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EXPERIMENTAL INVESTIGATIONS OF MODIFIED DIODE RECTIFIER WITH IMPROVED POWER FACTOR

Badania eksperymentalne układu zmodyfikowanego mostkowego prostownika diodowego o poprawionym współczynniku mocy

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Summary: **The importance of the problem of electrical power quality arises from the economical reasons. The electrical power quality is expressed by the set of coefficients like the total harmonic distortion, the total power factor, the power displacement factor. The normalised values of these factors are very demanding. From the analyses carried out by many scientific centres it is concluded that only the active power electronics systems can meet these demands. The presented problem is especially concerned with rectification systems. The classical diode and thyristor rectifier systems, widely applied in Poland, have the current total harmonics distortion ratio about 30% while the planned normalised value is about 5%. It makes the problem of improving of the electrical power quality of the rectifier's systems be common and important.**

Streszczenie: **Istotność problemu jakości mocy elektrycznej wynika z przyczyn natury ekonomicznej. Jakość mocy elektrycznej wyrażana jest poprzez zespół współczynników takich jak współczynnik THD, współczynnik mocy, współczynnik mocy przesunięcia. Znormalizowane wartości tych współczynników są bardzo wymagające. Analizy przeprowadzone w wielu jednostkach naukowych na świecie wykazały, że jedynie systemy energoelektroniczne pozwalają spełnić te wymagania. Omawiany problem jest szczególnie związany z układami prostowniczymi. Klasyczne prostowniki diodowe i tyrystorowe, szeroko stosowane w Polsce, posiadają współczynnik THD wynoszący około 30% podczas gdy planowane normy wymagają aby wartość tego współczynnika była mniejsza od 5%. Powoduje to, że problem jakości mocy elektrycznej pobieranej przez prostowniki jest ważny i aktualny.**

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

1. INTRODUCTION

This paper presents the results of the experimental investigations of the modified diode rectifier with improved power factor and near sinusoidal phase current. That system was constructed and developed in Power Electronics Department of Technical University of Kielce according to the idea presented in paper [1]. Fig. 1 illustrates the experimental rectifier system. Rectifier's implementation details are presented in [3]. This paper examines by means of experiment the theory and simulations results presented by author in paper [2].

A very important problem in practical constructions of rectifiers with improved power factor is proper realisation of the synchronisation of the control signals with the input

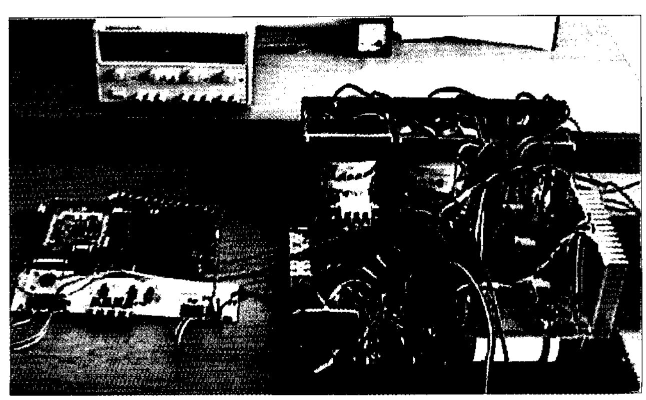

Fig. 1. Experimental modified rectifier system

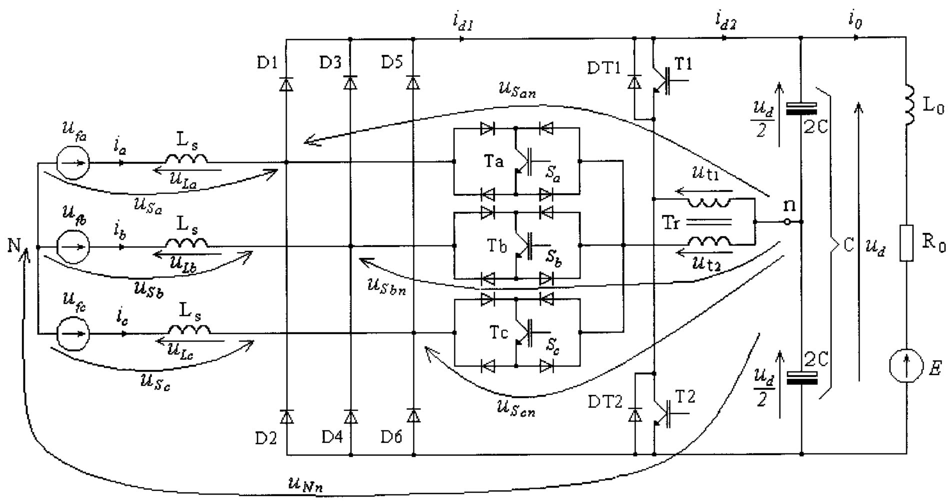

Fig. 2. Modified bridge rectifier

phase voltages. In this case the synchronisation is obtained on the basis of space vector theory at the input assumption that the input voltages are sinusoidal. The system controller is realised on the motion control evaluation board ADMC401 [9] with Analog Devices Inc. fixed point digital signal processor ADSP2171 inside [10].

