A SOLUTION TO REDUCE THE DEFORMING REGIME TO THE POWER RECTIFIERS

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Abstract: In this paper analyzes some aspects of the regime deformed produced by the controlled power rectifiers on supply networks. It proposes a technical solution, relatively simple and low cost for implementation to reduce the deforming regime and reactive power to the power rectifiers with conventional thyristor (SCR).

Keywords: power rectifier, reactive power, thyristor

1. INTRODUCTION

Static power converters with electronic commutation are used in many industrial processes and transports. Expansion of the power-controlled rectifiers creates serious problems in the power supply of the consumers due to reactive power consumption - variable within wide limits, low power factor, and amplification of deformation by the presence of voltage and current harmonics. Static power converter installations strongly distort users' electrical networks.

The paper highlights one of the relatively simple and efficient constructive solutions for reducing the reactive power, improving the power factor and diminishing the deformation effect of the power-controlled rectifiers made with semiconductor devices.

2. REACTIVE POWER ŞI DEFORMANCE EFFECT OF THE POWER RECTIFIERS

Rectifier systems with thyristors are variable inductive reactive loads for power supply networks. Seen as stand-alone power plants, the rectifiers are consuming reactive-energy. There are two causes that lead to this consumption, which is why two types of reactive power are defined at the rectifier:

- reactive switching power,
- reactive command power.

Reactive switching power is due to short-circuit product briefly conduction change (switching) between electronic devices (diodes or thyristors) of the phases between which the current is switched, even if uncontrolled rectifier. The switching time during which the short-circuit is taking place corresponds to an electric angle, called the *overlap angle*. During the switching process, the short-circuit current closing practically only the reactance network and the transformer (in the case of the rectifier with network transformer) is a reactive current which corresponds to the reactive power switching. As the circuit reactances are larger, the more reactive switching power is lower, but the duration of the switching process increases [1]. So, the reactive switching energy does not change substantially.

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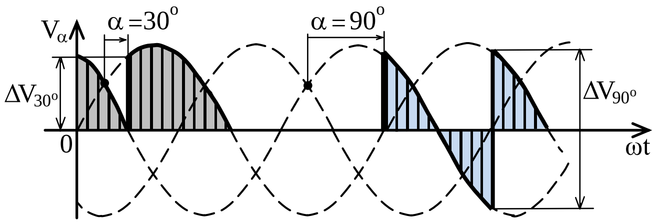

Fig. 1. Graphical explanation for switching voltage.

In case of controlled rectifiers, switching reactive power is all the greater as the control angle is greater. This is explained, as shown in Figure 1, by the fact that with the increase of the control angle α in rectifier regime, for example, increases the difference ΔV of the voltages between the switching phases and therefore the amplitude of the short-circuit current increases.

The reactive command power occurs in the case of controlled rectifiers for a $\alpha > 0$ control angle of thyristors.
If the filter inductor in the DC circuit of the rectifier is large enough, the load current does not change. It follows that whatever the rectifier's control angle, the waveform of the fundamental of the current in the AC circuit remains invariable. However, it moves behind the network voltage with the α control angle of thyristors as shown in Figure 2.

The reactive power absorbed by the network by the controlled rectifier by the α control angle can be approximated by a relationship of the form [2]

$$Q = V_{d0} I_d \sin\alpha \qquad (1)$$

where V_{d0} is the DC output voltage for a $\alpha = 0$ control angle (ideal diode rectifier), and I_d is the mean value of the DC current. From this relationship it results that the reactive control power increases sinusoidally with the angle α, from the zero value for $\alpha = 0$ to the maximum value $Q_{max} = U_{d0}I_d$ for $\alpha = 90^o$ and then, in the inverter mode, decreases from this maximum to zero for $\alpha = 180^o$. Since, due to the overlap angle, the command is in most real situations between 30 and 150 electrical degrees, it results that the reactive command power virtually can not be zero. In high power plants, reactive command power can take important values, which is why some measures are needed to diminish it.

