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ANALYSIS OF MODIFIED DIODE BRIDGE RECTIFIER WITH IMPROVED POWER FACTOR

Analiza układu zmodyfikowanego mostkowego prostownika diodowego o poprawionym współczynniku mocy

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Summary: **The subject of this paper is theoretical and simulation investigation of modified diode rectifier with improved power factor assembled according to proposition presented in [1]. The modified diode rectifier with additional power electronic valves used for modelling of multilevel voltage at the input of the diode rectifier is analysed. The mathematical model of the analysed rectifier system is presented. The control characteristics of the rectifier system are derived, constrains involved by the multilevel voltage generation scheme are pointed. The main conclusion derived from the performed analysis is that the modified rectifier system allow to obtain significant reduction of the THD(i) factor but only in the case of the nominal load.**

Streszczenie: **Tematem prezentowanej pracy są badania teoretyczne i symulacyjne prostownika o poprawionym współczynniku mocy, zrealizowanego według pomysłu przedstawionego w pracy [1]. W pracy przedstawiono szczegółową analizę zmodyfikowanego układu trójfazowego mostka diodowego, w którym zastosowano dodatkowe łączniki do kształtowania przebiegu czasowego napięcia na zaciskach wejściowych mostka diodowego. Zaprezentowany został model matematyczny układu oraz wyniki badań symulacyjnych. Wyprowadzono charakterystyki sterowania układu i wynikające z metody kształtowania wejściowego napięcia schodkowego na zaciskach mostka diodowego ograniczenia zakresu sterowania. Wykazano, że układ umożliwia uzyskanie istotnego zmniejszenia THD(i), jednakże tylko w warunkach obciążenia znamionowego.**

Key words: power electronics, electric power quality, rectifiers, improving THD(i).
Słowa kluczowe: energoelektronika, jakość energii elektrycznej, prostowniki, poprawa współczynnika odkształcenia.

1. INTRODUCTION

The subject of electric power quality is more and more significant [1–7]. A specially, methods of rectification are still developed [1, 4–7].

The main role of this paper is revision of our knowledge about rectifier system presented in [1]. System limitations are explained in a theoretical way and verified by simulations and experiment. The main advantages and disadvantages of the rectifier system are pointed out.

In this work the construction of rectifier with low level of harmonic distortion proposed by authors in paper [1] was analysed theoretically by simulation and experimental. Figure 1 presents electrical scheme of analysed rectifier system.

Standard three phase bridge rectifier is provided with three additional magnetic coils in each phase and one phase inverter with transformer for conditioning voltage level and three bidirectional keys.

2. BASIC PRINCIPLES OF RECTIFIER FUNCTIONALITY

Figures 2, 3 presents the principle of rectifier input currents generation.

Magnetic coils impedance is inserted between two three phase symmetrical generators (fig. 2). The first generator is responsible for three phase symmetrical voltages of electric power utility. Second generator is responsible for three pha-

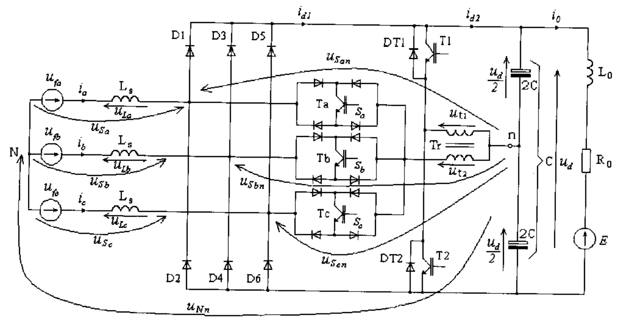

Fig. 1. Modified bridge rectifier

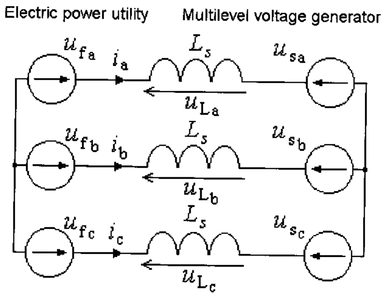

Fig. 2. Equivalent scheme of rectifier for illustrating the principle of generation near sinusoidal currents

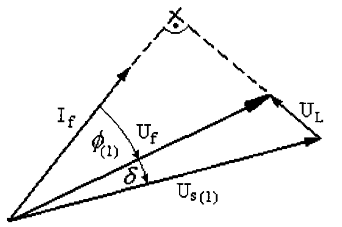

Fig. 3. Voltage and current vector diagram for first harmonics

se time plots of multilevel voltages generated at input diode matrix. If voltage between connection points is equal zero, which take place in the case of symmetry, then voltages of magnetic coils are the difference of appropriate generator's phase voltages. In ideal case of mono harmonic voltage at the input of diode matrix magnetic coil's voltages are sinusoidal and phase currents are sinusoidal so. Low high harmonic contents in voltages at the input of diode matrix result in low high harmonic contents in phase currents and the currents are near sinusoidal. Input power factor of the rectifier may be controlled by regulation of the phase angle between the vector phase voltage and the vector of first harmonic of multilevel voltage at the input of the diode rectifier (fig. 3). To obtain resistive or capacitive character of circuit it is necessary that the amplitude of multilevel voltage be greater than the amplitude of the phase voltage. Analogical schemes may be created for all harmonics.

