

Controllable Rectifiers with Input Power Factor Correction

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Abstract—Innovative single-phase and three-phase power factor correctors based on the Cuk circuit with a quasi-sinusoidal input current in phase with a voltage are analyzed. This kind of rectifiers with forced formation of the input current has such properties as the output voltage control in the full range, the bidirectional active power flow if it is needed. Also galvanic isolated and transformerless circuitry solutions of the rectifier cell are presented. The load and control characteristics of the single-phase power-factor-corrected rectifier cell based on modified Cuk circuit with symmetrized output circuit are obtained. The offered rectifier cells can be connected by input in various ways, in particular, the wye connection is used in three-phase rectifiers, and the series connection is applied in high-voltage single-phase rectifiers. All these rectifiers are necessary for new branches of electrical engineering, including chargers for electric car batteries, sources of controlled DC voltage for an inverter frequency electric drive with the output AC voltage amplitude control, energy storage systems and a number of electrical technologies. The modular composition principle makes it possible to enhance their applications and to form a broad range of power-factor-corrected DC sources by output voltage and power rating.

Keywords—power factor, power factor correction, controllable rectifiers, Cuk circuit, circuit of input current shaping, high-voltage rectifiers

I. INTRODUCTION

Power factor corrector (PFC) improves the entire efficiency of AC power supplying. Active PFCs as the basis of rectifiers with improved quality indicators of their input and output electrical energy, designed to power radio-electronic, telecommunication and computer and other important equipment in accordance with the standards of

electromagnetic compatibility IEC 61000-3-2, GOST R 51317-3.2-99, are mass produced by industry. In the most common purpose, they usually have a stabilized output voltage and the input power factor value of 1. There are a lot of reviews on PFCs [1-6] and guides on their choice, depending on the requirements for the power source [7].

In recent years, there has been an interest in both rectifiers and PFCs with an adjustable DC output voltage [8, 9]. The paper examines the PFCs created by the symbiosis of the converter based on the modified Cuk circuit and of the circuit of its input current forced shaping.

II. ADJUSTABLE UNIDIRECTIONAL AND BIDIRECTIONAL POWER FACTOR CORRECTORS

The PFC circuit based on the Cuk circuit is shown in Fig. 1 [9]. It has an unidirectional active power flow.

The circuit with bidirectional active power transmission is presented in Fig. 2 [10]. The bidirectional transmission of active power with a high quality of the input and output electrical energy is achieved here by means of three-stage nature of its conversion with increased losses compared to the two-stage conversion in the circuit of Fig. 1.

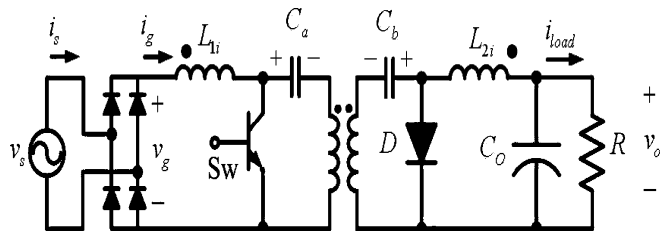


Fig. 1. Single-phase PFC rectifier based on Cuk circuit with unidirectional active power flow [9].

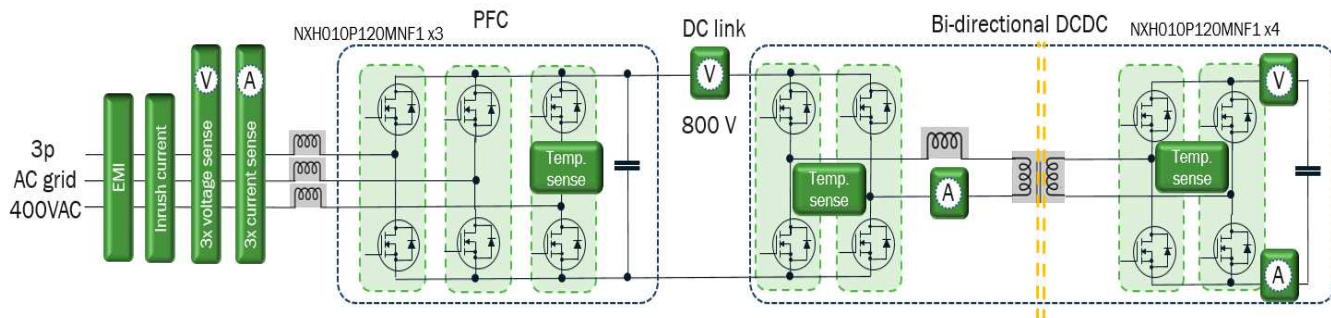


Fig. 2. Three-phase PFC AC-DC converter for electric vehicle DC charger with bidirectional active power flow [10].