Fig. 2 presents the electrical scheme of the rectifier constructed and developed in our department.

In this paper:

— The time plots of the rectifier's signals obtained by experiment are placed,
— The comparisons of the rectifier's functionality with active and inactive control algorithm are provided,
— The AC side rectifier's voltage synthesis is presented,
— The obtained spectrum of AC side voltage is presented,
— The input magnetic coil voltage and input phase currents time plots resulting from the co-operation of the input phase voltages and AC side rectifier's voltages are placed,
— The input phase current distribution is illustrated,
— The input phase current spectrum is presented,
— The control area limitations of the analysed rectifier system that have been led out in [2] are proofed by the experimental results.

2. RESULTS OF EXPERIMENTAL INVESTIGATION

Experiments were performed for two output resistance values: $R_0 = 57\Omega$ and $R_0 = 42\Omega$. Experiment I was carried out $R_0 = 57\Omega$ and experiments II for $R_0 = 42\Omega$. In both cases the rectifier system was supplied from the three phase auto-transformer.

2.1. Experiment I

I Experiment's conditions:

$$R_0 = 57\Omega,\ U_{jRMS} = 90\text{V},\ L_S = 7{,}5\text{mH},\ 2C = 2200\mu\text{F}$$

Voltage scale: 70.13V/V (a scale for cases where voltage is 1V/div or 0.5V/div)
Current scale: SkalaI = 5A/10mV or 2A/10mV
Transformer ratio: $\vartheta \approx 0{,}5$
Angle: $\delta = 0\ rad$

In this experiment the functionality of the rectifier system with active and inactive control algorithm were compared. The rectifier's system functionality was compared with regard to the current shape, current's harmonic spectrum, output DC voltage value and it's fluctuation.

Figures 3 and 4 present time plots of rectifier's input currents and phase voltages. Fig. 3 was made for inactive switching algorithm while fig. 4 for active algorithm. Phase voltages are generated by three phase auto-transformer. Significant impedance of auto-transformer windings causes distortion of phase voltage. From the fact that control signals are synchronised to phase voltage and control algorithm do not take into account distortion of phase voltage we draw the conclusion that this distortion has an influence on control accuracy.

Figures 5 and 6 present amplitude spectrums in logarithmic scale of rectifier's phase currents for case of inactive control algorithm (fig. 5) and case of active algorithm (fig. 6). Current spectrum obtained in case of active control algorithm have significant reduced but not zero amplitudes of 5th and 7th harmonics. This means that compensation is not ideal and probably is caused by transformer ratio. Unfortunately amplitudes of 11th and 13th harmonics are greater than in the case of inactive control algorithm. Harmonics of orders 17th and 19th present only in the case of inactive control algorithm. In both cases harmonics of orders being odd multiplication of 3 exist. These harmonics build zero sequence component of phase current. Existing of these harmonics is a symptom of system's and/or input source generator's asymmetries. Not complete 5th and 7th harmonics cancellation probably is caused by not ideal value of transformer ratio. Theoretical transformer ratio is $\vartheta = 0{,}464$ while implemented in experimental system transformer ratio value is $\vartheta = 0{,}5$ (transformer TS : 220V/2 x 110V).

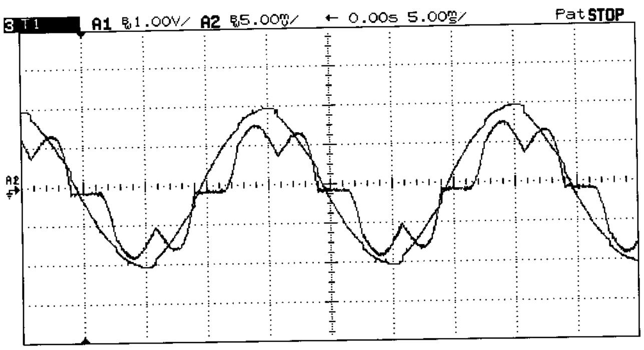

Fig. 3. Phase voltage and phase current (algorithm inactive)