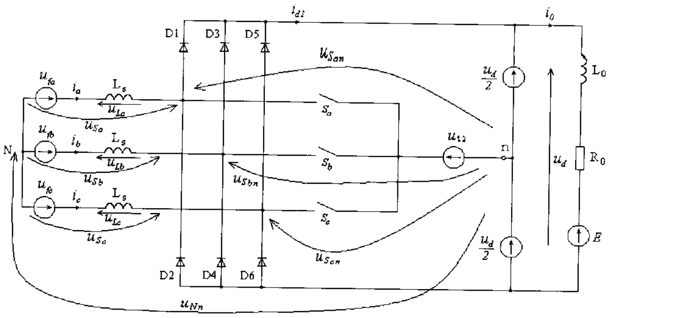

Fig. 4. Rectifier's equivalent scheme

3. INPUT VOLTAGE OF DIODE MATRIX

Time plots of voltages at the diode matrix input have strong influence on the phase currents time plots.

Voltage u_{t1} generated by an inverter has two values:

$$u_{t1} \in \left\{ \frac{u_d}{2}, -\frac{u_d}{2} \right\} \tag{1}$$

respectively:

$$\text{for } T_1 = 1,\quad T_2 = 0 \Rightarrow u_{t1} = \frac{u_d}{2} \tag{2}$$

$$\text{for } T_1 = 0,\quad T_2 = 1 \Rightarrow u_{t1} = -\frac{u_d}{2} \tag{3}$$

Voltage u_{t1} is transformed on the second side of transformer *Tr* with transformation ratio ϑ:

$$u_{t2} = \vartheta u_{t1} \tag{4}$$

Inverter and transformer functionality may be with good accuracy described by equivalent scheme from fig. 4.

Depending on the state of power electronics valves and phase current direction input voltage of diode matrix takes four values:

$$u_{t2} \in \left\{ -\vartheta \frac{u_d}{2},\ \vartheta \frac{u_d}{2} \right\} \tag{5}$$

$$u_{Sin} \in \left\{ -\frac{u_d}{2},\ u_{t2},\ \frac{u_d}{2} \right\} = \left\{ -\frac{u_d}{2},\ -\vartheta \frac{u_d}{2},\ \vartheta \frac{u_d}{2},\ \frac{u_d}{2} \right\} \tag{6}$$

respectively:

$$\text{for } s_i = 1 \Rightarrow u_{Sin} = u_{t2} \tag{7}$$

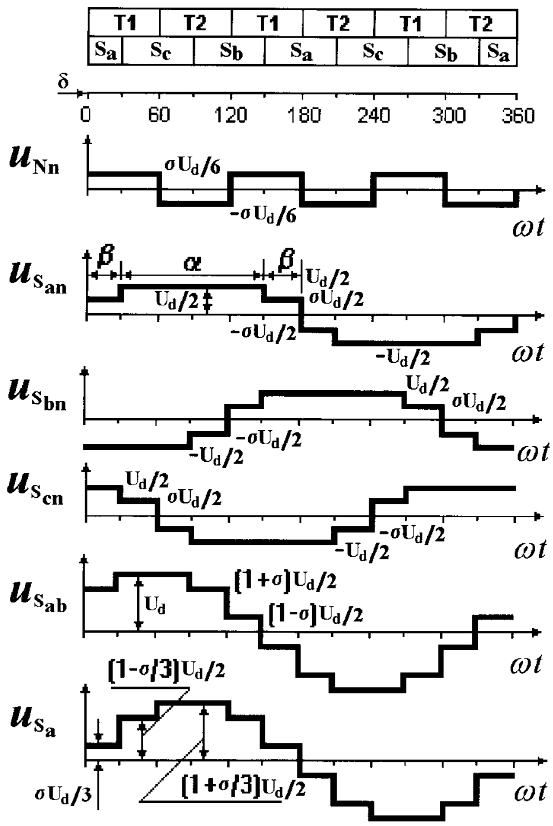

Fig. 5. Control pulse sequences T_1, T_2, S_a, S_b, S_c

$$\text{for } s_i = 0 \wedge i_i \geq 0 \Rightarrow u_{Sin} = \frac{u_d}{2} \qquad (8)$$

$$\text{for } s_i = 0 \wedge i_i < 0 \Rightarrow u_{Sin} = -\frac{u_d}{2} \qquad (9)$$

Control algorithm is presented in fig. 5.

Finally voltages u_{Sin} are described as:

$$u_{Sin} = \begin{cases} \vartheta \frac{U_d}{2} & \text{for } 0 \leq \theta < \frac{\pi}{6} \\ \frac{U_d}{2} & \text{for } \frac{\pi}{6} \leq \theta < \frac{5\pi}{6} \\ \vartheta \frac{U_d}{2} & \text{for } \frac{5\pi}{6} \leq \theta < \pi \\ -\vartheta \frac{U_d}{2} & \text{for } \pi \leq \theta < \frac{7\pi}{6} \\ -\frac{U_d}{2} & \text{for } \frac{7\pi}{6} \leq \theta < \frac{11\pi}{6} \\ -\vartheta \frac{U_d}{2} & \text{for } \frac{11\pi}{6} \leq \theta < 2\pi \end{cases} \qquad (10)$$

