approaches are shown in Fig. 1 to highlight the main groups of the bridgeless PFC converters [5–7].

Fig. 1,*a* shows a circuit based on two boost (step-up) voltage converters operating in the opposite half-cycles of AC supply voltage [5, 8]. The advantage of this solution is the simplicity of the topology and transistor switch control algorithms. The rectifier has a low number of components and draws AC sinusoidal current from the main.

The circuit diagram of another typical bridgeless device utilising two boost (step-up) converters is shown in Fig. 1,*b* [9]. The boost (step-up) converters are quite common components of the bridgeless rectifier topologies where the output DC voltage is required to be higher than the magnitude of AC voltage of the input supply.



a) *b)* *c)* *d)*

Fig. 1. Typical bridgeless converter circuit topologies

Many previous studies [5, 9–13] discuss the details of implementation of boost (step-up) converters in bridgeless rectifiers. The principle of operation and advantages of the circuit in Fig. 1,*b* are similar to the previous converter. However, to increase the voltage gain ratio, two resonant voltage circuits are introduced in this circuit.

The disadvantage of both considered circuits (Fig. 1,*a* and *b*) is that there is no common ground between the input power source and the output load. In addition, the circuit in Fig. 1,*b* has a disadvantage related to the change of resonance operation conditions when the load is varied (for example, an inductor is introduced in the load circuit). Therefore, this disadvantage limits the area of implementation of the circuit solution (Fig. 1,*b*).

As for the PFC rectifiers having a common ground, two typical circuits are highlighted as a result of the literature search. Fig 1,*c* shows the PFC rectifier circuit which includes an active rectifier based on a bridge voltage inverter [14], inductor storages and various semiconductor switches. The converter draws ac sinusoidal current from the main power source and produces a bipolar rectified DC voltage across the output terminals. The circuit has a common ground linking the input supply source and the output load to improve electromagnetic compatibility and operational safety. The disadvantage of this solution is an extremely complicated algorithm to control semiconductor switches having different functions and control methods. Another drawback is that the bipolar output of the rectifier requires bipolar load which is not suitable for many industrial applications.

The most promising circuitry solution to build a desired common ground bridgeless PFC converter is represented in Fig. 1,*d* [15]. This circuit is a combination of boost (step-up) and buck-boost (inverting) converters having a common storage inductor and output filter capacitor. The converter has a low number of power semiconductors, a simple algorithm to control the transistor switches and provides regulation of the output terminal voltage in a wide range.

The present circuit drawbacks include a comparable higher number of series-connected semiconductor devices in the circuits applied for the recharging of the storage inductor, and influence of the storage inductor processing modes (energy accumulation – charging, holding

Comparison of DC/DC converters' parameters

Converter type	Parameter		
	Max. volage acrossthe switching transistor, V_{ce}	**Average current through the diode, I_d**	**Voltage gain ratio**
Buck (Step-down)	V_{in}	$I_{out}/(1-\gamma)$	γ
Boost (Step-up)	V_{out}	I_{out}	$1/(1-\gamma)$
Buck-boost (Inverting)	$V_{in}+V_{out}$	I_{out}	$\gamma/(1-\gamma)$
Cuk (Inverting)	$V_{in}+V_{out}$	I_{out}	$\gamma/(1-\gamma)$

where V_{out} – the voltage across the load, V; V_{in} – the volage of the power supply source, V; I_{out} – the current through the load, A; γ – the duty cycle, $\gamma = t_{on}/T$, t_{on} – the time when the semiconductor switch is in conducting state (ON), sec, T – periodic time of the pulse width modulation frequency, sec.

accumulated energy in the inductor, discharging) on the signal produced by the controller to manage ON-OFF states of the semiconductor switches.

A common drawback of all considered types of converters is that they can not operate under the load short circuit conditions. However, a bridgeless buck-boost (inverting) converter reported in [16] prevents overcurrent through the semiconductor switches while operating under short circuit fault across the output terminals.