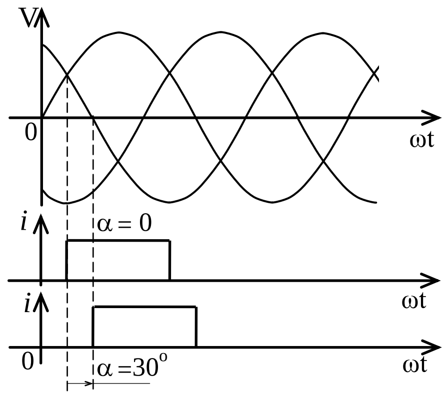

Fig. 2. The waveform of the network current.

The deforming effect produced by the power-controlled rectifiers in the power supply networks is primarily due to their network current which is never sinusoidal. In most cases, its waveform approaches the rectangular (Figure 2) and is dependent on the number of pulses and the type of network transformer connections.

Rectifiers produce in the power supply network, mainly harmonics of the order [1]

$$\upsilon = kp \pm 1, \quad k = 1,\ 2,\ 3,\ \ldots \qquad (2)$$

where p represents the number of rectifier pulses.
In industrial networks, three-phase bridge rectifiers predominate with a number of pulses $p = 6$. For this connection arises the harmonics of the 5, 7, 11 and 13 order. There may be higher order harmonics, but their values are so small that they can be neglected.

Under the real switching process, due to the fact that during switching there are two thyristors simultaneously in the conduction, the shape of the rectifier's network current changes. The higher the overlap angle, that is, the more inductances in the circuit, the smaller the amplitudes of the high frequency harmonics. The overlap angle also depends on the control angle. With its increase, the overlapping angle decreases, so the content of harmonics increases.

3. **TECHNICAL SOLUTIONS FOR REDUCING REACTIVE POWER AND DEFORMING REGIME FOR POWER RECTIFIERS**

In practice, numerous methods for reducing disturbances and reactive power consumption are applied for static power converters. For existing installations of this kind, condenser batteries and harmonic filters are used that become particularly complex and costly for high voltages and currents or heavy duty work. The reduction of these problems can be achieved by adopting special schemes for static converters with low reactive power consumption, with improved power factor and low disturbing effect for power supply networks. Well-known large-pulse rectifying schemes, bridged rectifiers connected in series and sequential control, semicomanded bridge schemes, etc. are well known and applied in practice. All of these schemes are characterized by low reactive power consumption and a more acceptable deforming regime, but have disadvantages in terms of large dimensions, high cost and limitation of working regimes only to the rectifier mode, such as semicomanded bridges. In this paper we present a way of solving these problems by using a conventional thyristor rectifier in a completely controlled bridge, to which are added two auxiliary thyristors T7 and T8, as shown in figure 3. This type of converter is able to work in both rectifier or inverter modes, and through a proper command strategy of the main and auxiliary thyristors, an important improvement in power factor and deforming regime is achieved, both on the power AC side and on the DC side. The auxiliary thyristors T7 and T8 can transfer the load current at any moment to the null conductor.

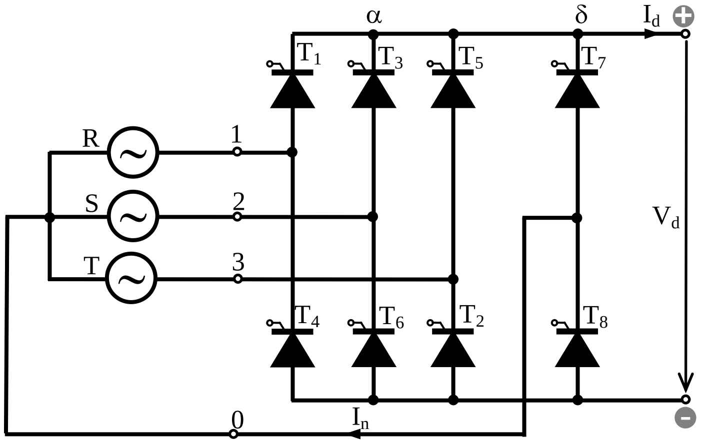

Fig. 3. Rectifier circuit with auxiliary thyristors.