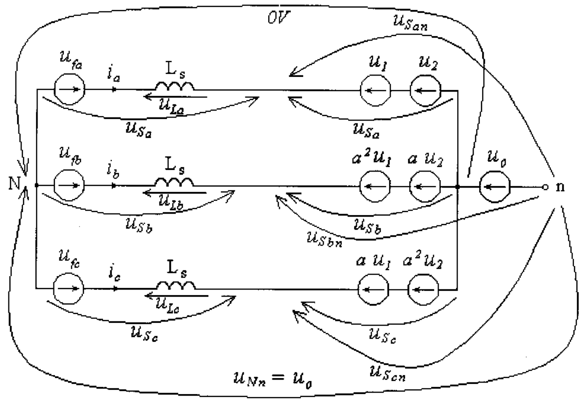

Fig. 6. Synthesis of equivalent voltage generator

The rectifier scheme useful for obtaining voltages at the input of diode matrix referenced to the neutral point of the electric power utility is presented at fig. 6. Control method proposed in [1] has some similarities to the group of control methods for rectifiers with modulation by 3rd harmonic current [6, 7]. Fig. 6 illustrates a mechanism of multilevel voltage synthesis using theory of symmetrical components.

Voltages u_{Si} may be obtained from:

$$u_{Si} = u_{Sin} - u_0 \quad \text{for} \quad i \in \{a,b,c\} \qquad (11)$$

Obtained voltage time plots are illustrated in fig. 7.

Mathematical description of u_{Si} voltage time plot measured in reference to the neutral point of electric power utility is presented by (12).

$$u_{Si} = \begin{cases} \vartheta \frac{U_d}{3} & \text{for } 0 \leq \theta < \frac{\pi}{6} \\ \frac{U_d}{2}\left(1 - \frac{\vartheta}{3}\right) & \text{for } \frac{\pi}{6} \leq \theta < \frac{2\pi}{6} \\ \frac{U_d}{2}\left(1 + \frac{\vartheta}{3}\right) & \text{for } \frac{2\pi}{6} \leq \theta < \frac{2\pi}{3} \\ \frac{U_d}{2}\left(1 - \frac{\vartheta}{3}\right) & \text{for } \frac{2\pi}{3} \leq \theta < \frac{5\pi}{6} \\ \vartheta \frac{U_d}{3} & \text{for } \frac{5\pi}{6} \leq \theta < \pi \\ -\vartheta \frac{U_d}{3} & \text{for } \pi \leq \theta < \frac{7\pi}{6} \\ -\frac{U_d}{2}\left(1 - \frac{\vartheta}{3}\right) & \text{for } \frac{7\pi}{6} \leq \theta < \frac{4\pi}{3} \\ -\frac{U_d}{2}\left(1 + \frac{\vartheta}{3}\right) & \text{for } \frac{4\pi}{3} \leq \theta < \frac{5\pi}{3} \\ -\frac{U_d}{2}\left(1 - \frac{\vartheta}{3}\right) & \text{for } \frac{5\pi}{3} \leq \theta < \frac{11\pi}{6} \\ -\vartheta \frac{U_d}{3} & \text{for } \frac{11\pi}{6} \leq \theta < 2\pi \end{cases} \qquad (12)$$

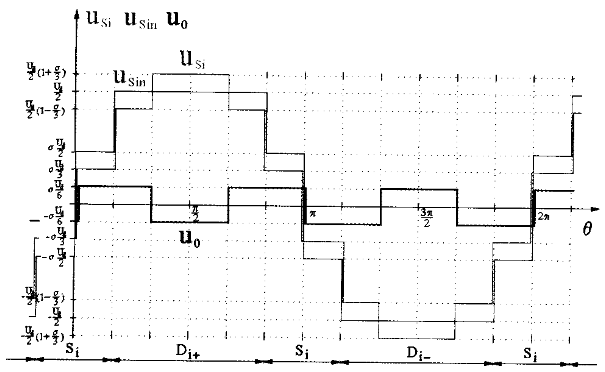

Fig. 7. Time plots of voltages

RMS values of individual harmonics of multilevel voltage u_{SN} are described by expression:

$$U_{SN(k)}=\frac{4U_d}{\sqrt{2}\pi k}\left[-\frac{\vartheta}{3}cos(k\theta)\Big|_0^{\frac{\pi}{6}}-\frac{1}{2}\left(1-\frac{\vartheta}{3}\right)cos(k\theta)\Big|_{\frac{\pi}{6}}^{\frac{\pi}{3}}+\right.$$
$$\left.-\frac{1}{2}\left(1+\frac{\vartheta}{3}\right)cos(k\theta)\Big|_{\frac{\pi}{3}}^{\frac{\pi}{2}}\right] \quad (13)$$

RMS value of the first harmonic is expressed as follows:

$$U_{SN(1)}=\sqrt{\frac{3}{2}}\frac{1}{\pi}\left[1+\vartheta\left(\frac{2}{\sqrt{3}}-1\right)\right]U_d=mU_d \quad (14)$$

