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THREE PHASE WARSAW BOOST RECTIFIER FOR HIGH POWER VARIABLE SPEED POWER GENERATION

Paper presents topology of the Warsaw rectifier that has been patented in 1992. Warsaw rectifier tested at that time, used hysteresis current controllers. This paper shows principles of operation of the Warsaw rectifier and presents control system based on the PWM modulation with constant switching frequency. Author also presents simulation results of the Warsaw rectifier in high power variable speed power generation system, performed in PSIM. Such topology is similar to Vienna rectifier but has different connection of basic modules.

1. INTRODUCTION

Nowadays, variable speed generation systems are becoming more popular in comparison to the fixed speed systems. There have been already presented several articles about using variable speed generation systems in e.g. wind turbine systems [1]–[3] or Diesel engine power generation systems [1], [4], [5]. Variable speed power generation has several advantages over fixed speed one, such as higher power generation efficiency, lower fuel consumption, if the Diesel engine [1], [4]–[6] or gas turbine [7] is used as driving engine, lower weight and volume of the whole system. The most popular generators that are used in variable speed application are doubly-fed induction generators [1] and permanent magnet generators [2]–[5], [8]. Basic topology of the variable speed power generation system is presented in Fig. 1. Such a system requires driving engine (DE), generator (GEN), AC/DC converter (REC) and DC-link capacitor (C_{dc}). Presented topology (Fig. 1) shows only conversion of the variable amplitude (V_g) and frequency (f_g) voltage to the DC voltage (v_{dc}). Output voltage (v_{dc}) can be either used in the DC grid or as an input voltage of the DC/AC converter. Depending on the desired properties of the power generation system, different topologies of the rectifiers are in use [1]–[16].

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The simplest rectifier topology consists of the three-phase diode rectifier and step-up DC/DC converter [3], [4], [8]. Voltage boost in step-up DC/DC converter can be accomplished by using one [3] or two [4], [8] transistors. The most disadvantageous property is inability to provide sinusoidal current from the generator.

Another rectifier topology is widely known as three-phase PWM rectifier [1], [2]. It consists of six transistors and is able to produce two-level DC voltage. Three-phase PWM rectifier provides bidirectional power flow. The most disadvantageous property is the need of dead-time implementation in the control system to avoid short-circuit through the one leg of the converter.

The next group of rectifiers are based on bidirectional switch (BS), presented in Fig. 2. There have been published many articles that in which such a switch is used or can be used in rectification process [9]–[14]. It allows to provide high quality sinusoidal current from the generator and does not require any blanking time implementation because of additional diodes that protects from possible cross short-circuit coming from the output capacitor. The article focuses on the rectifier, widely known as Warsaw rectifier (Fig. 3) that is based on the aforementioned bidirectional switch (Fig. 2).

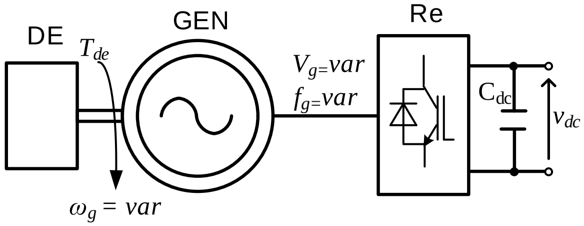

Fig. 1. Topology of the variable speed power generation system

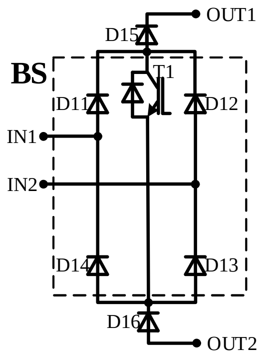

Fig. 2. Bidirectional switch (BS) used e.g. in Warsaw rectifier

Topology of the Warsaw boost rectifier has been patented in 1992 in Poland [9]. Later, there have been several publications [10]–[12] which presents the properties of the Warsaw rectifier. Publications [10]–[12] have also presented detailed analysis of the Warsaw rectifier operation and few simulation and experimental results. Phase currents in [10]–[12] were controlled by hysteresis controllers. Warsaw rectifier [10]–[12] is similar to Delta-Switch rectifier [13]–[15]. There have been published several articles presenting Delta-Switch rectifier, which include principles of operation, control system and simulation and experimental results. In [13], [14] Delta-Switch rectifier was used in a low power aircraft application. There haven't been published any papers yet, where two level with bidirectional switch (Fig. 2) Warsaw rectifier was used, thus the aim of the article is to present performance of the Warsaw rectifier in high power variable speed power generation system.