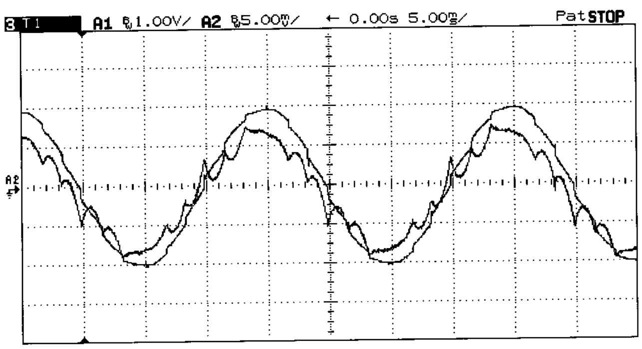

Fig. 4. Phase voltage and phase current (algorithm active)

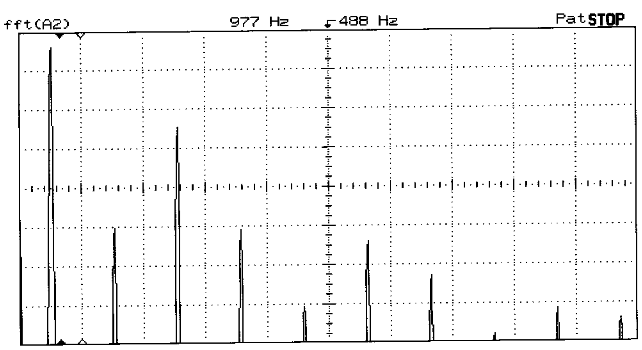

Fig. 5. Phase current's spectrum (algorithm inactive) (amplitudes of harmonics in logarithmic scale)

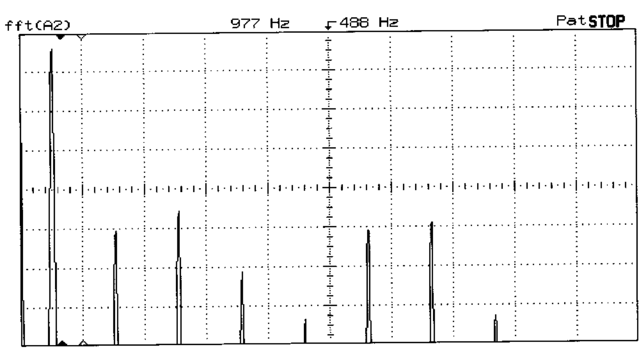

Fig. 6. Phase current's spectrum (algorithm active) (amplitudes of harmonics in logarithmic scale)

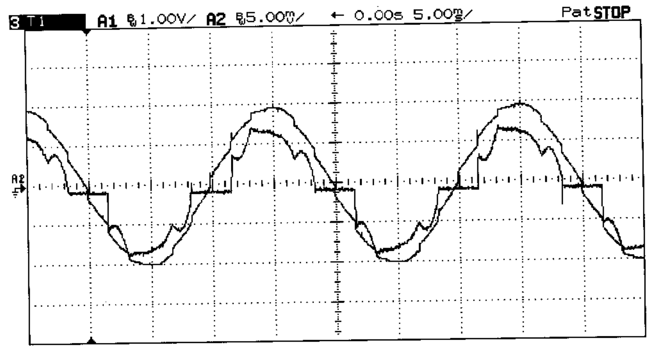

Fig. 7. Phase voltage and input diode rectifier current (algorithm active)

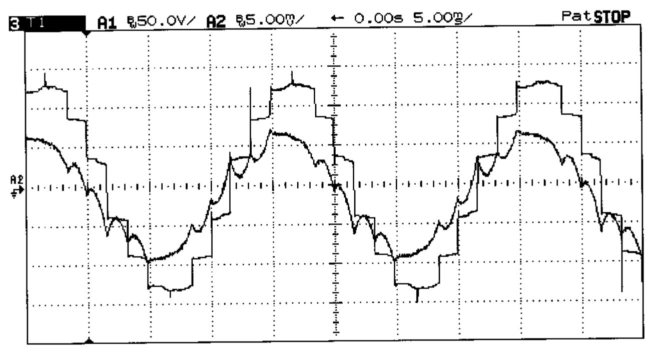

Fig. 8. Multilevel voltage referenced to neutral point of electric power utility and phase current (algorithm active)

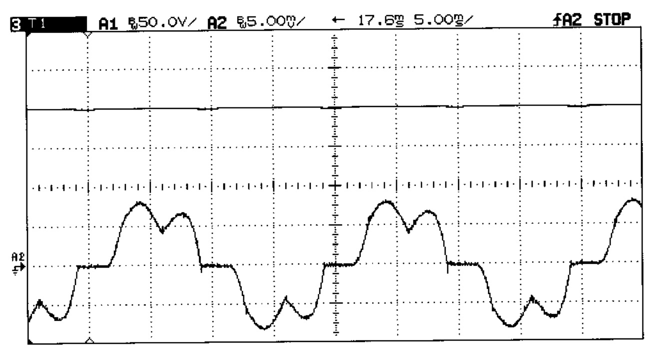

Fig. 9. Phase current and DC output voltage (algorithm inactive)