Optimal value of the transformation ratio with regard to high harmonics cancellation is [1, 4]:

$$\vartheta=0.464 \quad (15)$$

For this value of the transformation ratio we obtain [1, 2]:

$$U_{SN(5)}=0 \text{ and } U_{SN(7)}=0 \quad (16)$$

and the modulation ratio:

$$m\approx 0.418 \quad (17)$$

Dynamics of phase currents is described by equations:

$$for\ s_i=1 \qquad \Rightarrow\frac{di_i}{dt}=\frac{1}{L_S}\left(u_{fi}+u_{Nn}-u_{t2}\right) \quad (18)$$

$$for\ s_j=0\wedge i_j>0 \quad \Rightarrow\frac{di_j}{dt}=\frac{1}{L_S}\left(u_{fj}+u_{Nn}-\frac{u_d}{2}\right) \quad (19)$$

$$for\ s_k=0\wedge i_k<0 \quad \Rightarrow\frac{di_k}{dt}=\frac{1}{L_S}\left(u_{fk}+u_{Nn}+\frac{u_d}{2}\right) \quad (20)$$

$$i\neq j\neq k \quad i,j,k\in\{a,b,c\} \quad (21)$$

Generating positive current corresponds to switching of voltage u_{Sin} between values u_{t2} and $\frac{u_d}{2}$ while generating negative current corresponds to switching between values u_{t2} and $-\frac{u_d}{2}$. This fact results in limited possibility of reactive, capacitive power generation and impossibility of working in inverter mode. Presented here properties are illustrated in chapter simulation results.

4. CONTROL AREA ANALYSIS

For performing conditions of equations (8) and (9) it is necessary to fulfil requirements:

$$\frac{\pi}{6}+\varepsilon\geq\varphi+\delta\geq-\left(\frac{\pi}{6}+\varepsilon\right) \quad (22)$$

Angle ε is a difference between zero crossing of current first harmonic and zero crossing of instantaneous current value. Conditions (8) and (9) are defined for instantaneous current's values. Inequality (22) is a simple result of conditions of diode conduction stated in (8) and (9).

If we assume that the phase voltage is not deformed, in other words has only the first harmonic, we can state active power flow into the converter as (25). Assuming that the AC/DC converter has zero power losses and neglecting high harmonics of rectifier's output voltage the active output power of the rectifier may be represented by (26). The assumption that high harmonics of supply voltages are zero while high current harmonics exist is equivalent to assume that output impedance of electric power utility is neglected. Omitting harmonics of output voltage of order greater than 0 is equivalent to assume that the output voltage is ideally filtered. The assumptions above have an influence on electric power balance of the rectifier and may have some implications on reactive power balance. In the case of ideal filtration of the rectifier's output voltage pulse component of the output voltage $u_p\rightarrow 0$ although the reactive power has not zero value. The value of the reactive power may be pointed from equations (27), (28) describing input circuits of the converter.

Equations (23) and (24) describe phase current of one converter's phase (23) and output current of the converter (24) respectively.

$$I_{L(1)}=\frac{U_{L(1)}}{\omega L_S} \quad (23)$$

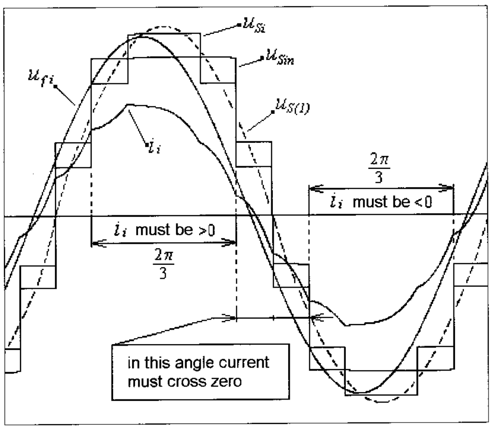

Fig. 8. Possible region of phase angle between current and multilevel voltage

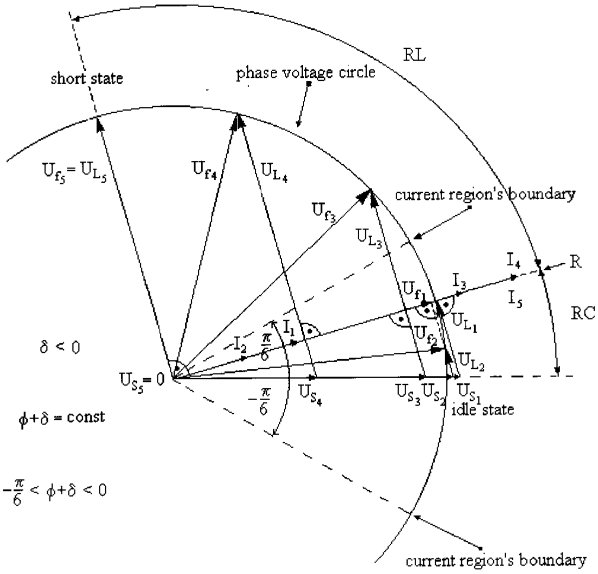

Fig. 9. Vector diagram for the case of current lead to multilevel voltage

$$I_0 = \frac{U_d - E}{R_0} \tag{24}$$

Active power of the converter is described as (25), (26).

