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A HIGH POWER FACTOR THREE-PHASE RECTIFIER BASED ON ADAPTIVE CURRENT INJECTION APPLYING BUCK CONVERTER

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Abstract. The problem addressed in this paper is how to restore the power taken by the current injection network in the case of optimal injection of third harmonic, in a simple way, providing self-adjustment of the rectifier to the load current variations. Goals of the presented research are to use only one current sensor, and to improve third harmonic injection technique. A new rectifier topology is proposed, as well as the improved control algorithm which modify the rectifier output current. Algorithm of the rectifier design is presented. Analytical results are verified by experiments.

Keywords: AC/DC converters, Harmonics, Power factor correction, Power Quality, Three phase systems, EMC/EMI, Efficiency, Current injection.

1. INTRODUCTION

Extensive use of power electronics systems gained concern about the power quality. Prominent among nonlinear power electronics loads are three-phase rectifiers. They are widely used in variable speed drives, power supplies and uninterruptible power supplies systems. A method to reduce harmonic pollution caused by the three-phase rectifiers is the third harmonic current injection. The technique applies injection of the third harmonic currents in the rectifier supply lines in order to modify the input current waveform and to reduce its distortion.

Application of the technique in three-phase diode bridge rectifiers is presented in [1] and [2]. The rectifiers proposed in [1] and [2] utilize passive current injection networks, suitable for application at high power levels. To provide proper current injection, a part of the input power has to be transmitted to the current injection network. In the case of the optimal third harmonic current injection, that reduces the input current THD to about 5%, the power taken by the current injection network equals 8.57% of the input power [3].

The problem addressed in this paper is how to restore the power taken by the current injection network in a simple way, providing self-adjustment of the rectifier to the load current variations. A class of the rectifiers focused in this paper is suitable for application at high power levels. The rectifiers consist of a diode bridge, a current injection device, and a current injection network. The current injection network consists of two resonant LC branches, and an adaptive resistance emulation system.

In this paper a new rectifier topology that applies transformers to extract power from the resonant branches of the current injection network and a buck converter to adjust the equivalent transfer ratio of the transformers to the optimal value is proposed and compared to standard solutions. The analysis of the proposed topology is performed under the assumption that the diode bridge

operates in the continuous conduction mode and the design guidelines are given. Finally, the analytically obtained results are confirmed on an experimental setup of 2 kW of the output power.

Goal is to minimize the number of sensors used in circuits and to get as good as possible THD of input current. Also, it is important to use only one power converter (buck) for optimal third harmonic injection as well as for optimal generation of current harmonics at even triples of line frequency in parallel to the load.

In the second section a basic principles of resistance emulation are pointed out. A novel rectifier with adaptive resistance emulation is proposed in section 3, using only one current sensor, while in section 4 experimental results are expressed. In section 5 the possibility for further improvements of input current THD is examined. The 6th section contains the conclusion.

2. THE CURRENT-INJECTION NETWORKS APPLYING ADAPTIVE RESISTANCE EMULATION

Assuming that input voltages form a positive-sequence undistorted three-phase voltage system, and under the constraint that the diode bridge operates in the continuous conduction mode, voltages at the diode bridge output terminals (Fig. 1.) are given by their Fourier series expansions as

$$v_A = V_m \frac{3\sqrt{3}}{\pi} \left(\frac{1}{2} + \sum_{n=1}^{+\infty} \frac{(-1)^{n+1}}{9n^2 - 1} \cos \left(3n \left(\omega_0 t - \frac{\pi}{2} \right) \right) \right) \quad (1)$$

and

$$v_B = V_m \frac{3\sqrt{3}}{\pi} \left(-\frac{1}{2} + \sum_{n=1}^{+\infty} \frac{1}{9n^2 - 1} \cos \left(3n \left(\omega_0 t - \frac{\pi}{2} \right) \right) \right) \quad (2)$$

The third harmonic components of the diode bridge output terminal voltages are

$$v_{A,3} = v_{B,3} = -V_m \frac{3\sqrt{3}}{8\pi} \sin(3\omega_0 t) \quad (3)$$

and they are utilized to perform the current injection.