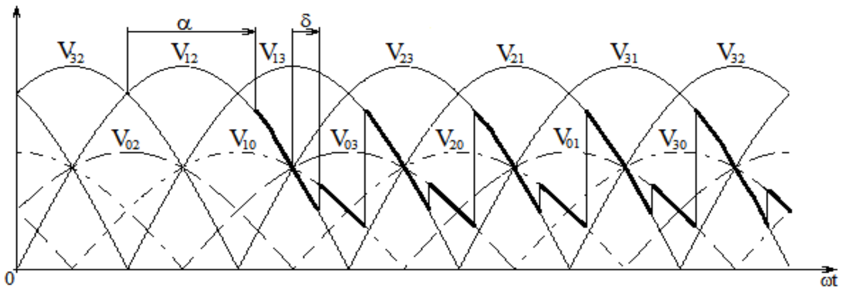

Fig. 4. The output voltage of the rectifier with auxiliary thyristors.

As shown in Figure 4, the auxiliary thyristors are controlled so that the waveform of the output voltage is improved by compiling some portions of the line and phase voltage waves. For example, assuming conducting the main thyristors T_1 and T_6, the load current Id flows on the path l - T_1 - load - T_6 - 2 - 0 - l, the voltage at the load terminals being V_{12}. If T_8 is commanded with the angle α, T_6 will exit the conduction and T_8 will take the load current that will close on the path l - T_1 - load - T8 - 0 - l. The voltage at the load terminals is now given by the phase voltage V_{10}. At the command of the main thyristor T_2, the current of T_8 is taken over by it and therefore the load current will flow on the path l - T_1 - load - T_2 - 3 - 0 - 1. The voltage across the load being V_{13}.
In the rectifier regime, the power factor is optimized by controlling the α and δ angles so as to minimize the duration as voltage and current on one phase are opposite signs. As shown in Figure 4, this is obtained by setting the angle δ to zero (the natural switching point of the phase voltages) and using the control angle α of main thyristors for power control.

In inverter regime, the power factor is negative and is optimized by reducing the duration as the current and the phase voltage have the same sign. Assuming instantaneous switching, this can be achieved by setting $\alpha = 150°$ and varying δ between 0 and 120° for power control.

As shown in Figure 3, with the main and auxiliary thyristor conduction ($30° \le \alpha \le 150°$), the mean V_d value can be determined by:

$$V_d = \frac{\sqrt{6}}{\pi} V[\cos(\alpha + \frac{\pi}{6}) + \cos\delta] \tag{3}$$

where V is the effective value of the voltage between phases in the secondary of the network transformer.
For $\alpha \le 30°$ and $\alpha \ge 150°$ auxiliary thyristors do not conduct, the bridge operates as a conventional bridge and

$$V_d = \frac{3\sqrt{2}}{\pi} V \cos\alpha \,. \tag{4}$$

Equations (3) and (4) are valid for both rectifier and inverter regimes.

The AC source impedance causes the overlapping switching, which limits the range of the angles of control α and α. The maximum value for the main angle α is given by [8]

$$\alpha_{max} = \arccos\frac{1 - k_1 \cos\varepsilon}{k_1} - \frac{\pi}{6}, \quad k_1 = \sqrt{\frac{2}{3}} \frac{V}{\omega L I_d} \,, \tag{5}$$

where ε is the angle corresponding to the thyristor lockout time, $\varepsilon = \omega t_{off}$, and L is the inductance of the phase of the AC power source (equivalent phase leakage inductance of the network transformer). The maximum value for the angle δ can be determined by the relationship [8]

$$\delta_{max} = \arccos\frac{k_2 \cos\alpha_{max} - 1}{k_2} - \frac{\pi}{6}, \quad k_2 = \frac{\sqrt{2} U}{2\omega L I_d} \,. \tag{6}$$