$$P = 3U_f I_{L(1)} \cos\varphi = 3U_{S(1)} I_{L(1)} \cos(\varphi + \delta) \tag{25}$$

$$P = U_d I_0 = \frac{U_d (U_d - E)}{R_0} \tag{26}$$

Reactive power is described by equations:

$$Q = Q_S + Q_L \tag{27}$$

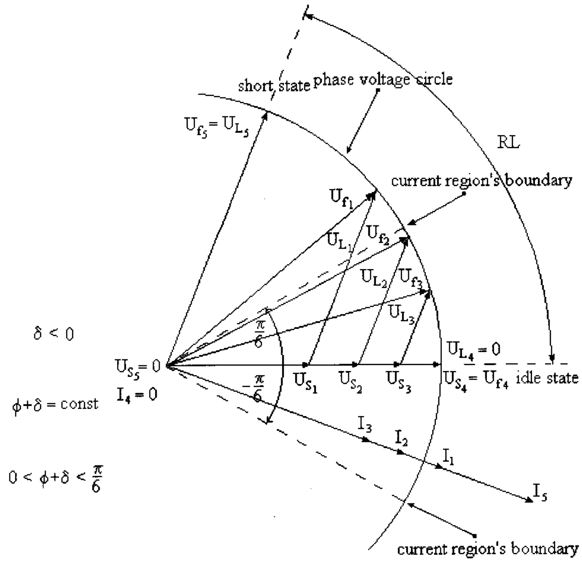

Fig. 10. Vector diagram for the case of current lagged to the multilevel voltage

$$Q = 3U_f I_{L(1)} \sin(\varphi) = 3U_{S(1)} I_{L(1)} \sin(\varphi + \delta) + 3\omega L_S I_{L(1)}^2 \tag{28}$$

Dependencies between rectifier's unit voltages are described by equations (29), (30), (31), (32). Equations (29), (30), (31) may be obtained by the analysis of the vector diagram or from dependencies describing active power (25) and reactive power (28).

$$U_{S(1)} = U_f \frac{\cos\varphi}{\cos(\varphi + \delta)} \tag{29}$$

$$U_{L(1)} = U_f \frac{-\sin\delta}{\cos(\varphi + \delta)} \tag{30}$$

$$U_{L(1)} = -\frac{\sin\delta}{\cos\varphi} U_{S(1)} \tag{31}$$

$$U_{S(1)} = mU_d \tag{32}$$

Basing on equations of active power (25) and dependencies between first voltages harmonics (29), (30), (31), (32) we can describe the equations system (33) representing active power of the system.

$$\begin{cases} P = -\dfrac{3U_f^2}{\omega L_S} \cdot \dfrac{\sin\delta \cos\varphi}{\cos(\varphi + \delta)} \\ P = -\dfrac{3(mU_d)^2}{\omega L_S} \cdot \dfrac{\sin\delta \cos(\varphi + \delta)}{\cos\varphi} \\ P = \dfrac{U_d (U_d - E)}{R_0} \end{cases} \tag{33}$$

Resolving this equations system in relation to output voltage U_d, phase angle φ and reactive power P, we obtain U_d as:

$$U_d = E - \frac{3mR_0U_f \sin\delta}{\omega L_S} \tag{34}$$

The obtained value of the voltage U_d makes it possible to point the value of voltage $U_{S(1)}$ basing on equation (32) and the value of active power P according to equation (26). The dependence on the phase angle from angle δ is expressed by:

$$\varphi = ar\,\mathrm{ctg}\left(\mathrm{ctg}\,\delta - \frac{1}{\sin\delta}\cdot\frac{U_f}{U_{S(1)}}\right) \tag{35}$$

Values of voltage $U_{L(1)}$, phase current $I_{L(1)}$ may be solved according to (31) and (23) respectively. Charts of the signals and parameters for conditions: $U_f = 90$ V, load circuit voltage $E = 0$ V inductance $L_S = 7.5$ mH, load resistance $R_0 = 42\ \Omega$ in dependency of angle δ are presented in fig. 11.

The obtained dependencies are valid only in a very close range of δ angle. In this limited range condition (22) is true. As a result of this condition, range of control is limited to the period of δ angle for which multilevel voltage u_s is properly generated (fig. 12).

In the case of load circuit voltage $E = 0$ V the dependence describing phase shift angle φ as a function of angle δ takes the form of:

$$\varphi|_{E=0} = ar\,\mathrm{ctg}\left(\mathrm{ctg}\,\delta + \frac{\omega L_S}{3m^2R_0\sin^2\delta}\right) \tag{36}$$

Limiting considerations to the case of load circuit voltage $E = 0$ V and zero reactive power Q, which is equivalent to $\varphi = 0$, it is possible to point angle δ as a function of load circuit resistance R_0. Now we are finding the value of angle δ in the case of which there is no reactive power in the rectifier system. By assuming the value of the equation (36) is zero and resolving the next expression for angle δ the following will be obtained:

$$\delta|_{\varphi=0,E=0} = \frac{1}{2}\arcsin\left(-\frac{2\omega L_S}{3m^2R_0}\right) \tag{37}$$

Taking into account limits results from (22), the fact so $\delta < 0$ and assuming that $\varepsilon \approx 0$ we obtain inequality:

$$-\frac{\pi}{6} \le \frac{1}{2}\arcsin\left(-\frac{2\omega L_S}{3m^2R_0}\right) < 0 \tag{38}$$

Solutions of inequality (38) assign the range of output resistance R_0 value for which work of system with zero reactive power Q is possible.