2. WARSAW RECTIFIER – TOPOLOGY AND PRINCIPLE OF OPERATION

Topology of the original Warsaw Rectifier is presented in Fig. 3. It includes three rectifiers (BR1, BR2, BR3) connected in parallel, with inside placed embedded bidirectional switches. Each rectifier module (BR1, BR2, BR3) includes also two diodes that protects transistors from potential short-circuit coming from DC output. A Delta-Switch rectifier used in [13]–[15] differs from the Warsaw Rectifier in bidirectional switch and in the way of voltage source connection to the switch. In [13]–[15] the bidirectional switch (BS) includes only two transistors.

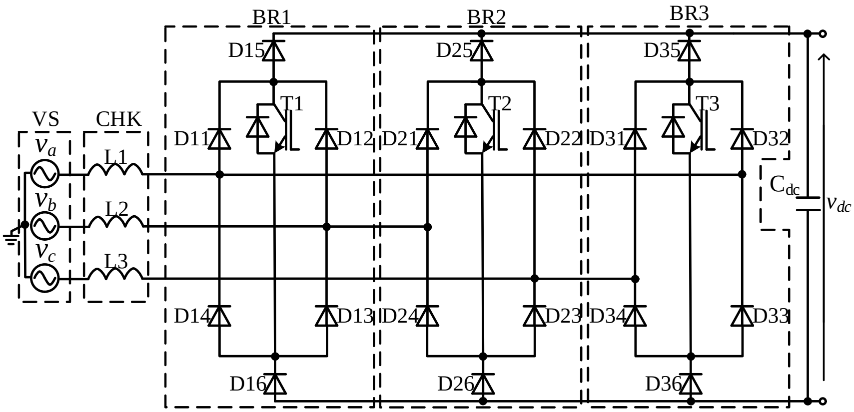

Fig. 3. Original Warsaw rectifier topology [9]–[12]

A three phase Warsaw rectifier in variable speed power generation system is supplied from the permanent magnet generator voltages (VS), that are described as follows:

$$v_a = \frac{\omega_g}{\omega_{gn}} \cdot V_{gm} \cdot \sin(\omega t) \tag{1}$$

$$v_b = \frac{\omega_g}{\omega_{gn}} \cdot V_{gm} \cdot \sin(\omega t - 2\pi/3) \tag{2}$$

$$v_c = \frac{\omega_g}{\omega_{gn}} \cdot V_{gm} \cdot \sin(\omega t + 2\pi/3) \tag{3}$$

where: ω_g is the actual generator speed, ω_{gn} is the nominal generator speed, V_{gm} is the amplitude of the phase voltage for $\omega_g = \omega_{gm}$.

Three chokes connected in series to each phase (L1, L2, L3) allows to boost the voltage that means the output voltage is higher than the maximum input AC voltage. In the presented Warsaw rectifier topology, the maximum input voltage corresponds to the maximum value of the line-to-line generator voltage, as follows:

$$V_{inm} = \sqrt{3} \cdot \frac{\omega_g}{\omega_{gn}} \cdot V_{gm} < V_{dc} \tag{4}$$

where: V_{inm} is the amplitude of the rectifier's input voltage, the V_{dc} is the DC voltage during the steady-state operation.

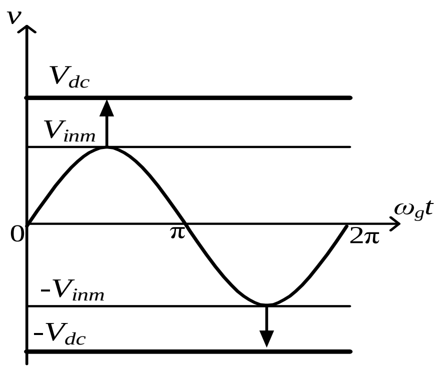

Fig. 4. Relation between the amplitude of the rectifier's input voltage V_{inm} and output DC voltage V_{dc}