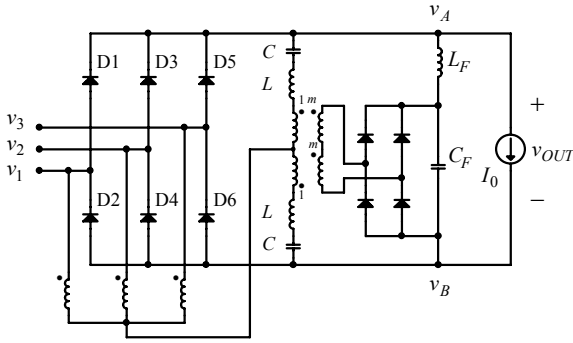


Fig. 1. A basic rectifier circuit with passive resistance emulation

To improve the rectifier efficiency, resistance emulation techniques with power recovery have to be applied. The resistance emulation systems provide the input port voltage proportional to the input port current, and they transfer the power taken by the input port to the output port.

Basic structure of the rectifier that applies passive resistance emulation is presented in Fig. 1. Current controlled voltages are obtained at primaries of the transformers of the resistance emulation system. Secondaries of the transformers are connected to a CL filter by a diode bridge. The diode bridge is applied to provide rectification of the third harmonic currents, while the CL filter with a stiff voltage input and a stiff current output is applied to transfer the power taken by the resistance emulator to the rectifier output. Voltage across the CL filter capacitor C_F is equal to the dc component of the output voltage,

$$V_{OUT} = \frac{3\sqrt{3}}{\pi} V_m \quad (4)$$

thus the amplitude of the square wave voltages across the transformer primaries is

$$V_R = \frac{1}{m} \frac{3\sqrt{3}}{\pi} V_m \quad (5)$$

where m is the equivalent transformer turns-ratio (for parallel connection of transformers secondaries).

Theoretically, internal losses in the current injection network components could determine the injected current amplitude, but precise realization of the transformers turns ratio is necessary [4]. Additional problem that has to be solved is how to compensate for variations of the component losses and the load current.

The input current THD is dependent on the resonant circuit characteristic resistance, and it decreases with the characteristic resistance increase. This dependence is presented in Fig. 3. as a function of normalized characteristic resistance ρ , defined as

$$\rho = \frac{I_0}{V_{OUT}} \sqrt{\frac{L}{C}} \quad (6)$$

By choosing the parameter ρ one can determine values of capacitors and inductors in resonant branches, keeping in mind that branches are resonant at third harmonic of line frequency [4].

In order to achieve the adaptivity of the resistance emulation system, it is necessary to introduce a power converter to process the power which has to be dissipated within resonant branches [3]. The choice is on buck converter due its inherent ability to control the output current.

3. THE NOVEL RECTIFIER TOPOLOGY

The circuit presented in Fig. 1. applies a diode bridge in the resistance emulation network. Secondary windings of the transformers are connected in series. This connection of the secondary windings imposes constraint that injected currents i_{IA} and i_{IB} are equal, leading to elimination of harmonic components of these currents at even triples of the line frequency [4].

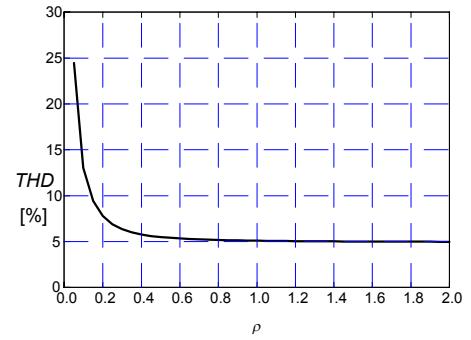


Fig. 3. The input current THD versus ρ

Voltages at primaries of the transformers have a specific waveform, shown in Fig. 2.

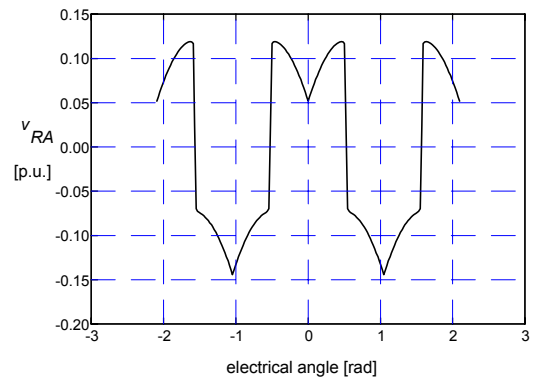


Fig. 2. Voltage waveform at the transformer primary

Impedance of the current injection network branches is very small at the triple of the line frequency, so the diode bridge output terminal voltages and the controlled voltage sources have to balance each other. The optimal value of the transformers turns-ratio is shown to be [4]