It should be noted that buck (step-down) and boost (step-up) converters have significantly reduced rated values of currents, voltages and powers of the semiconductors and capacitors compared to buck-boost (inverting) converters. For example, under the input voltage change ratio $\varepsilon_V = V_{\text{in(max)}}/V_{\text{in(min)}} = 1.5 \div 2$, the rated power of the storage inductor in the buck-boost (inverting) circuit is 2–3 times higher than in the buck (step-down) and boost (step-up) ones. Therefore, the buck-boost (inverting) converter type is appropriately used in applications where it can functionally replace both converters: buck (step-down) and boost (step-up). The implementation of the buck-boost (inverting) converter in a power supply circuit topology ensures both high rated power, reliability and efficiency of the device as well as the operation over the entire range of the load change up to the short circuit fault.

Proposed circuit of bridgeless PFC converter. To avoid the mentioned above problem in the bridgeless converter design, it is proposed to replace the voltage converters with the buck-boost (inverting) converters operating as a current source to supply the output load having a capacitive filter. Under the current source mode, the load does not affect the currents through the power semiconductor switches. The currents depend only on the parameters of the input voltage, storage inductors, and duty cycle of PWM (Pulse Width Modulation) control. When the value and character of the load are changed, the terminal voltage across the capacitive output filter is maintained constant by the adjustment of the duty cycle ratio of the power semiconductors' control. The duty cycle control actually reflects the ratio of the charging and discharging times of the storage inductors. The principle of operation is based on the energy balance approach where power from the source is stored in the inductor during the charging time interval and is then transferred to the load when the inductor is being discharged (the volt-second balance).

The proposed converter circuit is based on the topology of the two-channel bridgeless PFC initially suggested by the authors in [17, 18]. The topology [17] was developed using modelling and simulation analysis and verified by practical prototype tests and investigations. Fig. 2 shows the proposed circuit of the two-channel bridgeless PFC converter which differs from [17] by adding an LC filter to the input terminals to reduce high-frequency ripples in the current drawn from the main.

As noted earlier, the proposed circuit consists of two buck-boost (inverting) converters corresponding to the opposite polarities of AC input voltage. Both converters form a two-channel PFC device where one channel is employed to process power within the positive half-cycle of AC voltage, while another channel is responsible for power processing during the negative half-cycle. The diodes installed in series with the transistors protect the opened (OFF state) semiconductor switches from the reverse voltage application.

The circuitry of the buck-boost (inverting) converter for the positive polarity of AC input voltage includes a fully controlled transistor switch *VT*1, *VD*1, a storage inductor *L*2, a controlled transistor switch *VT*3, *VD*3, and a reverse diode *VD*4. When the transistor switches, *VT*1 and *VT*3 are closed (in ON state) the storage inductor *L*2 is being charged. Both transistors are controlled by the same signal synchronously, however, the operational functions of the transistor switches under OFF state are different. The transistor *VT*1 in OFF state ensures disconnection of the link "supply voltage source – load". Therefore, the inductor *L*2 performs as a current source relatively the output load. Simultaneously the opened transistor *VT*3 cuts the shunt circuit through the diode *VD*4 while the inductor *L*2 is being discharged reversing voltage polarity across the inductor terminals.

Another buck-boost (inverting) converter processing the power during the negative polarity of AC input voltage includes a fully controlled transistor switch *VT*2, a diode *VD*2 and a storage inductor *L*2. However, this converter