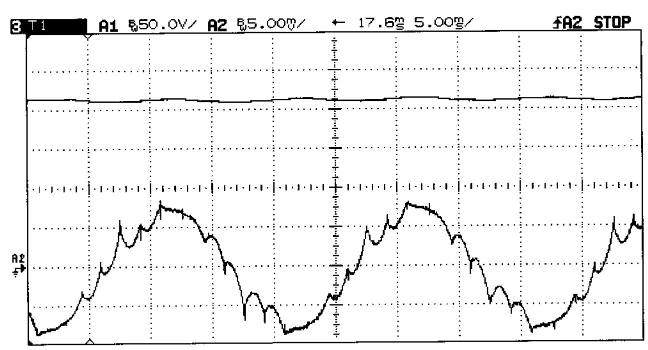

Fig. 10. Phase current and DC output voltage (algorithm active)

The positive or negative diode current is conducted in the angle of $\frac{2\pi}{3}$ (Fig. 7). The compliment part of the phase current is conducted by the bi-directional valve and is a difference of phase current form fig. 8 and diode current from fig. 7.

It can be seen in figures 9 and 10 that in the case of active control algorithm the output DC voltage fluctuation is greater than in the case of inactive control algorithm.

2.2. Experiment II

II Experiment's conditions:

$U_{jRMS} = 90V$, $I_f = 3{,}9A$, $R_0 = 42\Omega$, $U_d = 202V$, $L_S = 7{,}5mH$, $2C = 2200\mu F$

Voltage scale: 70,13V/V (a scale for cases where voltage is 1V/div or 0,5V/div)

Current measurement: Current probe I 5A/10mV oscilloscope 5mV/dz

Transformer ratio: $\vartheta \approx 0{,}5$

In this experiment the angle δ was regulated to obtain phase displacement angle value $\varphi \approx 0$.

From multilevel voltage time plot in fig. 12 we can find so voltage of DC output isn't ideal DC voltage source, the some effect can be seen in fig. 10. Especially it can be seen at the maximum and minimum values of multilevel voltage in fig. 12.

2.2.1. Amplitude spectrum of rectifier's current and voltage

In figures 13 and 14 amplitude spectrums of phase currents are presented. Amplitudes of spectrums are pointed in logarithmic scale. Spectrum from fig. 13 is obtained in case of inactive switching algorithm while in fig. 14 spectrum of phase current in case of active switching algorithm is presented.

Spectrums of multilevel voltage (fig. 16) and phase currents (fig. 14) contain significant reduced (when compare to the voltage spectrum fig 15 and current spectrum from fig. 13), but not zero 5th and 7th harmonics. It's mean that cancellation of this harmonics isn't ideal because multilevel voltage realisation isn't ideal from one hand and phase voltages of three phases transformer are not mono-harmonic on the other hand. There also exist 3rd, 9th and 15th harmonics in phase current (fig. 14). The reasons of this are not ideal symmetry of phase voltages and internal impedance of the input voltage generator (the auto-transformer in this case) and asymmetries in the rectifier's structure (the input coil's reactance, not ideal synchronisation and switching algorithms).

2.2.2. Multilevel voltage synthesis

Multilevel voltage synthesis is illustrated in figures from 17 to 19.

Fig. 17 presents input u_{t1} and output u_{t2} voltages of inverter's transformer. Obtained from the switching algorithm the multilevel voltage u_{Sin} referenced to neutral point of capacitive voltage divider is presented in fig. 18. In fig. 19 multilevel voltage u_{Si} referenced to the neutral point of electric power utility is presented. This voltage's time plot was obtained according to the rules described in [2]. Figure 20 presents result of co-operation of input phase voltage u_{fi} and multilevel voltage u_{Si} in creation of input coil's voltage u_{Li} as a difference of phase voltage and multilevel voltage and the final result—obtained phase current i_i.

It may be seen in fig. 19 that input phase voltage is distorted. This distortion is caused by the phase current flow through out impedance of the auto-transformer. The input phase voltages are used for the rectifier's synchronisation. The distortion of the phase voltages is a source of undesired errors in rectifier's synchronisation unit and causes secondary problems.