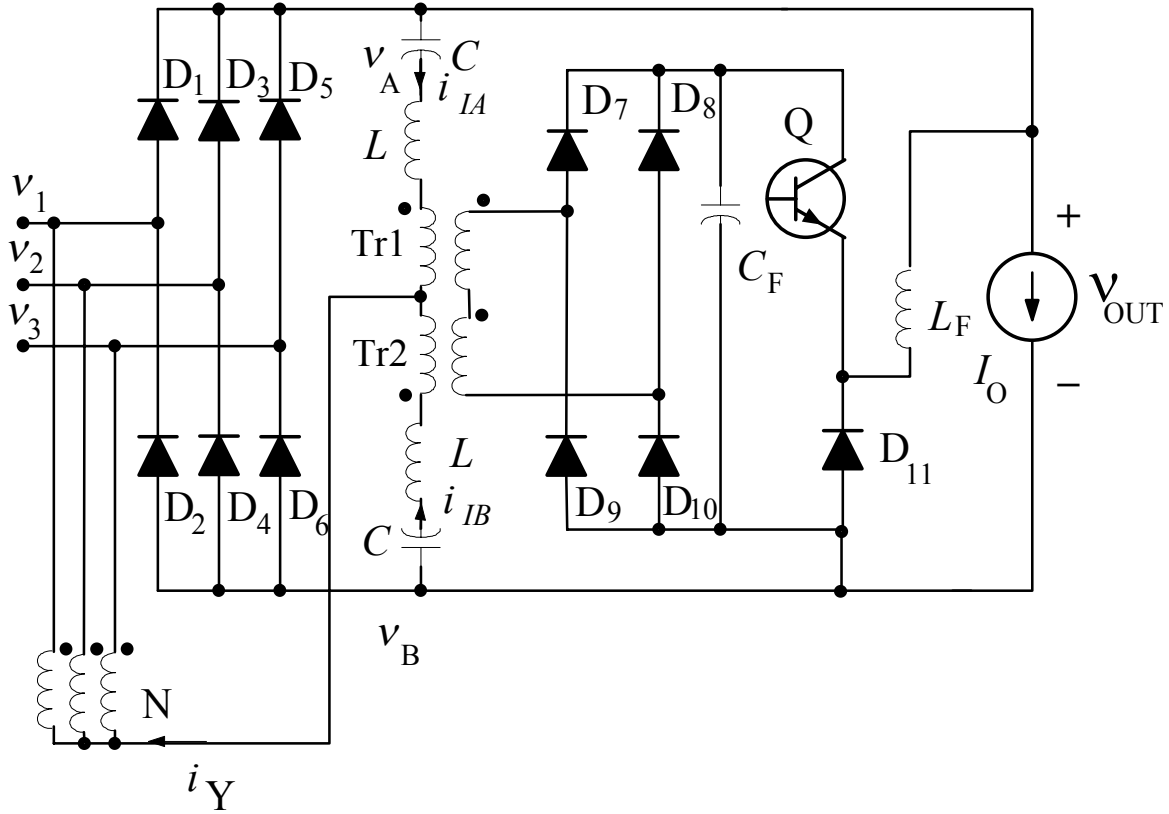


Fig. 4. Proposed rectifier topology with adaptive resistance emulation

$$m = \frac{16}{\pi} \quad (9)$$

but in practice it has to be higher to compensate for internal losses of the rectifier components.

The proposed adaptive rectifier topology is presented in Fig. 4. The role of the buck converter is to keep the amplitude of the injected current at the optimal level to achieve the minimal THD of input currents. In order to achieve the lowest possible THD of the input current, the necessary amount of even triples of the line frequency current [5] is added to the rectifier output current by appropriate modulation of the buck converter output current (current through L_F). Varying the buck converter equivalent conversion ratio, the equivalent transformer turns-ratio is varied, resulting in simple adjustment to variations of the load current and component parameters.

The control circuitry maintain the amplitude of the injected current so that the RMS value is

$$I_Y = \frac{\pi}{2\sqrt{2}} I_0 \quad (10)$$

in order to achieve the optimal third harmonic current injection.

The implemented control circuitry is based on a single insulated DC current sensor. The current sensor used has one hole of diameter large enough to put two current carrying conductors in. The first conductor is carrying the dc load current in one direction, while the second one is

carrying the rectified injected current. The rectification of the injected current is performed by an auxiliary diode bridge, connected in series with injection device. The output voltage of the current sensor thus represents the current error, which is further processed through PI regulator, in order to derive the duty cycle control voltage for the boost converter.