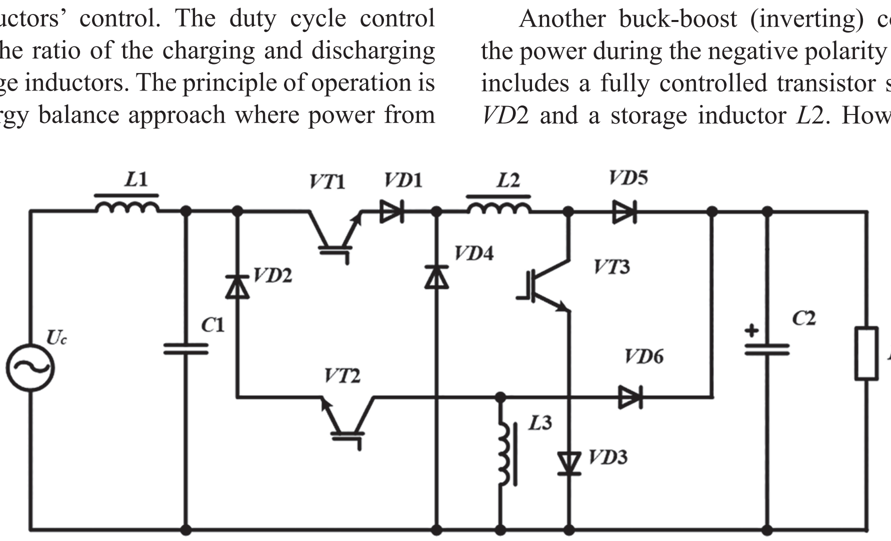


Fig. 2. Two-channel bridgeless power factor corrector

has no additional transistor switch as the shunt circuit for the inductor *L*2 is not required. The algorithm of the converter is very similar to the previous one excluding the additional transistor control.

The diodes *VD*5 and *VD*6 provide decoupling of the converting channels connected in parallel to the terminals of capacitor *C*2 of the output filter. Due to the channel decoupling, all three transistors are controlled using the same single PWM signal. This approach significantly reduces the complexity of both the control system and operational algorithm.

Both channels of the bridgeless PFC are connected to the input voltage source through an LC filter (*L*1, *C*1) to suppress higher harmonic components of the input current related to the operating frequency of switching power semiconductors. The capacitor value of the input LC filter is determined from the condition of the voltage resonance that occurred in the storage inductor and the capacitor connected in series. Though the voltage magnitudes across the PFC components under resonance conditions are higher than the main voltage, these magnitudes are constant and independent of the load value and character. Such the resonance approach ensures a significant reduction in the size and weight of the input filter inductor.

Modelling and Simulation Results. Fig. 3 shows a block diagram of the simulation model of the proposed two-channel PFC developed in the MATLAB/Simulink software environment. The model structure reflects the circuit of the PFC converter displayed in Fig. 2. In order to provide a correct and stable simulation procedure, all inductive components of the Simulink model have an additional high ohmic resistor installed in parallel.

The model has been investigated under constant output voltage conditions (adjusted in the range of 100–300 V for the various testes) and varying load power from 0.5 to 10 kW. The results of the simulation discussed in this paper have been obtained for a PFC model having the following parameters:

AC input voltage is 220 V;
supply voltage frequency is 50 Hz;
switching frequency of semiconductor is 33 kHz;
input filter inductor: *L*1 = 3.3 mH;
input filter capacitor: *C*1 = 0.33 μF;
storage inductors: *L*2 = *L*3 = 0.1 mH;
output filter capacitor: *C*2 = 1.2 mF;
DC output constant voltage is 200 V;
load power is 2 kW.

The simulation results have demonstrated that the proposed circuit of PFC provides operation at a power factor close to one under a low level of THD (Total Harmonic Distortion). The time diagrams of the AC source voltage and the drawn current are shown in Fig. 4 and 5,*a* respectively, whereas Fig. 5,*b* demonstrates a zoomed segment of the ac current curve to show in detail the maximum ripple values.

The results obtained from the simulation have also confirmed the predicted performance of the voltage across the input filter inductor, the output filter capacitor and the switching semiconductors. The fundamental harmonic of the supply voltage affects the voltage across the output filter capacitor *C*2 during the time interval when the transistors are in ON state. This requires an increase in the capacity of *C*2 to reduce low frequency ripples. On the other hand, a DC component of the output voltage causes the asymmetry of the half-waves of AC voltage across the inductors and the input filter capacitor.

It has been shown that under the load power of 2 kW the level of the ripple of the drawn current is 5.6 %, THD is 4.63 % and the ripple of DC output voltage is 3.3 %. The reduction of the output filter capacitor to 600 μF increases the first harmonic ripple of the DC output voltage to 6.8 %.

The voltage curves across inductors *L*1, *L*2, *L*3 and capacitor *C*1 versus time are shown in Fig. 6–9 respectively. The diagrams demonstrate the influence of the output voltage DC component on the voltages across the inductors and the input filter capacitor.