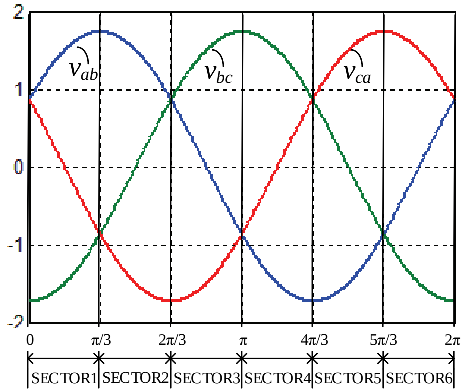

Fig. 5. Operation sectors of the Warsaw Rectifier against line-to-line voltages

Relation between V_{inm} and V_{dc} is also presented in Fig. 4. The Warsaw Rectifier operates like boost type converter, thus it is needed to define ratio between maximum rectifier's input voltage V_{inm} and output DC voltage V_{dc}. It has been called as Boost Factor (BF) and can be described as:

$$BF = V_{dc} / V_{inm} \tag{5}$$

Warsaw Rectifier's operation can be divided into six sectors (SECTOR1, SECTOR2, …, SECTOR6), depending on the instantaneous values of the line-to-line voltages. Fig. 5 presents three line-to-line voltages and corresponding to them sectors of operation.

Operation of the Warsaw Rectifier is similar to the typically used three phase diode bridge but the existing transistors allows to control both DC output voltage v_{dc} and three phase currents (i_a, i_b, i_c). Warsaw Rectifier is a three phase converter, thus the phase currents can be described as follows:

$$i_a = I_{gm} \cdot \sin(\omega t + \varphi) \tag{6}$$

$$i_b = I_{gm} \cdot \sin(\omega t - 2\pi / 3 + \varphi) \tag{7}$$

$$i_c = I_{gm} \cdot \sin(\omega t + 2\pi / 3 + \varphi) \tag{8}$$

where: φ is a displacement angle.

In order to present operation of the rectifier, let's consider SECTOR1. In this sector, two line-to-line voltages – v_{ab} and v_{bc}, determines the current flow in the circuit.

Phase currents signs are as follows:

$$i_a > 0 \tag{9}$$

$$i_b < 0 \tag{10}$$

$$i_c > 0 \tag{11}$$

Figures 6 and 7 presents the current flow in SECTOR1, during different states of operation. Semiconductor devices which are active, are marked with solid line and not used (not active) ones with dotted line. As it can be seen, only two of the rectifier modules are used to control the system – BR1 and BR2 (from Fig. 3). In effect, two currents are controlled to follow sinusoidal waveform, and the third one is just a consequence of that control. Fig 6 presents the current flow, when transistors T1 and T2 are turned on, and Fig. 7 presents pass of the current in the case of transistors T1 and T2 are turned off. If we neglect the voltage drops across the semiconductor devices, both states can be described as:

T1 and T2 turned on (Fig. 6):

$$v_a - L_1 \frac{di_a}{dt} - L_2 \frac{di_b}{dt} - v_b = 0 \tag{12}$$

$$v_c - L_3 \frac{di_c}{dt} - L_2 \frac{di_b}{dt} - v_b = 0 \tag{13}$$

T1 and T2 turned off (Fig. 7):

$$v_a - L_1 \frac{di_a}{dt} - L_2 \frac{di_b}{dt} - v_b - v_{dc} = 0 \tag{14}$$

$$v_c - L_3 \frac{di_c}{dt} - L_2 \frac{di_b}{dt} - v_b - v_{dc} = 0 \tag{15}$$

Moreover, if we assume that the duty cycle d is described by following equation:

$$d = \frac{t_{on}}{t_{on} + t_{off}} \tag{16}$$

where: t_{on} is the on-state time of the transistor and t_{off} is the off-state time of the transistor, the SECTOR1 operation can be described as:

$$v_a - L_1 \frac{di_a}{dt} - L_2 \frac{di_b}{dt} - v_b - (1 - d_a) v_{dc} = 0 \tag{17}$$

$$v_c - L_3 \frac{di_c}{dt} - L_2 \frac{di_b}{dt} - (1 - d_b) v_{dc} = 0 \tag{18}$$

where: d_a and d_b are the duty cycles of the transistors' control signals T1 and T2, respectively.