2.2.3. Rectifier's input phase current distribution

The rectifier's input phase current (fig. 21) has two components: the diode rectifier's input current (fig. 22) and the bi-directional key's current. Fig. 23 presents current of transistor of bi-directional key. This current is obtained by rectification of bidirectional key's current by the diode's bridge. The sum of currents of the bi-directional keys creates the output current of the transformer presented in fig. 25. The realised control method assumes the symmetry of the system: electric power utility—rectifier. The input transformer current is illustrated in fig. 24. From the shapes of the input and the output transformer's currents time plots we can make a conclusion that there are asymmetries in the rectifier system and/or input voltage generator. The proof of this thesis you can find in the chapter: Amplitude spectrum of rectifier's signals. In the current spectrum the not zero values of harmonics of the orders being the odd multiplication of 3 exist. These harmonics build the zero sequence component of the phase current. This kind of current component exists only in the cases of circuit's asymmetries. The main source of this asymmetry is not symmetrical voltage generation in the auto-transformer.

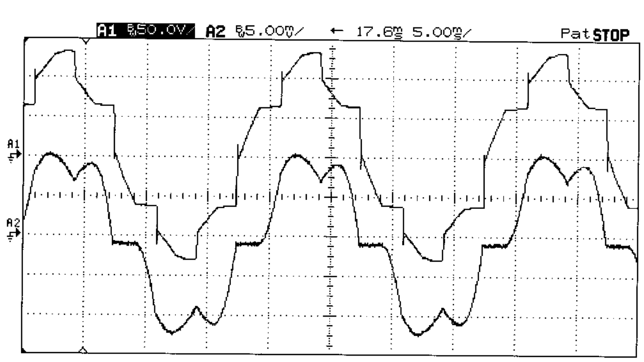

Fig. 11. Input voltage of diode bridge referenced to neutral point of electric power utility and phase current (algorithm inactive)

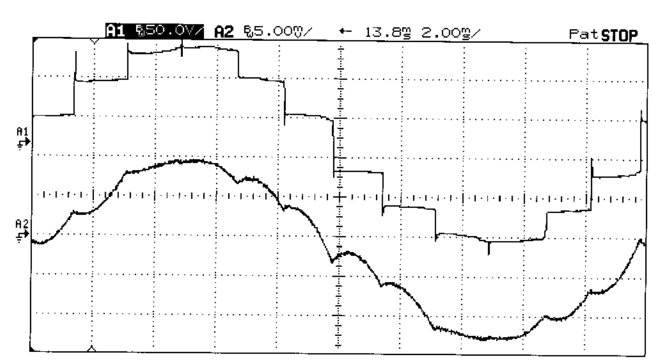

Fig. 12. Multilevel voltage referenced to neutral point of electric power utility and phase current (algorithm active)

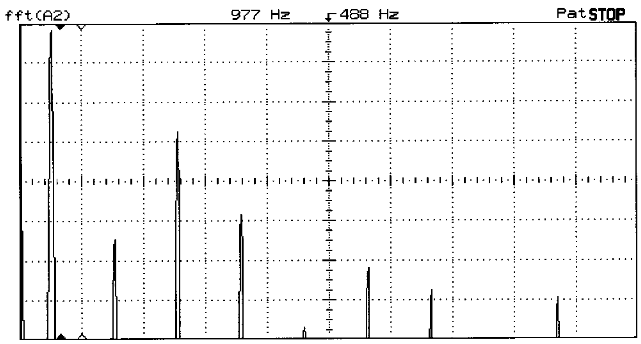

Fig. 13. Phase current's spectrum (algorithm inactive) (amplitudes of harmonics in logarithmic scale)

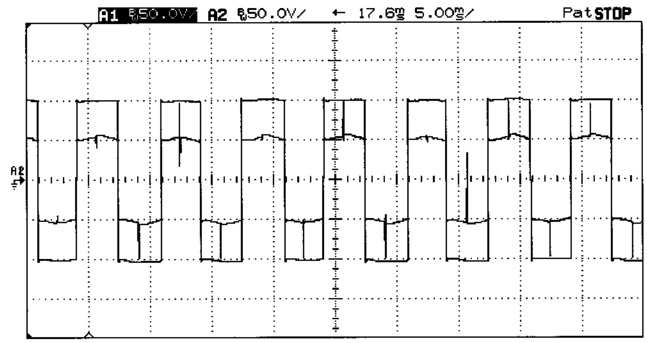

Fig. 17. Input and output voltages of inverter's transformer (algorithm active)

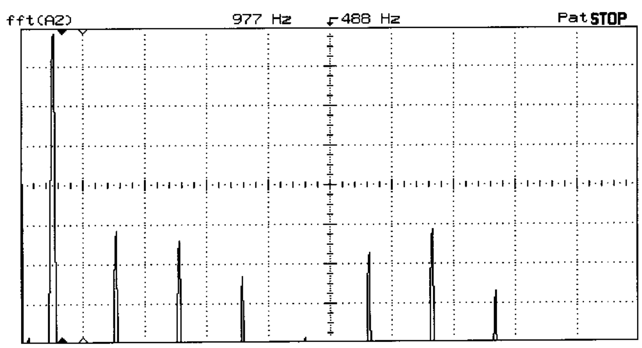

Fig. 14. Phase current's spectrum (algorithm active) (amplitudes of harmonics in logarithmic scale)