The maximum inverter control angle for the conventional converter without auxiliary thyristors is

$$\alpha_2 = \arccos(\frac{1}{k_2} - \cos\varepsilon) \,. \tag{7}$$

a) ***The rectifier regime (R)***

In the rectifier regime, the DC voltage and power are controlled by varying the angle α between 0 and 150 electrical degrees. The auxiliary thyristors are alternately controlled at $\delta = 0$ degrees and behave like diodes. There are three modes of operation in this regime as follows:

- R1 : $0 < \alpha < 30°$, the converter operates as a three-phase standard bridge, the auxiliary thyristors are inversely polarized and do not drive;
- R2 : $30° < \alpha < 90°$, $\delta = 0°$, the main thyristors lead the current for a duration corresponding to $150° - \alpha$, and the auxiliary thyristors for a duration corresponding to the angle $\alpha - 30°$;
- R3 : $90° < \alpha < 150°$, $\delta = 0°$, at least one auxiliary thyristor is in conduction at all times - the output voltage consists of one phase and zero voltage segment. The voltage across the load is zero when driving both auxiliary thyristors, the load current circulates freely through them. In this regime, no current flows through either side of the bridge.

b) ***The inverter regime (I)***

During the inverter regime, the power is controlled by changing the auxiliary angle δ between zero and δ_1, while α can be stored at α_1. It is also possible to distinguish three modes of operation in which case the waveforms of voltage and current, as follows:

- I1: $0 < \delta < 60°$, $\alpha = \alpha_1$, the output voltage is composed of phase voltage segments or is null. One of the auxiliary thyristors are always conducting.
- I2: $60° < \delta < \delta_1$, $\alpha = \alpha_1$, the output voltage consists of segments of phase to phase and phase voltages.
- I3: $\alpha_1 < \alpha < \alpha_2$, the auxiliary thyristors are not controlled, the converter operates as a conventional bridge.

4. RESULTS OF THE EXPERIMENTAL STUDY

In this paper an experimental study was carried out, by simulation and by measurements on a real installation, of the efficiency of the proposed technical solution for reducing the deforming regime of the power controlled rectifiers. Only the rectifier regime was considered, when rectifier diodes are used instead of the two auxiliary thyristors (T7 and T8 in fig. 3). The plant used for practical measurements is a three-phase high-power rectifier made with conventional thyristors (SCR).
The main energy parameters of the rectifier are:

- rated supply voltage = 3×380 / 220V, 50Hz;
- rated continuous output voltage = 220V, d.c.;
- nominal output current = 200A, d.c.

The rectifier connects to the power supply network via a three-phase transformer in the triangle-star connection with rated phase to phase voltage 380 / 245V (+ 10%, -15%).

4.1. Simulation results.
The Matlab-Simulink block diagram for numerical simulation is shown in Figure 5. For simulation a three-phase rectifier with the parameters of the actual rectifier, above, with diodes instead of the auxiliary thyristors.

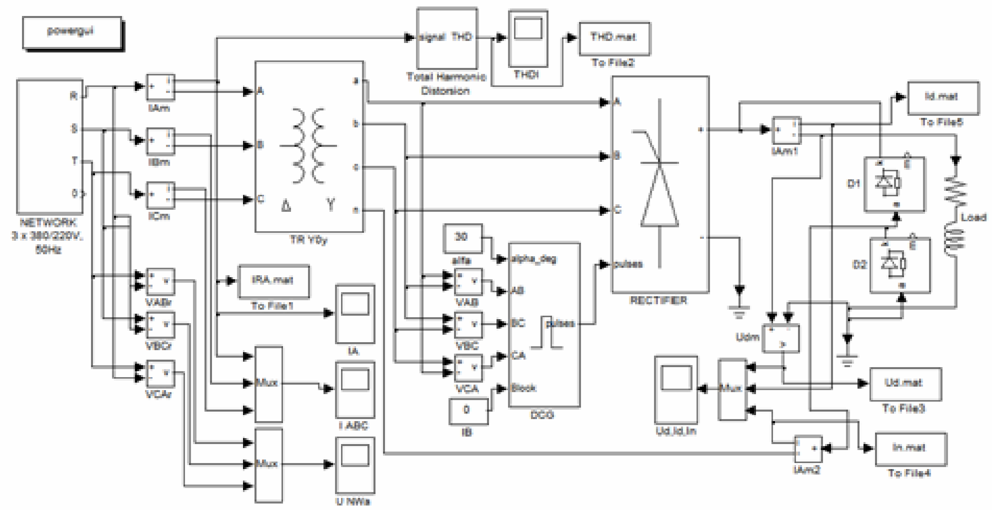

Fig. 5. The block diagram for the rectifier simulation.