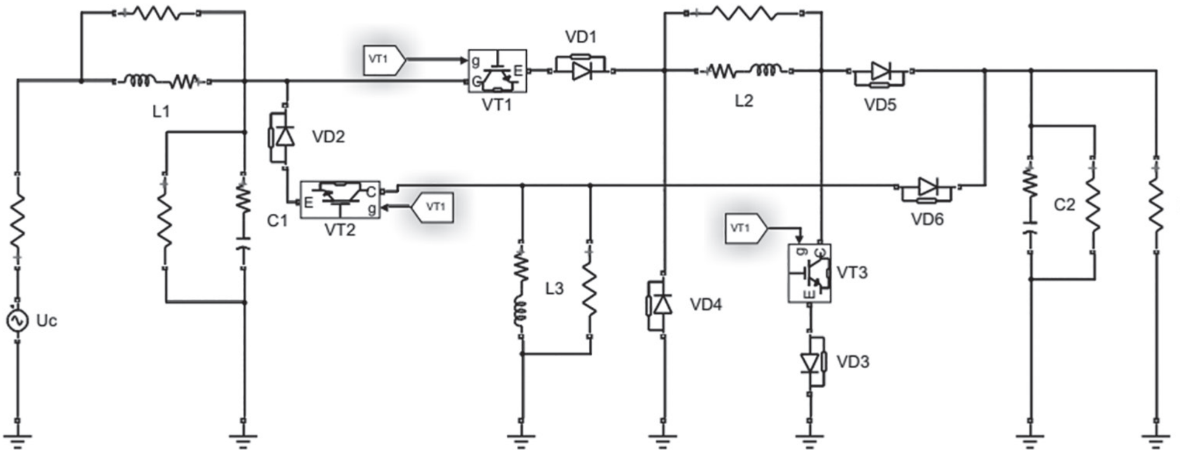


Fig. 3. Simulink model of the proposed bridgeless PFC converter

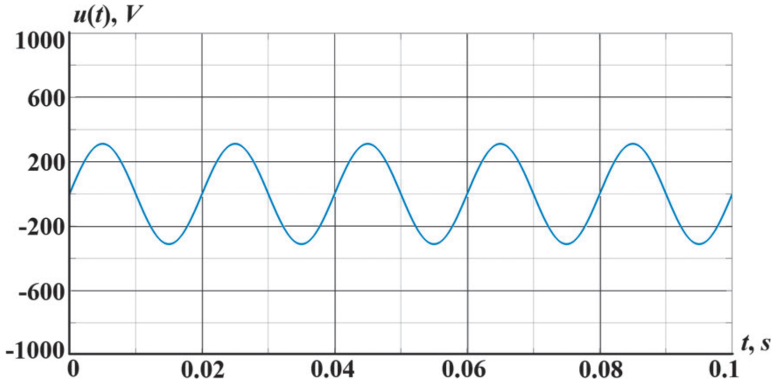
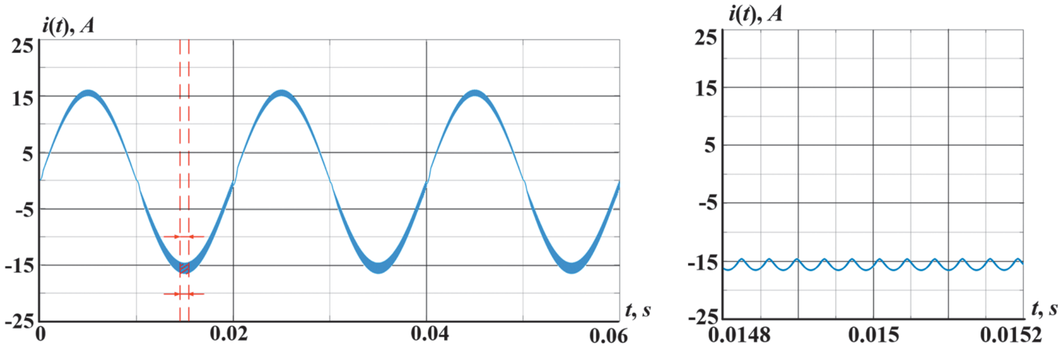
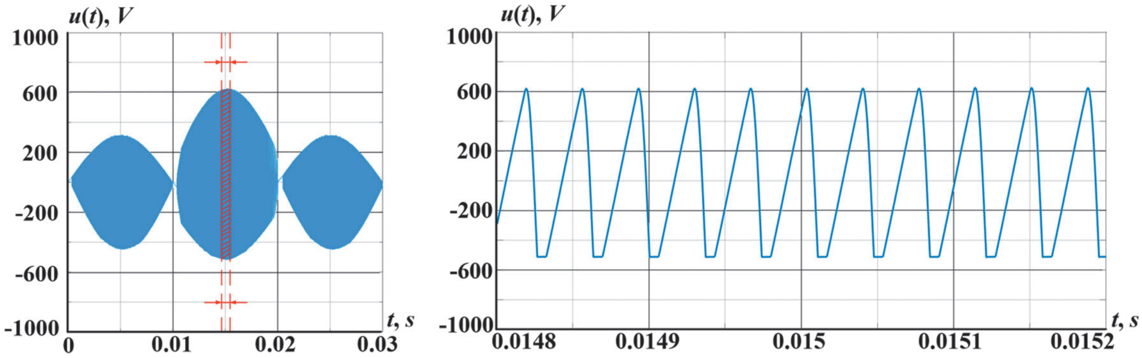