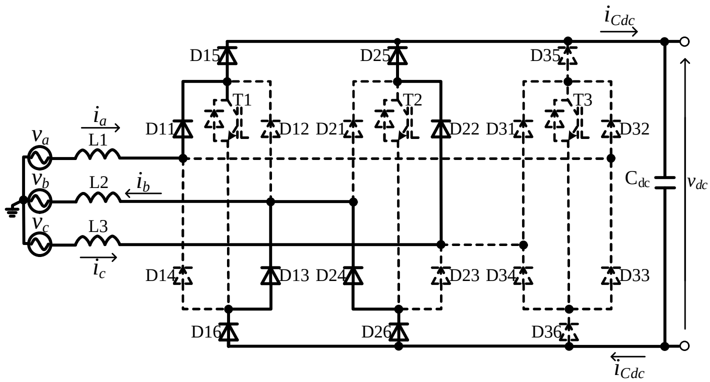

Fig. 6. Current flow in Warsaw rectifier when transistor T1 and T2 are turned on

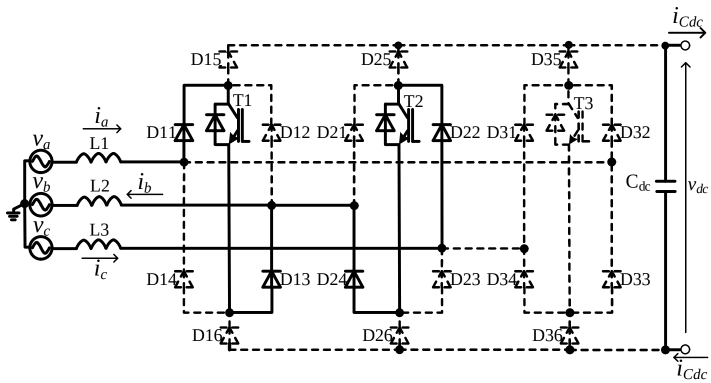

Fig. 7. Current flow in Warsaw rectifier when transistor T1 and T2 are turned off

3. WARSAW RECTIFIER CONTROL SYSTEM

Control system of the Warsaw Rectifier needs to provide:

- stable DC output voltage,
- high quality, sinusoidal phase currents – low value of the Current Total Harmonic Distortion (THDI),
- unity value of the Power Factor (PF).

To fulfil those requirements, a control system has been proposed and is shown in Fig. 8.

Control system of the presented rectifier, requires measurement or estimation of several values:

- generator phase voltages (electromotive forces), which is simply represented by sensors VS1, VS2 and VS3,
- phase currents that can be measured by current sensors CS1, CS2, CS3,
- output DC voltage, measured by voltage sensor VS4.

Firstly, in the control system there is a voltage controller (PI type controller) R_{vdc} that allows to get stable DC output voltage at the desired (reference) value V^*_{dc}. The reference value V^*_{dc} and measured one v_{dcf} are substracted. The error signal on the input of the voltage controller R_{vdc}, creates on the output of that controller signal that corresponds to the reference value of the phase currents amplitude I^*_m. Measured DC output voltage v_{dc} is filtered with the low-pass filter LPF to let only DC component pass through. Later, I^*_m signal is multiplied with the unity sinusoidal signals $\sin_a$, $\sin_b$ and $\sin_c$, that are created in phase-locked loop block PLL, in order to get reference phase currents – i^*_a, i^*_b, i^*_c. PLL output signals are described as follows:

$$\sin_a = \sin(\omega t + \varphi) \tag{19}$$

$$\sin_b = \sin(\omega t - 2\pi/3 + \varphi) \tag{20}$$

$$\sin_c = \sin(\omega t + 2\pi/3 + \varphi) \tag{21}$$

where: φ is a displacement angle. In the case of unity power factor operation:

$$\varphi = 0^\circ \tag{22}$$

Afterwards, the reference phase currents i^*_a, i^*_b, i^*_c and measured currents i_a, i_b, i_c, are being substracted, respectively. Three current controllers R_{ia}, R_{ib} and R_{ic} (P-type controllers) are used to create signals u^*_{La}, u^*_{Lb} and u^*_{Lc}, respectively, that are required to follow the desired current shape (sinusoidal). Additional feedforward signals that are generator phase voltages (electromotive forces) v_a, v_b, v_c will speed up the control action.