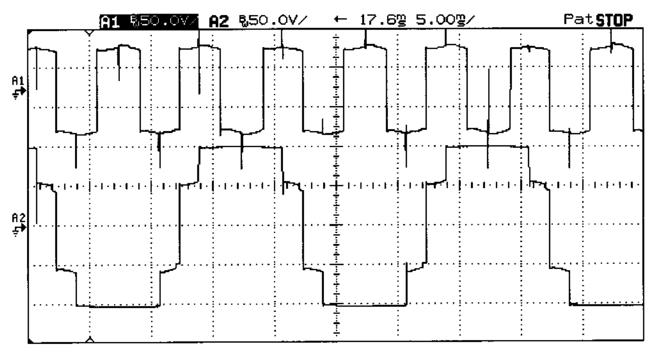

Fig. 18. Output voltage of inverter's transformer and multilevel voltage referenced to neutral point of capacitive voltage divider (algorithm active)

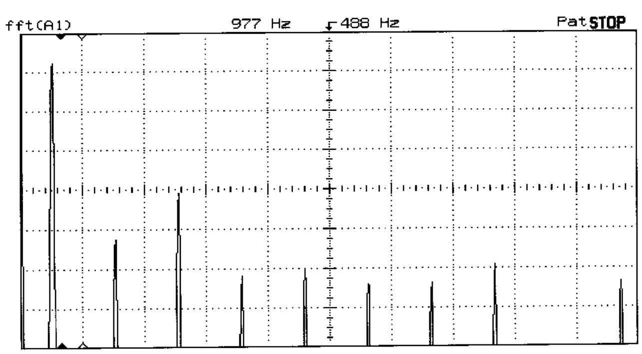

Fig. 15. Input diode bridge voltage's spectrum (algorithm inactive) (amplitudes of harmonics in logarithmic scale)

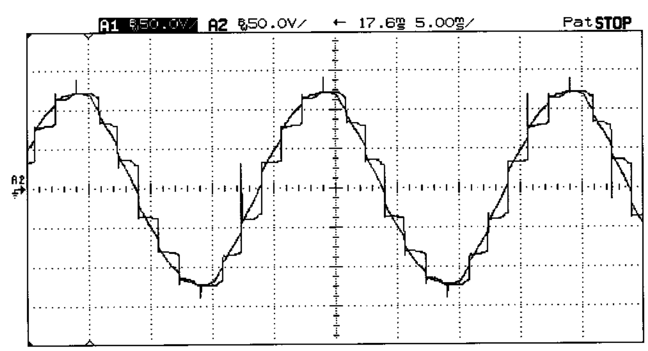

Fig. 19. Phase voltage and multilevel voltage referenced to neutral point of electric power utility (algorithm active)

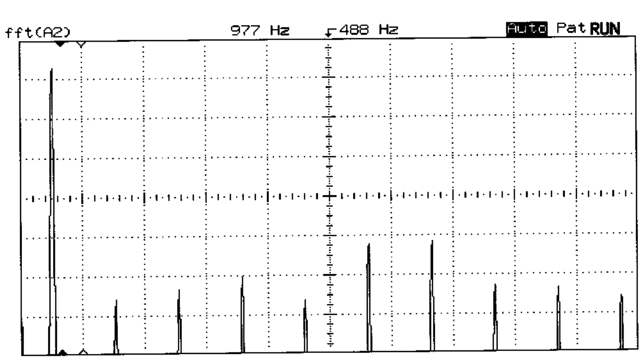

Fig. 16. Multilevel voltage's spectrum (algorithm active) (amplitudes of harmonics in logarithmic scale)

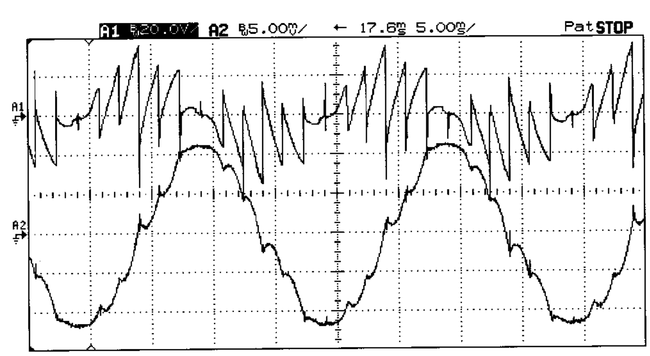

Fig. 20. Input magnetic coil voltage and phase current (algorithm active)