Fig. 4. AC voltage source



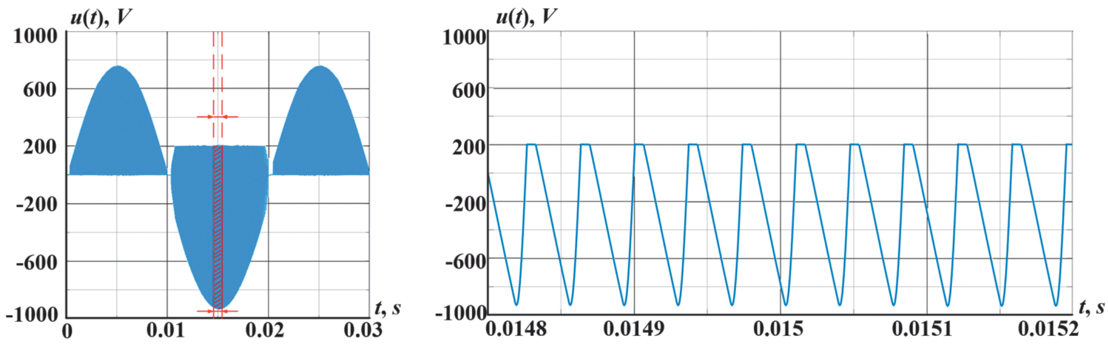
а) *б)*

Fig. 5. AC current drawn from the voltage source



а) *б)*

Fig. 6. Voltage across the input filter inductor $L1$



а) *б)*

Fig. 7. Voltage across the input filter capacitor $C1$

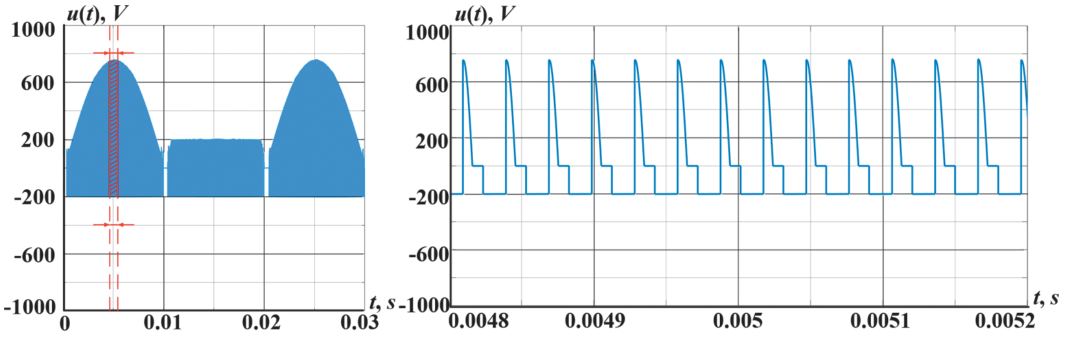


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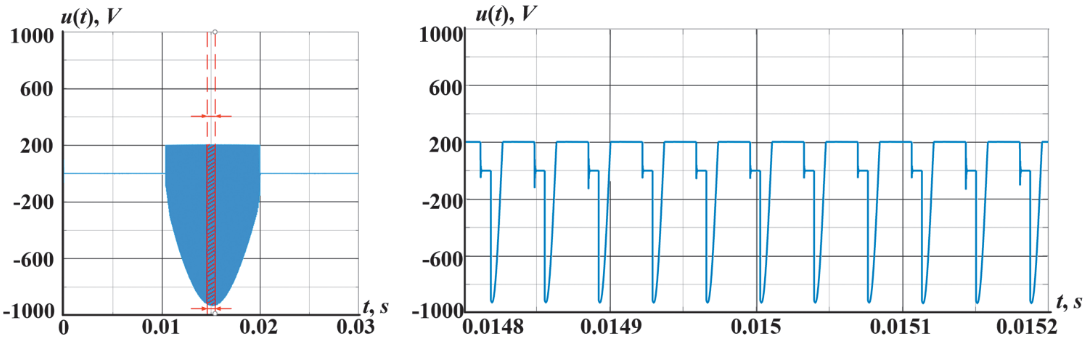
Fig. 8. Voltage across the storage inductor $L2$



а) *б)*

Fig. 9. Voltage across the storage inductor $L3$

It has been found that the peaks of the instantaneous voltages across the converter elements under varying load power are to be determined at the resonant frequency of the charging circuits $L2$–$C1$, $L3$–$C1$ and they are independent of the load. However, the instantaneous voltages across the transistor switch $VT3$, $VD3$, in OFF state are always equal to the voltages across the capacitor $C1$ (the load voltage).

Conclusion. The proposed two-channel bridgeless PFC converter is designed to rectify ac input voltage from the main grid in dc output voltage operating with the common ground. The implementation of inverting converters in the PFC ensures high load capacity and safe operation under short circuit faults at the load side. The integration of common ground between the power source and dc load improves electromagnetic compatibility, facilitates the design of protection and control systems, and increases the safety of servicing personnel.

The input circuit operation under a resonance condition has the reduced inductance of the input filter inductor and prevents unpredictable overvoltage across the converter elements. It also makes simple determining the components' voltage rating at sufficient accuracy under the draft design stage.

The converter was modelled and simulated using Matlab/Simulink software under varying load conditions. The results of the simulation demonstrated and confirmed the predicted device performance parameters and operational characteristics.