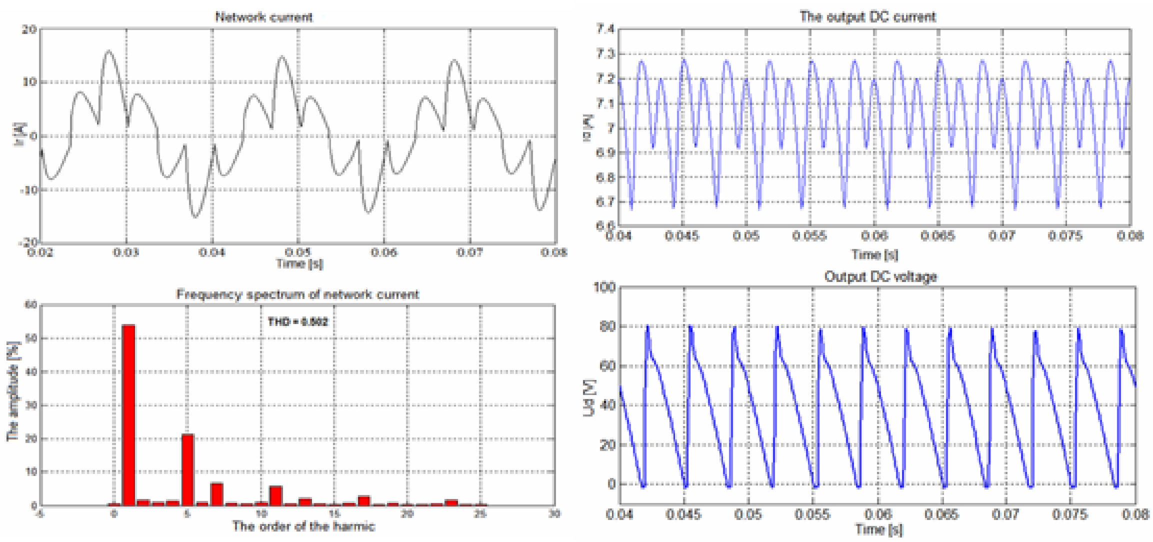

Fig. 6. Current and voltage waveforms and frequency spectrum to the diodeless rectifier.