On such way, the control circuitry maintains condition (10) to achieve the near optimal current injection. Consequently, the introduced error in the injected current amplitude is 4.72% in comparison to an optimal case, what can be considered negligible.

4. EXPERIMENTAL RESULTS

In order to verify the analytically obtained results, several simulations and a number of experiments are performed.

The adaptive rectifier from Fig. 4. is built and tested at different power levels. An average efficiency of 95% is achieved, while load power is varied by varying the supply voltage, due to convenience. Three load points are tested, corresponding to the phase voltage of 216V, 200.7V and 182.7V, respectively. In the applied current injection network, inductors are of inductance $L = 28.5\text{mH}$ and capacitors are of capacitance $C = 40.7\mu\text{F}$. The supply voltage frequency is $f_0 = 50\text{Hz}$. The load resistor is connected in series to inductor of sufficient inductance to

emulate current sink. The load resistor resistance is $R_0 = 162\Omega$.

Waveforms of the corresponding input line currents are shown in Fig. 5., for three different rectifier input voltages. The correspondig waveforms of the injected currents are shown in Fig. 6. This adaptive control of current injection network maintains the total harmonic distortion of about 8.4% within the specified range of input voltages (different load levels).

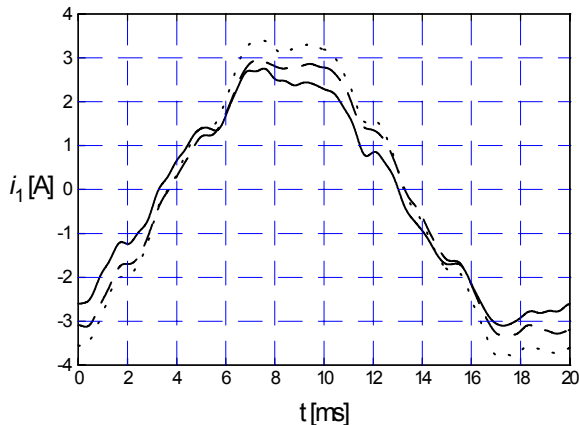


Fig. 5. Input current for different supply voltages, rectifier of Fig. 4.

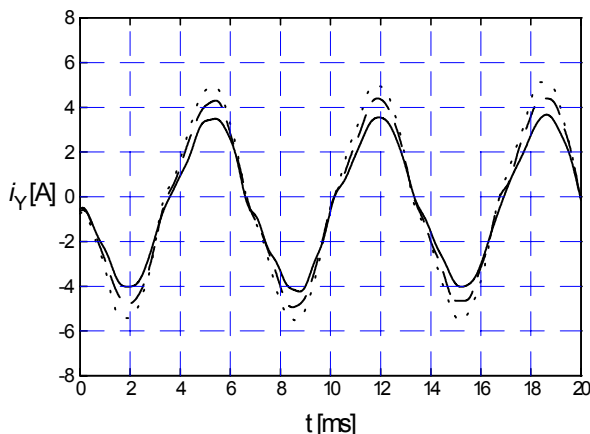


Fig. 6. Injected current for different supply voltages, rectifier of Fig. 4.

5. FURTHER IMPROVEMENT OF THE POWER RECOVERY CONTROL

The rectifier under consideration is performing the optimal third harmonic injection, as described in [3], and the best achievable rectifier input current THD is shown to be 5.12%. The question is, can be THD of the rectifier input current further improved while using the optimal third harmonic injection. According to [5], in optimal case the load current can not be constant, but have to contain also harmonic components at even triples of line frequency, in order to improve input current THD. The sum of output load current and harmonic components at even triples of line frequency is expressed by (11),

$$i_0(t) = \frac{\pi}{3} I_0 \sin(\omega_0 t) \quad (11)$$

for range $-30^\circ \leq \omega_0 t \leq 30^\circ$ and this waveform is periodic with period equal to one sixth of the line period. In such case it is necessary to introduce additional modulation of the buck converter output current in the proposed rectifier topology. Thanks to the fact that the extracted power in resonant branches is 8.57% of input power, or 9.37% of output rectifier power, the buck converter output current is 9.37% of load current for lossless case, or even less if there are losses within power recovery circuit. This constant power recovery current has to be modulated with waveform (12),

$$-i_0(t) + I_0 = I_0 \left(1 - \frac{\pi}{3} \cos(\omega_0 t)\right) \quad (12)$$

where the range of argument remains the same as for (11). This waveform contains all harmonics of even triples of line frequency except zeroth. The total buck converter output current should have the waveform as shown in Fig. 7., and it is obvious that the buck output current is positive all the time. In that case the rectifier input current THD of 3.2% can be achieved, which means that optimal third harmonic current injection and generation of harmonic components at even triples of line frequency is performed by one single buck power converter.