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Двухканальный безмостовой корректор коэффициента мощности

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В статье рассмотрено схемотехническое решение бестрансформаторного устройства выпрямления переменного напряжения с общей нейтралью сети питания переменного тока и нагрузки постоянного тока. Общая нейтраль обеспечивает повышение безопасности работы обслуживающего персонала. Предложен двухканальный безмостовой корректор коэффициента мощности, который способствует формированию потребляемого активного тока, имеющего форму близкую к синусоидальной, и обладает повышенной нагрузочной способностью. Повышенная нагрузочная способность обеспечивается применением двух инвертирующих преобразователей. Устройство сохраняет работоспособность при изменении режимов работы нагрузки от холостого хода до *короткого замыкания. Параметры входных цепей формируются из условия резонанса напряжений на частоте работы силовых ключей. Резонанс напряжений позволяет на стадии проектирования установить максимальные мгновенные значения напряжений на элементах преобразователя. Резонанс напряжений исключает наличие коммутационных перенапряжений на элементах преобразователя. Приведены рекомендации по определению параметров элементов с учётом резонанса напряжений. Представлены временные диаграммы напряжений и токов, полученные в ходе исследований на имитационной модели. Статья представляет интерес для инженеров по силовой электронике, которые нацелены на разработку корректора коэффициента мощности выпрямительных устройств преобразователей.*

Ключевые слова: *выпрямители, корректор коэффициента мощности, однотактный преобразователь, инвертирующий преобразователь, нейтраль питающей сети, коэффициент нелинейных искажений.*

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