The input signals of the conversion block CONV are referring to the phase units (Y-connected system), where each phase could be controlled independently. Warsaw Rectifier is a Δ-type rectifier, thus we need to convert phase units to the line-to-line ones. Applied conversion block CONV calculates required line-to-line units of the reference voltages u^*_{ab}, u^*_{bc}, u^*_{ca} from the input signals u^*_a, u^*_b, u^*_c as follows:

$$u^*_{ab} = u^*_a - u^*_b \tag{23}$$

$$u^*_{bc} = u^*_b - u^*_c \tag{24}$$

$$u^*_{ca} = u^*_c - u^*_a \tag{25}$$

Aforementioned block also uses information about the current operating sector *sec* that comes from "Sector detection" block. In order to determine the actual sector of operation, "Sector detection" block uses measured/estimated generator phase voltages (electromotive forces) v_a, v_b, v_c. All sectors are shown on Fig. 5 and also listed

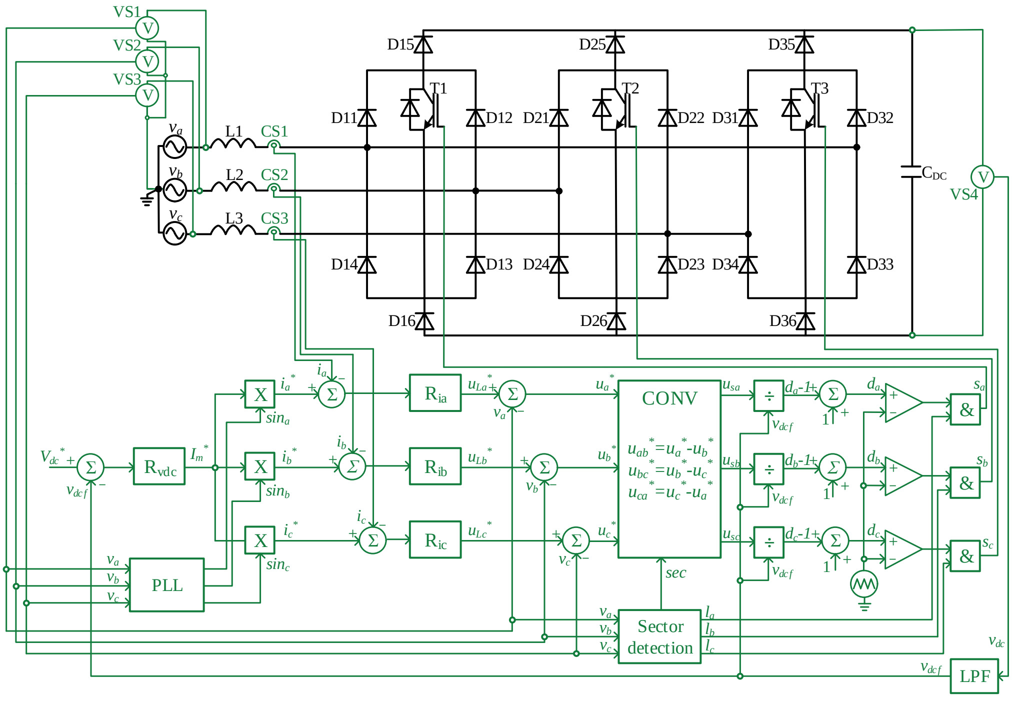

Fig. 8. Warsaw Rectifier control system

in Table 1. Sector detection block also creates logic signal l_a, l_b, l_c (Fig. 5, Table 1) and in pair with the logic AND gates, determines which two transistors will be used in the switching operation.

The most important signals are the duty cycles d_a, d_b and d_c. They are created by dividing output signals of the CONV block u_{sa}, u_{sb}, u_{sc} by the value of the measured and filtered DC voltage v_{dcf}, and adding unity signal. Such an operation realizes, e.g. equations (17) and (18) for SECTOR1.