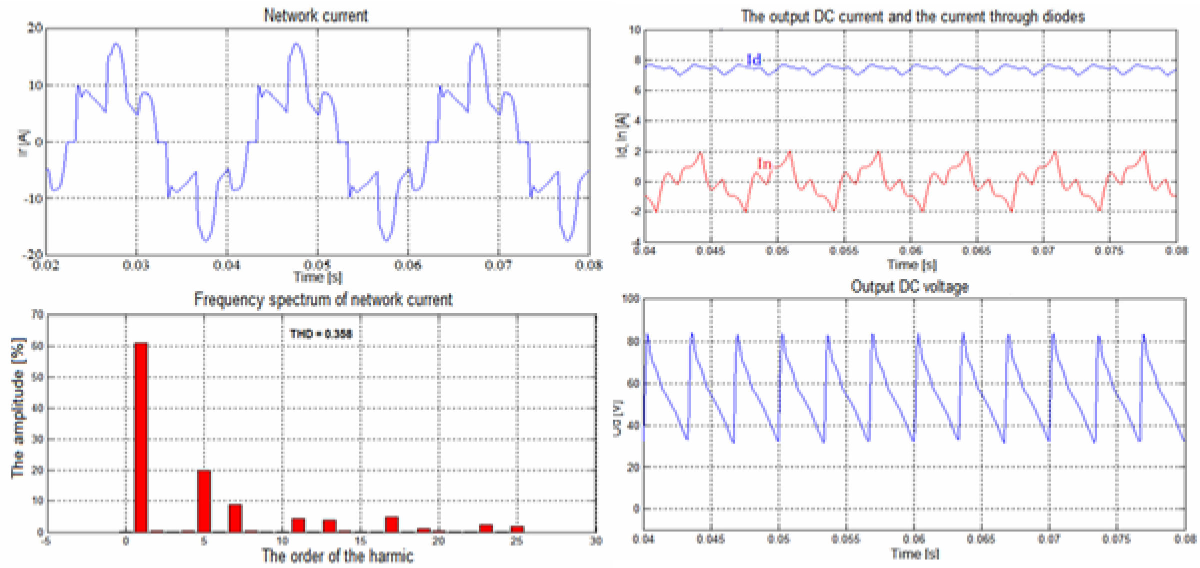

Fig. 7. Current and voltage waveforms and frequency spectrum to the extra diodes rectifier.

In Figures 6 and 7 respectively, the waveforms of the Ir network current, the Id DC current and the Ud DC voltage at the output and the In current through the diodes to the diodeless rectifier (Figure 6) and the rectifier with the two diodes connected to the output . Significant is the distortion of the network current, that can be observed from the harmonic analysis presented for these two cases. Thus, it is found that the THD factor decreases from 0.502 (to the rectifier without additional diodes, fig. 6) to 0.358 when the additional diodes are connected to the rectifier output. There is obvious that a reduction of the network current distortion and the DC voltage ripple at the output of the rectifier with the connected diodes.

4.1. Results of direct measurements.

To measure the efficiency of the proposed technical solution, direct measurements were made on a power rectifier with the data presented above using a three phase energy analyzer. Figures 8 and 9 show the waveforms of the network currents and their frequency spectrum of the rectifier without and with the output diodes.

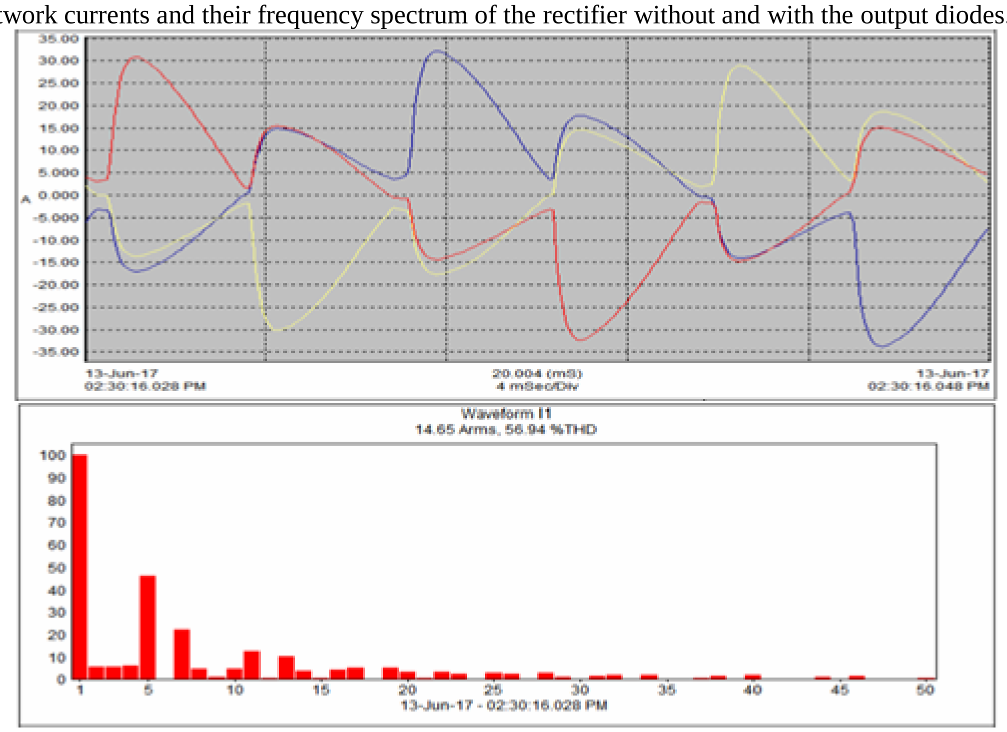

Fig. 8. The waveform (top) and frequency spectrum (bottom) of the network currents of the rectifier without additional diodes.