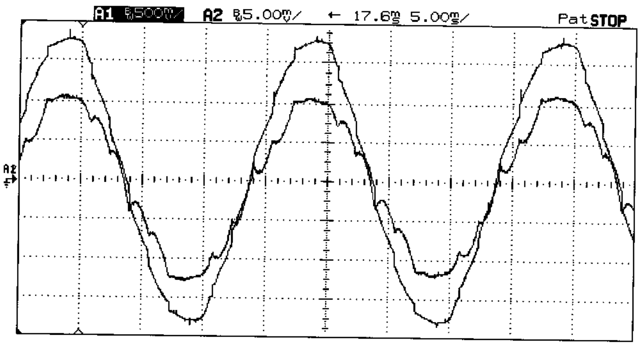

Fig. 21. Phase voltage and phase current (algorithm active)

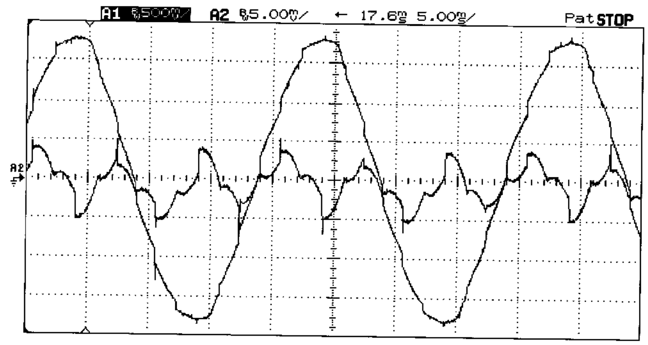

Fig. 24. Phase voltage and input current of transformer (algorithm active)

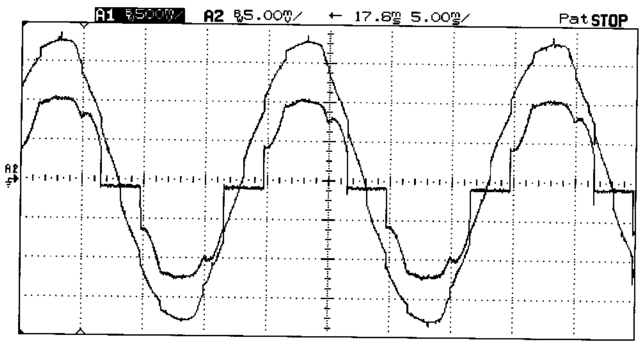

Fig. 22. Phase voltage and diode rectifier's input current (algorithm active)

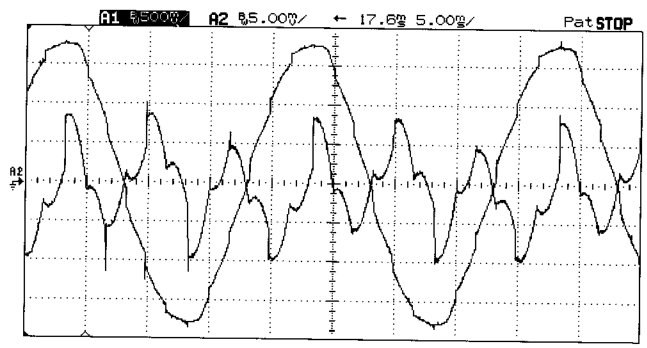

Fig. 25. Phase voltage and output current of transformer (algorithm active)

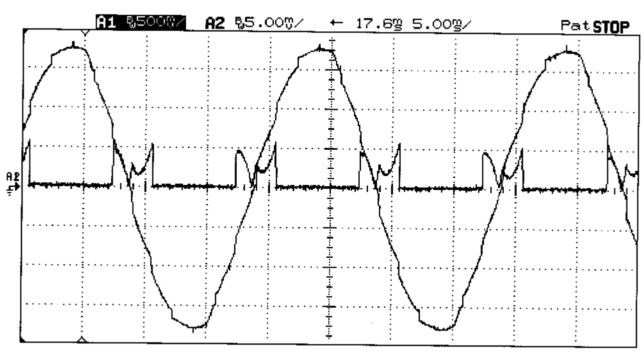

Fig. 23. Phase voltage and transistor key's current (algorithm active)