Table 1. List of operation sectors and respective values of u_{sa}, u_{sb}, u_{sc}, and logic signals l_a, l_b, l_c

Sector	u_{sa}	u_{sb}	u_{sc}	l_a	l_b	l_c
SECTOR1	u_{ab}^*	$-u_{bc}^*$	$-u_{bc}^*$	1	1	0
SECTOR2	u_{ab}^*	u_{ab}^*	$-u_{ca}^*$	1	0	1
SECTOR3	$-u_{ca}^*$	u_{bc}^*	$-u_{ca}^*$	0	1	1
SECTOR4	$-u_{ab}^*$	u_{bc}^*	u_{bc}^*	1	1	0
SECTOR5	$-u_{ab}^*$	$-u_{ab}^*$	u_{ca}^*	1	0	1
SECTOR6	u_{ca}^*	$-u_{bc}^*$	u_{ca}^*	0	1	1

4. TEST RESULTS

Tests of the Warsaw Rectifier were provided using PSIM software for a case of adjustable speed permanent magnet generator. So the Warsaw Rectifier was tested in conditions of variable voltage and frequency. Table 2 shows a data of the generation system.

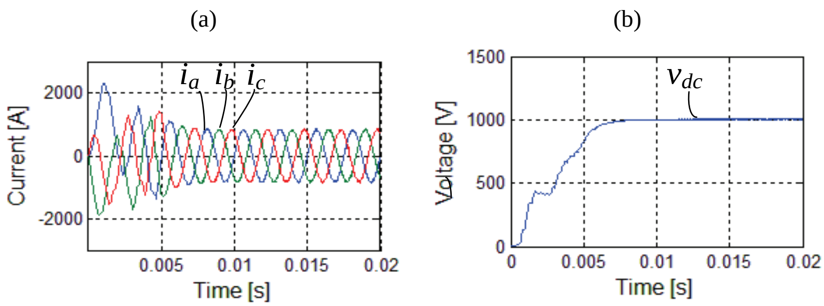

Fig. 9. Start of the rectifier operation in case of step response – Warsaw Rectifier load (P_{load} = 400kW) connection to the rotating permanent magnet generator (V_{inm} = 400 V, f_g = 400 Hz). (a) Phase currents i_a, i_b, i_c (b) Output DC voltage v_{dc}

Table 2. Data of the generation system

	Fig. 9 step response	Fig. 10 steady state	Fig. 11 steady state
V_{inm}	400 V	200 V	400 V
V_{dc}	1000 V		
BF	1,41	3,54	1,41
f_g	400 Hz	200 Hz	400 Hz
f_{PWM}	5 kHz		
L_1, L_2, L_3	100 μH		
C_{dc}	3 mF		
P_{load}	400 kW	200 kW	400 kW

Figure 9 shows case of transient state of the BR start in case of connection a 400 kW load. There are three phase currents. In initial condition the currents supply a DC link capacitor and load so they are practically not controllable. After 6 ms the capacitor is charged to the reference voltage V_{dc} = 1000 V and the currents are responding reference vales.

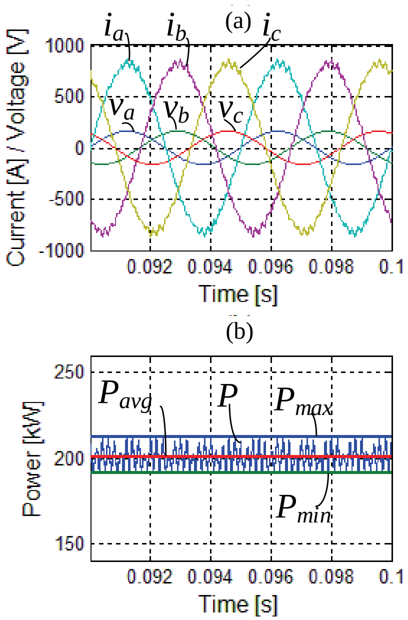

Fig. 10. Steady state of the BR operation
(a) Phase voltages v_a, v_b, v_c and currents i_a, i_b, i_c
(b) Input power P, for P_{load} = 200 kW
and f_g = 200 Hz