$$R_0|_{\varphi=0,E=0} \ge \frac{4\omega L_S}{3\sqrt{3}m^2} \tag{39}$$

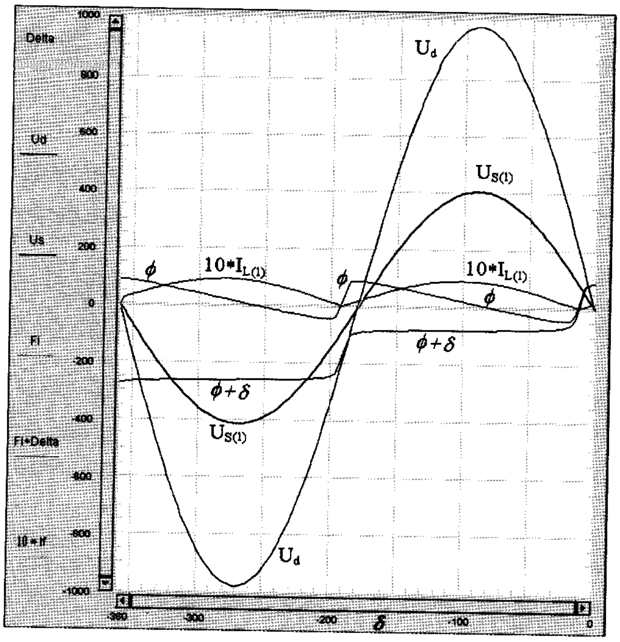

Fig. 11. Dependencies of rectifier's signals and parameters from angle δ

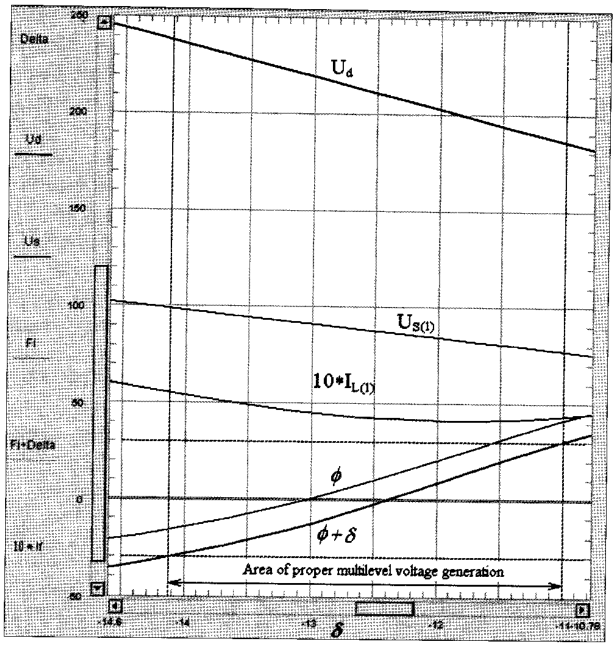

Fig. 12. Dependencies of rectifier's signals and parameters from angle δ

The minimal value of load resistance R_0 for which the work of rectifier with displacement factor $\cos(\varphi) = 1$ is possible arises from (39). The value of minimal load resistance is proportional to the reactance of input magnetic coil.

5. SIMULATION RESULTS

Simulation investigations were made for the simulation scheme from fig. 13 in TCAD program. The results of the simulations are presented at fig. 14 to 20.

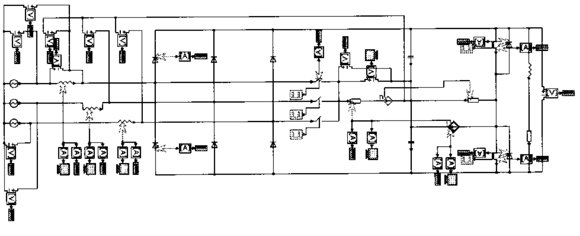

Fig. 13. Simulation scheme of rectifier

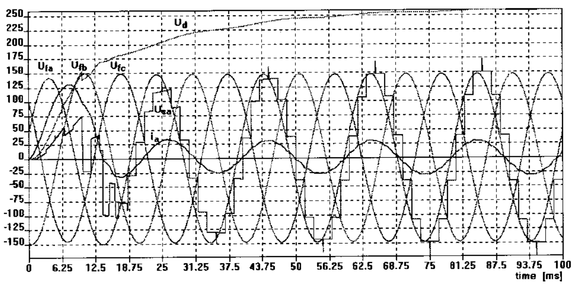

Fig. 14. Simulation time plots of rectifier's voltages and phase current at the start period

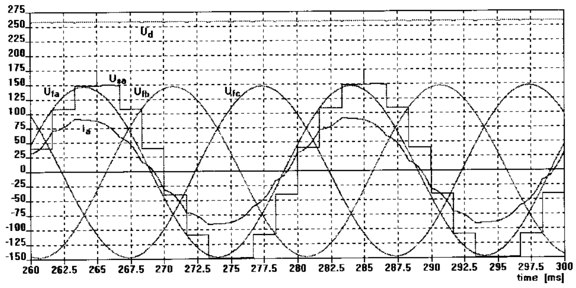

Fig. 15. Simulation time plots of rectifier's voltages and phase current in steady state

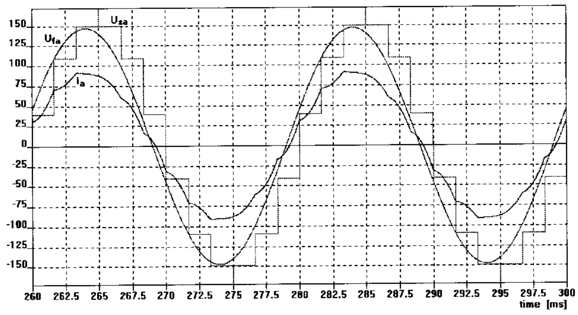

Fig. 16. Simulation time plots of phase voltage, multilevel voltage and phase current