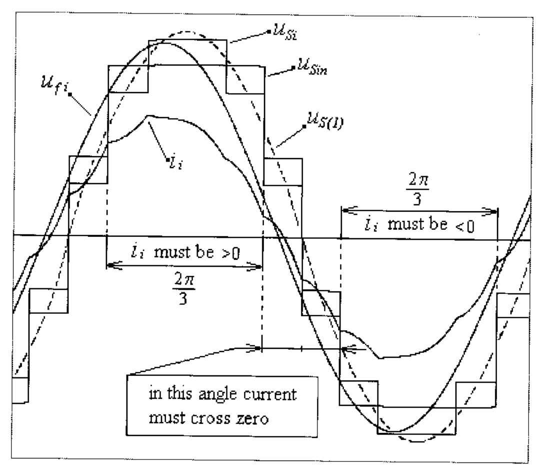

Fig. 26. Possible region of phase angle between current and multilevel voltage

2.2.4. Control area limitations

Limitations of control area arise from the multilevel voltage generation algorithm. As a result of unidirectional conduction of diode we obtain restriction on rectifier's control area to the range of angles agree with inequality (1) [1, 2].

$$\left(-\frac{\pi}{6}+\varepsilon\right)\leq\varphi+\delta\leq\frac{\pi}{6}+\varepsilon \qquad (1)$$

Inequality (1) is a simply result of conditions of diode conduction. Angle   is the difference between zero crossing of current first harmonic and zero crossing of instantaneous current value. Satisfying condition (1) lets properly generate multilevel voltage at the input of diode matrix. Problem is illustrated in fig. 26.

Figures 27 and 28 present behaviour of rectifier system in the cases of situations when condition (1) isn't true. There are a periods of time with zero value of phase current. In these periods multilevel voltage isn't properly generated because there it is not possibly to obtain conduction of diode in angle of $2\pi/3$. Described problem is a cause of significant phase current's deformation. Fig. 27 presents multilevel voltage deformation and it's result in phase current's deformation caused by control with angle $\varphi+\delta<-\pi/6$. In fig. 28 we can see multilevel voltage deformation and it's result in phase current's deformation for case of $\varphi+\delta>\pi/6$. In both ca-

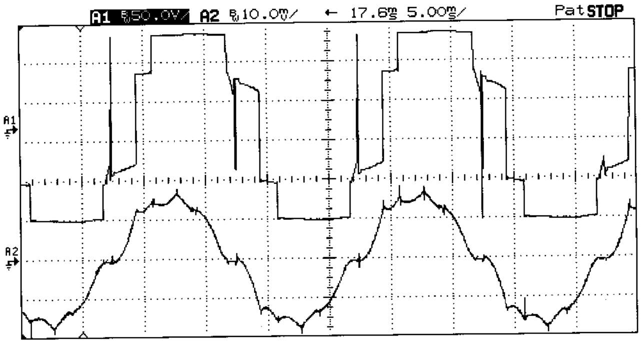

Fig. 27. Multilevel voltage referenced to neutral point of capacitive voltage divider and phase current for $\varphi+\delta<-\frac{\pi}{6}$ (capacitive input impedance) (algorithm active)

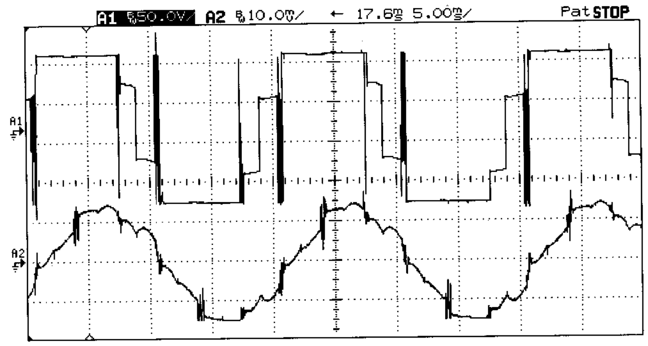

Fig. 28. Multilevel voltage referenced to neutral point of capacitive voltage divider and phase current for $\varphi+\delta>\frac{\pi}{6}$ (inductive input impedance) (algorithm active)

ses angle of diode conducting is less than value of $2\pi/3$. It is possibly to obtain control area not limited to the region described by (1) but it needs a solution with transistors provided anti parallel to the input diodes and switched on in periods of time when multilevel voltage u_{Sin} has value $U_d/2$ or $-U_d/2$. Where still will be a problem with control values of currents because were will be no possibility of modulation of the value of multilevel voltage. Such case wasn't checked in experimental way but author checked it only by simulation.

3. CONCLUSIONS

The results obtained from the experiments generally meet the results of theoretical and simulation analysis [2]. From the above we can draw a set of conclusions:

- The rectifier system proposed in [1] may be exploited in a closely limited range of load power,
- The best results are obtained in the case of nominal load,
- For the nominal load range it is possible to generate near sinusoidal phase current with phase displacement angle $\varphi \approx 0$.
- Diode's conducting angle has to have value of $2\pi/3$ radian. It is possible for phase displacement angle φ and angle between phase voltage and multilevel voltage δ satisfying condition (1).

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