Modifications of the PFC according to Fig. 1 are shown in Fig. 3. Here the input diode rectifier of the circuit in Fig. 1 has been replaced by an AC transistor switch consisting of two transistors with inverse current diodes. The circuit of the PFC in Fig. 3a does not have the galvanic isolation, and the circuit in Fig. 3b has the isolation. Replacing the output diode with an AC switch gives the PFC the property of a bidirectional rectifier.

A feature of the circuit in Fig. 3a is the half-wave asymmetry of the input current, due to the asymmetry of the output circuit. Fig. 4 presents a PFC circuit with a symmetrized output circuit. This solution provides the identity of the different-signs half-waves of the input current, as shown in Fig. 5.

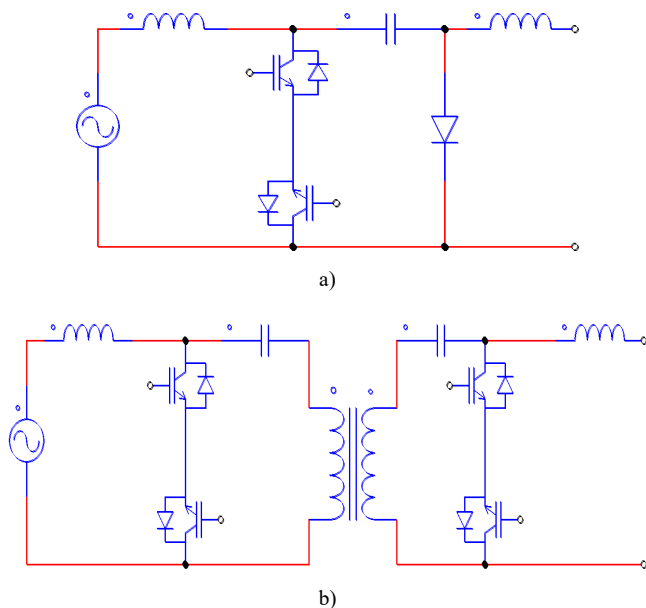


Fig. 3. Single-phase PFC rectifiers based on Cuk circuit: a) unidirectional in active power, b) bidirectional in active power.

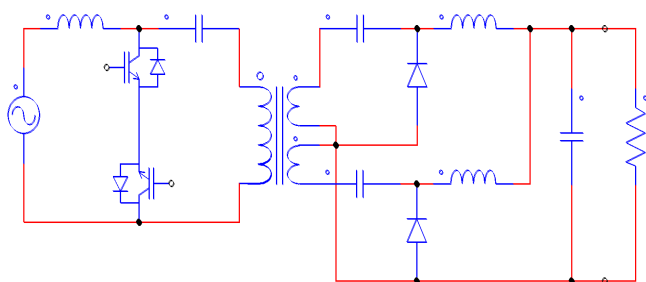


Fig. 4. Single-phase unidirectional in active power PFC rectifier based on modified Cuk circuit with symmetrized output circuit.

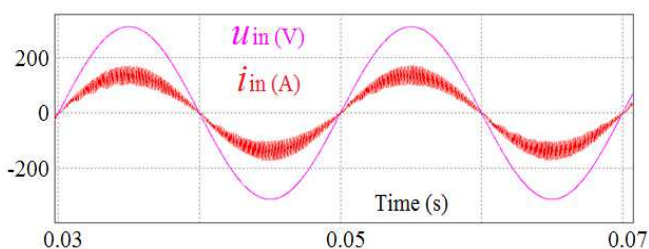


Fig. 5. Simulated waveforms of input voltage and input current of single-phase PFC rectifier based on modified Cuk circuit with symmetrized output circuit.

The computer experiments have been performed in PSIM environment designed for electromagnetic processes simulation in equipment of power electronics and motor control. The simulated control and load characteristics of the considered PFC cell are shown in Fig. 6a and Fig. 6b, respectively. Here U_{out} and I_{in} are the RMS values of the output (load) voltage and input current, R_{out} is the load resistance, and the modulation index M is defined as follows:

$$M = I_{in\ set} / U_{inm},$$

where $I_{in\ set}$ and U_{inm} are the amplitudes of the input current setpoint and the supplying voltage, respectively.

The analytical calculation of the proposed rectifier is possible by the direct method of algebraization of differential equations [8], which allows obtaining the integral (effective, i.e. RMS, and average) values of the desired currents and voltages directly through the coefficients of differential equations, avoiding the procedure for solving them. In this case, the initial differential equations have variable coefficients¹ and, due to the non-standard method of converting them into algebraic equations, the technique consideration in a separate publication is required.