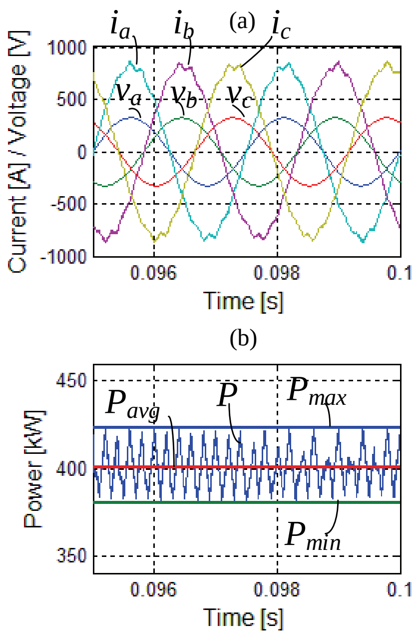

Fig. 11. Steady state of the BR operation
(a) Phase voltages v_a, v_b, v_c and currents i_a, i_b, i_c
(b) Input power P, for P_{load} = 400 kW
and f_g = 400 Hz

A steady state of the BR operation in case of 200 Hz supply voltage and load P = 200 kW is shown in Fig. 10. There are phase voltages and phase currents. The currents are sinusoidal and practically there isn't any delay. The quality factors of the currents are presented in Table 3. In Table 3 there are listed performance results such as Current Total Harmonic Distortion THDI and Power Factor PF (for phase A). Moreover Input Power Pulsation Factor IPPF was calculated:

$$IPPF = \frac{P_{\max} - P_{\min}}{P_{avg}} \cdot 100\% \tag{26}$$

where: $P_{\max}$ is the maximum power value, $P_{\min}$ is the minimum power value, P_{avg} is the average power value. The factor IPPF represents power pulsation which may result in torque pulsation of the permanent magnet generator. Such a torque pulsation is transferred to driving engine.

Similar test of the rectifier operation in case of generator frequency 400 Hz and load power P = 400 kW are shown in Fig. 11. Main factors of the rectifier quality power are shown in Table 3.

Table 3. Test results – performance of the Warsaw Rectifier

	Fig. 10	Fig. 11
THDI	2.63 %	2.55 %
PF	0.99	0.99
IPPF	10.7 %	10.4 %

Table 3 and respective figures are confirming high quality of the generator phase currents. There is also no phase shift between phase voltages and currents, thus unity power factor is also provided.

5. CONCLUSIONS

The paper presents topology of the Warsaw Rectifier, its principles of operation and simulation results where the rectifier is supplied from variable voltage and frequency source, i.e. permanent magnet generator. Simulation results confirms that the control scheme, based on the PWM modulation with constant switching frequency, is adequate. Performance results listed in Table 3 also confirms that topology is able to provide sinusoidal phase currents with low level of distortion and stable two-level DC output voltage, in high power application where switching frequency is significantly reduced. The Warsaw Rectifier can also provide low input power pulsations that in generators are proportional to the torque pulsations. The Warsaw boost rectifier has topology that reminds Vienna rectifier but it has different connection. Moreover, the Warsaw boost rectifier operates as two level unit whereas the Vienna rectifier, developed two years later, is a modification which provides three level operation.

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TRÓJFAZOWY „WARSAW RECTIFIER” W UKŁADZIE WYTWARZANIA ENERGII DUŻEJ MOCY O REGULOWANEJ PRĘDKOŚCI GENERATORA

Artykuł przedstawia topologię prostownika „Warsaw Rectifier”, jego zasadę działania oraz wyniki symulacyjne, w których prostownik zasilany był ze źródła napięcia o zmiennej amplitudzie i częstotliwości, np. generatora z magnesami trwałymi. Wyniki symulacyjne potwierdzają poprawność opracowanego układu sterowania, opartego na modulacji szerokości impulsów o stałej częstotliwości łączeń. Przedstawione wyniki w tabeli 3 również potwierdzają, że topologia umożliwia pobór sinusoidalnego prądu oraz stabilizację napięcia wyjściowego prostownika w układach o dużej mocy, w których częstotliwość łączeń jest ograniczona. Układ prostownika umożliwia zapewnia małe pulsacje mocy, które w generatorze przekładają się na małe pulsacji momentu. Topologia Warsaw Rectifier jest podobna do topologii Vienna Rectifier, natomiast różni się sposobem połączeń. Co więcej, rozważany prostownik Warsaw Rectifier wytwarza dwupoziomowe napięcie wyjściowe, podczas gdy prostownik Vienna wytwarza stałe, trójpoziomowe napięcie.