6. SPECTRUM ANALYSIS OF RECTIFIER'S SIGNALS

Figures from 21 to 24 present phase current and voltages spectrum obtained in the way of the rectifier's system simulation. Figure 21 illustrates spectrum of multilevel voltage at the input of diode rectifier referenced to the central point of capacitive voltage divider n. In this voltage high harmonics

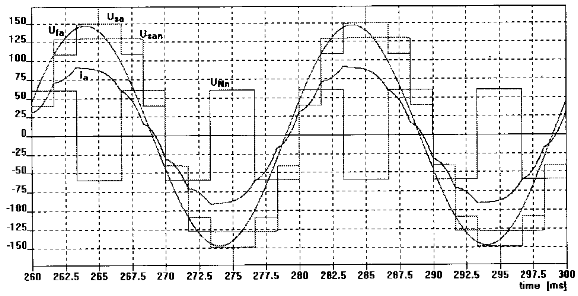

Fig 17. Simulation time plots of phase voltage, multilevel voltage, output transformer voltage and phase current

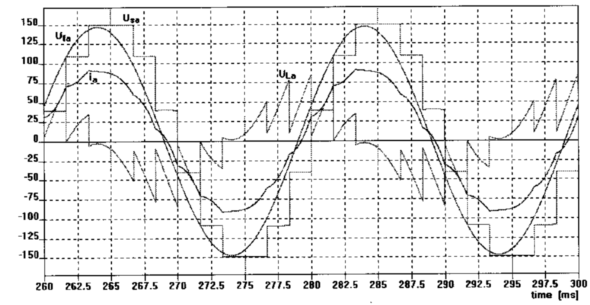

Fig. 18. Simulation time plots of phase voltage, multilevel voltage, input magnetic coil voltage and phase current