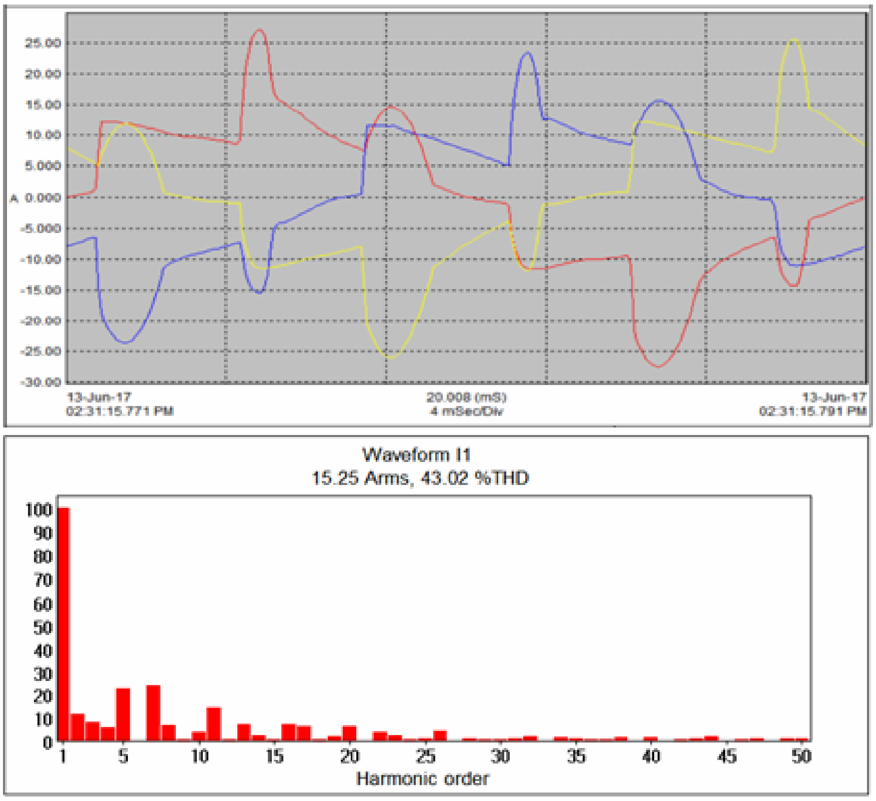

Fig. 9. The waveform (top) and frequency spectrum (bottom) of the network currents of the rectifier with output additional diodes.

For comparison, in Figures 10 and 11 are shown the waveforms of the network currents, the diode current and the DC voltages from the rectifier output in the same two above-mentioned situations, captured from the display of a digital oscilloscope.