The transformerless alternative circuit of the considered single-phase unidirectional in active power PFC rectifier is presented in Fig. 7.

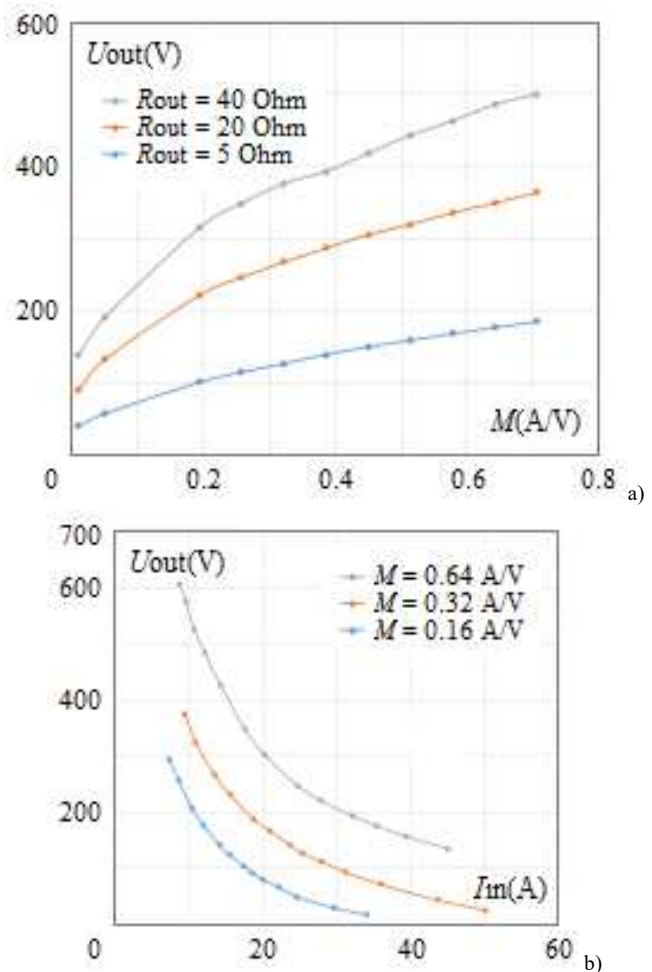


Fig. 6. Characteristics of single-phase PFC rectifier cell based on modified Cuk circuit with symmetrized output circuit: a) control characteristic, b) external characteristic.

1. A.D. Kostrykina, "Research of controlled rectifier with correction of input power factor [Issledovanie upravlyаемого выпрямителя s korekciej vhodnogo koeffitsienta moshchnosti]" (in Russian), B.S. thesis, Electron. and Electrical Eng. Dept., NSTU, Novosibirsk, Russia, 2021.

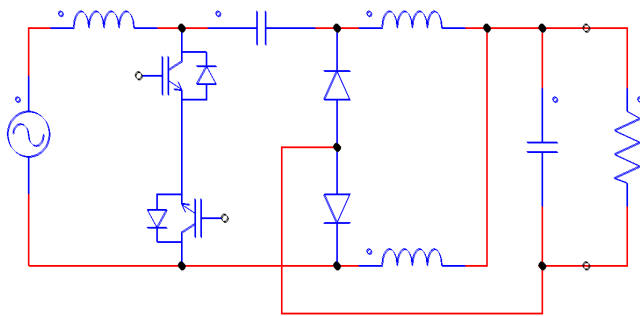


Fig. 7. Single-phase transformerless unidirectional active power PFC rectifier based on modified Cuk circuit with symmetrized output circuit.

A three-phase rectifier circuit, assembled from three considered single-phase cells (with or without an isolating high-frequency transformer), is shown in Fig. 8. Its simulated waveforms of the one input voltage and three input currents are presented in Fig. 9 for the case when the circuit of Fig. 4 is used as elementary single-phase cell.

All the presented rectifier circuits are equipped with the same control systems with current regulators of input currents. The control characteristics of the single-phase rectifier are almost linear due to the accepted principle of its input current shaping.

It is possible to build high-voltage (HV) rectifiers on the basis of the considered cells. The circuit of the HV rectifier for an AC electric locomotive, receiving the DC voltage of 3 kV at the output for the on-board network of the electric locomotive is obtained by cascading the cells connected in series at the inputs and in parallel at the output, see Fig. 10.