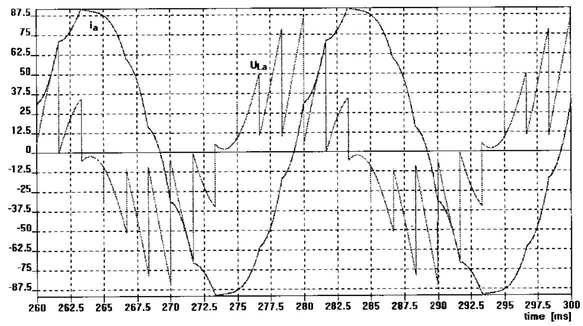

Fig. 19. Input phase current and input magnetic coil voltage

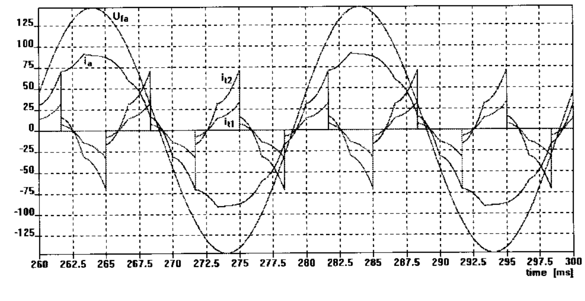

Fig. 20. Distribution of phase current in input junction

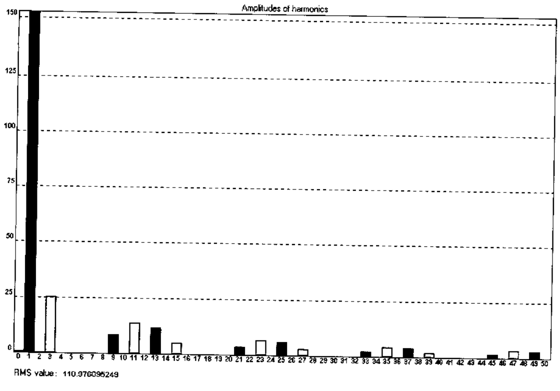

Fig. 21. Spectrum of multilevel voltage

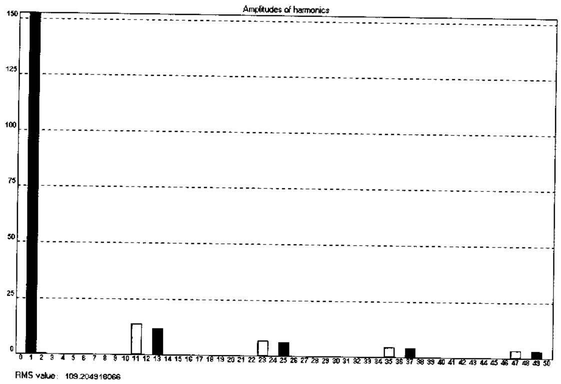

Fig. 22. Spectrum of multilevel voltage

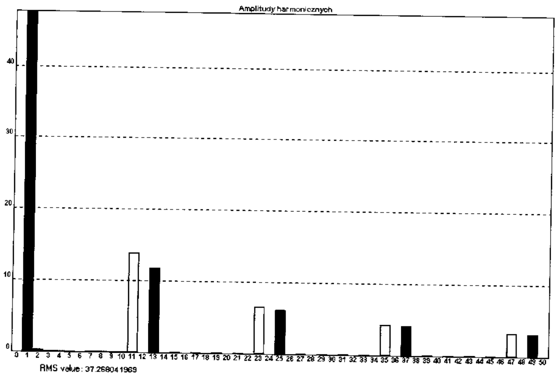

Fig. 23. Spectrum of input magnetic coil voltage

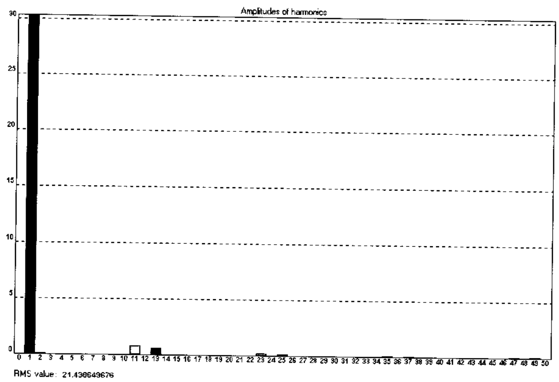

Fig. 24. Spectrum of phase current

of orders being multipliers of 3 exist. These harmonics create zero sequence component of multilevel voltage u_{S_n} and are used for modulations.

Figure 22 presents the spectrum of multilevel voltage referenced to the neutral point N of electric power utility. The spectrum of this voltage has no zero sequence component harmonics.

Figure 23 presents the spectrum of input magnetic coil voltage. This spectrum contains the same harmonics like the spectrum of multilevel voltage u_{SN}. The values of high harmonics' amplitudes are identical like in the case of multilevel voltage u_{SN} referenced to the neutral point of electric power utility, only the value of the amplitude of first harmonic is smaller because it is the difference of the amplitude of phase voltage and the amplitude of the first harmonic of multilevel voltage.

Figure 24 presents the spectrum of phase current. The amplitudes of high harmonics are reduced by input magnetic coil reactance.

The order of the lowest number parasitic harmonic is 11. Harmonics number 5 and 7 do not exist in the simulated multilevel voltage time plot so also do not exist in phase current time plot. The rectifier system has advantages similar to the 12-pulse diode rectifier.

7. CONCLUSIONS

System's properties

Disadvantages:

— The system has very strong limitations. Independent regulation of output voltage U_d and phase angle φ is impossible,

— The rectifier's output voltage U_d regulation is possible only in the restricted region of angle δ values.

Advantages:

— The analysed system, although simply construction of power circuits and low switching frequency of transistors, has very well properties $THD_i \approx 3\%$ [2].

— The analysed converter is a modification of standard 6-pulse diode rectifier and may be obtained by means of modernisation the existing industrial rectifier systems. The power converted by an additional circuit is only a part, about 7% of overall rectifier's system power rating. It results in little transistor currents, additionally the frequencies of transistors switching are low (maximally 150Hz). The proposed solution is inexpensive.

The rectifier system proposed in [1] may be exploited in a closely limited range of load power. In this range it is possible to generate near sinusoidal phase current for phase displacement angles performing condition (22). The rectifier has a limited possibility of reactive, capacitive power generation. The realisation of reactive inductive power generation is easier than the capacitive one. Generation of reactive capacitive power is possible only in the very narrow range of angle δ. The system may be used for near constant power loads

Symbol's indexes

a, b, c, i, j, k — phase indexes,

Symbols

$u_{fi}, u_{fj}, u_{fk}, u_{fa}, u_{fb}, u_{fc}$ — instantaneous value of phase voltage,
U_f — RMS value of phase voltage,
$u_{Si}, u_{Sa}, u_{Sb}, u_{Sc}$ — instantaneous value of multilevel voltage referenced to neutral point of electric power utility,
$U_{S(1)}$ — RMS value of first harmonic of multilevel voltage,
$U_{L(1)}$ — RMS value of first harmonic of input inductance's voltage,
$u_{Sin}, u_{San}, u_{Sbn}, u_{Scn}$ — instantaneous value of multilevel voltage referenced to central point of capacitive voltage divider,
u_1 — instantaneous value of 1 sequence component of voltages $u_{San}, u_{Sbn}, u_{Scn}$
u_2 — instantaneous value of 2 sequence component of voltages $u_{San}, u_{Sbn}, u_{Scn}$
u_0 — instantaneous value of 0 sequence component of voltages $u_{San}, u_{Sbn}, u_{Scn}$
$u_{t(1)}$ — instantaneous value of one phase inverter's output voltage,
$u_{t(2)}$ — instantaneous value of transformer's output voltage,
u_{Nn} — instantaneous value of voltage between connection points of utility generator and generator equivalent to rectifier input circuit,
u_d — instantaneous value of rectifier's output voltage,
U_d — average value of rectifier's output voltage,
I_0 — average value of rectifier's output current,
E — average value of load voltage,
P — active power,
Q — reactive power,
Q_S — reactive power at the input of diode matrix,
Q_L — reactive power of input inductance,
φ — phase displacement angle,
δ — phase angle between phase voltage and multilevel voltage,
m — modulation factor,
$i_i, i_j, i_k, i_a, i_b, i_c,$ — instantaneous value of phase current,
$I_{L(1)}$ — RMS value of first harmonic of phase current (inductance current),
L_S — phase inductance,
L_0 — load inductance,
R_0 — load resistance,
C — dc output capacitance.

8. LITERATURE

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