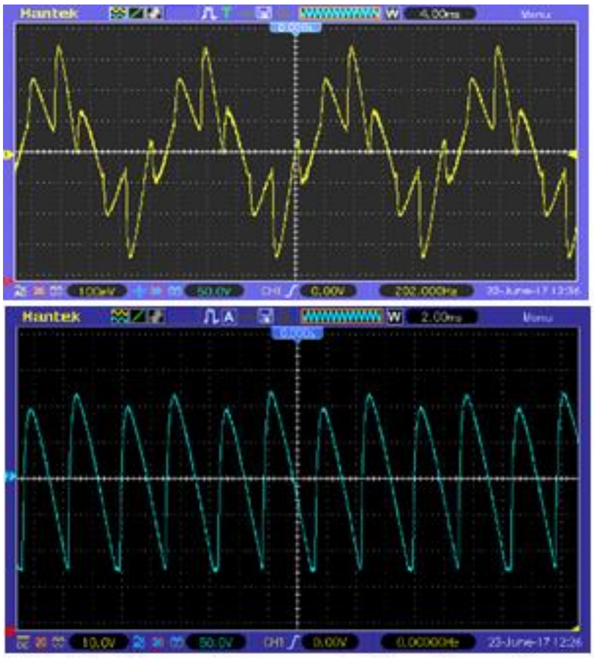

Fig. 10. The waveforms acquired from the rectifier: network current (top); DC output voltage (down).

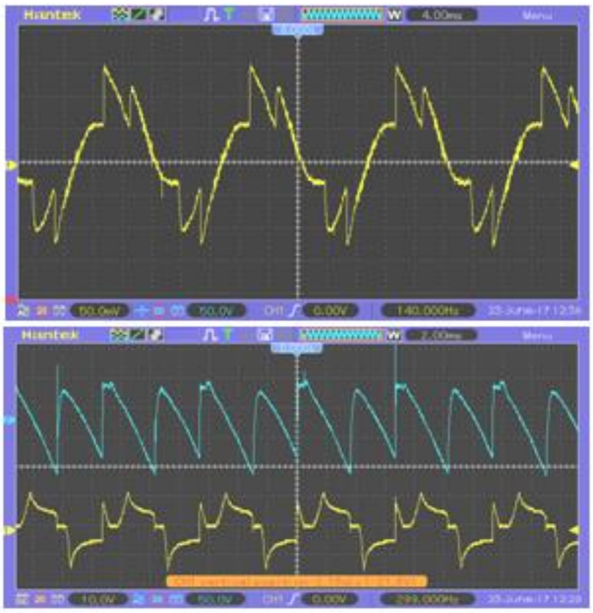

Fig. 11. The waveforms acquired from the rectifier with output additional diodes: the network current (top); DC voltage and diode current (down).

5. CONCLUSIONS

From the analysis of the results obtained by direct measurements on the three-phase controlled rectifier, the following major conclusions can be drawn:

- Data purchased and processed using a three-phase energy analyzer highlights the significant reduction of network current distortion by applying the technical solution analyzed in this paper. Thus, there is a significant decrease in the total harmonic distortion THD of the network current from 56.94% to 43.02% when applying this technical solution. There is also an improvement in the power factor and implicitly a reduction in reactive power, as shown by the analyzer's power ratio and synthetically presented in the Table 1.

Table 1.

ENERGY BALANCE REPORT OBTAINED WITH THE ENERGY ANALYZER	
The rectifier without additional diodes	**The rectifier with output additional diodes**
Start Date: 13-Jun-17 Start Time: 02:30:16.000 PM Duration: 0.000 (S) W: 4.102E+3 W VAR: 9.137E+3 W VA: 10.02E+3 W Power Factor: 0.408 Displacement Power Factor: 0.472 TAN: 1.882 VoltageRatio: 1.000 CurrentRatio: 1.000	Start Date: 13-Jun-17 Start Time: 02:40:15.000 PM Duration: 0.000 (S) W: 3.440E+3 W VAR: 6.818E+3 W VA: 7.646E+3 W Power Factor: 0.542 Displacement Power Factor: 0.591 TAN: 1.792 VoltageRatio: 1.000 CurrentRatio: 1.000

- Table 1 shows an increase worth taking into consideration for the total power factor and implicitly a reduction of the reactive power in the case of the adoption of the analyzed technical solution.
- The waveforms of the network currents viewed on the oscilloscope are similar to those of the energy analyzer.
- The results obtained with the energy analyzer validate to a great extent the results obtained by numerical simulation on the computer regarding the distortion of the network currents, THD coefficients having comparable values.
- The analyzed technical solution is characterized by simplicity, low cost price (especially when using two diodes instead of auxiliary thyristors for the rectifier mode) and is justified by the important advantages that can be obtained from the point of view of the deforming regime.

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