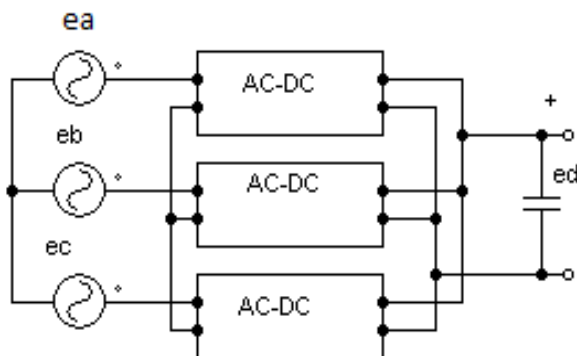


Fig. 8. Three-phase rectifier circuit, assembled from three single-phase unidirectional PFC rectifier cells based on the modified Cuk circuit with a symmetrized output circuit.

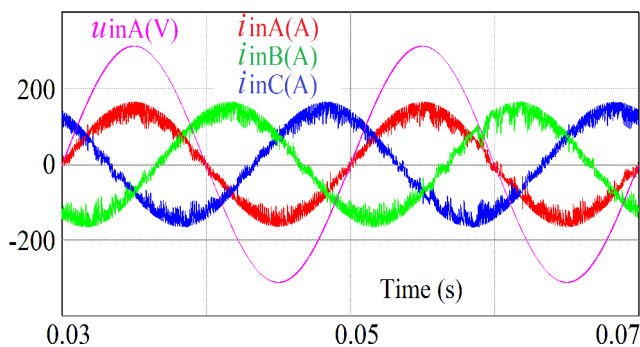


Fig. 9. Simulated waveforms of input voltage and input currents of three-phase PFC rectifier assembled from three single-phase unidirectional modified PFC rectifier cells.

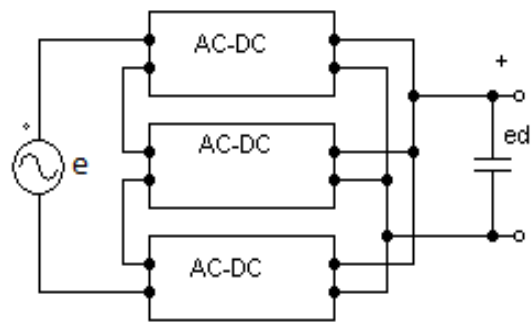


Fig. 10. The circuit of one phase HV rectifier for AC electric locomotive.

The number of serial cells at the input depends on the voltage class of the transistors used. When the energy recuperation is required, instead of the unidirectional cells (Fig. 4 or Fig. 7), it is necessary to apply the bidirectional cell shown in Fig. 3b.

III. AREAS OF ADJUSTABLE PFCs APPLICATION

The main scope of traditional (conventional) PFCs application is stabilized DC power supplies (without the possibility of recuperation).

The areas of adjustable PFCs application, which allow maintaining the unity input power factor at any possible direct output voltage, are functionally more diverse. They are as follows:

- 1) High-speed power supplies for regulated, recuperative DC electric drives.
- 2) Adjustable unidirectional or bidirectional sources of controlled DC voltages for inverters in systems of frequency electric drives of AC motors.
- 3) Adjustable unidirectional (for charging batteries) or bidirectional (for charging and discharging batteries) sources of controlled DC currents. Such devices are required for electric vehicles and capacitor accumulators of electric energy.
- 4) High-efficient adjustable power supplies for electrical technologies, in particular, sources for electrothermal processes.

Lastly, let the considerations about the appropriateness of the terminology used be given. The term power factor corrector (PFC) is used to refer to a class of AC-DC converters with a stabilized DC output voltage and with the unit value of input power factor. These are mainly power sources for radio-electronic equipment.

In recent years, the demand for adjustable DC voltage sources for the purposes of DC and AC electric drives, charging and discharging devices for supercapacitors and batteries, and electrical technologies devices has increased. A class of AC-DC converters is being developed, in which the output voltage is regulated not only while maintaining the value of the input power factor equal to one. A higher level of the input energy quality can also be achieved by providing a greater degree of electromagnetic compatibility with the supply network, taking into account its imperfection (the presence of higher harmonics, asymmetry, and reactive power). Therefore, such converters, in accordance with their extended functions for the formation of input energy, seem more appropriate to call power factor shapers (PFS).

IV. CONCLUSION

The rectifiers with correction of the input power factor by shaping the instantaneous value of the input current of the converter based on the modified Cuk converter, which provides unit input power factor over the entire range of regulation, and stabilization of the output voltage, are presented. Rectifiers can be made with or without galvanic isolation, with bidirectional active power transmission, with output voltage regulation up and down from the nominal value.

Such innovative PFC rectifiers are demanded in different industry branches, including advanced electric drive systems and charging and discharging batteries systems for electric cars. The modular composition principle makes it possible to enhance their applications and to form a broad range of PFC DC sources by output voltage and power rating.

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