To verify that statement, a experimental setup is built, and some harmonic injection (not optimal) in paralel to load current is performed. In real case, the power recovery buck converter have to have high efficiency and to operate in continuous current mode, what impose hard requirements on buck inductor, which have to process approximately one tenth of output load current, modulated on described way. Parameters of the current injection network built for experiments are $L = 25$ mH and $C = 45\mu\text{F}$. The rectifier operates at phase voltages of $V_{RMS} = 240$ V, with the line frequency of $f_0 = 50$ Hz. The output dc current is set to be $I_0 = 4$ A. The adjusted value of equivalent transformer turns-ratio is $m = 7.669$ and it is tuned to correspond the minimal THD of the input currents. The input voltage waveform is distorted with $THD = 3.13\%$, while waveform of the corresponding input current is presented in Fig. 7. In Fig. 8. waveform of the resonant branch current i_{IA} is presented. The input current distortion of $THD = 4.83\%$ is achieved. The rectifier built for the experimental purposes operates at the input power level of 2290 W, and the output power of 2166W is measured. This result corresponds to the rectifier efficiency of 94.6%.

6. CONCLUSIONS

Three-phase high power factor rectifiers that apply current injection networks with resistance emulation and power recovery are analyzed in this paper. The adaptive resistance

emulation system is focused, with only one current sensor employed. It is shown that low total harmonic distortions of the input currents and high efficiency could be achieved applying only linear elements, diodes and only one controlled switching element. A new rectifier topology is proposed, as well as the improved control algorithm which modify the rectifier output current. Algorithm of the rectifier design is presented. Analytical results are verified by experiments.

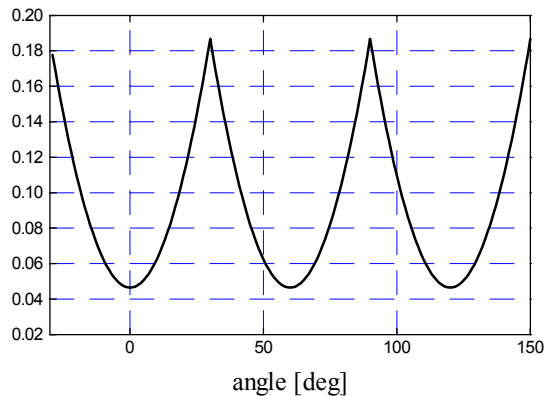


Fig. 7. The buck output current waveshape in an ideal case (relative to output current)

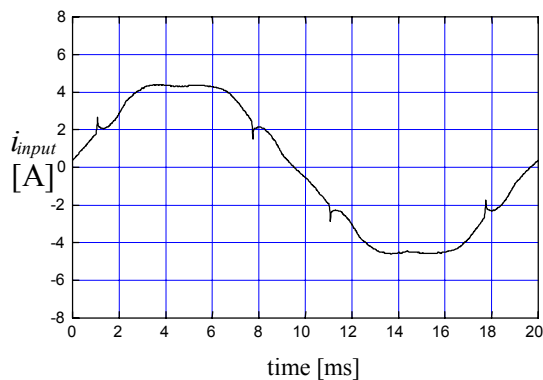


Fig. 8. Input current of the proposed rectifier, modulated buck output current case

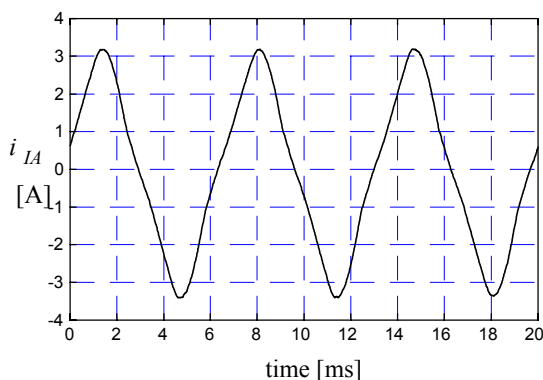


Fig. 9. Injected current of the proposed rectifier, modulated buck output current case

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