EMC Increasing of PWM Rectifier in Comparison with Classical Rectifier

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Abstract. *Pulse width modulated rectifier is a very popular topic nowadays. The modern industrial production demands continuous and lossless conversion of electrical energy parameters. This need leads to wide spread of power semiconductor converters. The rapid development in power electronics and microprocessor technology enables to apply sophisticated control methods that eliminate negative side effects of the power converters on the supply network. The phase controlled thyristor rectifiers overload the supply network with higher harmonics and reactive power consumption. That is why the PWM rectifier is being examined. In comparison with the phase controlled rectifier it can be controlled to consume nearly sinusoidal current with power factor equal to unity. Another advantage is its capability of energy recuperation. The PWM rectifier can assert itself for its good behavior in many applications, for example as an input rectifier in indirect frequency converter, or in traction. Traction vehicles equipped with PWM rectifier do not consume reactive power, do not load the supply network with higher harmonics, and the recuperation is possible. The paper deals with the PWM rectifier functional model realization and examination. Electromagnetic compatibility of PWM rectifier and classical phase controlled rectifier is compared on the basis of the input current harmonic analysis.*

Keywords

PWM rectifier, thyristor rectifier, pulse width modulation, control algorithm, measured waveforms, harmonic analysis, power factor.

1. Introduction

Modern electric devices are usually fed by diode or thyristor rectifiers. These rectifiers have simple construction, easy control algorithms and are cheap to produce. But on the other side they load supply network with higher harmonics and with reactive power. Nowadays those problems are going more serious. Grid disturbances may result in malfunction or damage of other electrical devices. Therefore many methods for reduction or elimination of harmonics pollution in the power system are investigated and developed.

1.1 Phase Controlled Rectifiers

The phase controlled thyristor rectifiers belong to the category of the worst electrical network polluters. The phase control and the commutation of semiconductor devices impact on the phase displacement between the first harmonics of consumed current and supply voltage. This displacement leads to power factor degradation and to reactive power consumption. The consumed current harmonics cause the non-sinusoidal voltage drops on the supply network impedances and the supply voltage deformation which may cause the malfunction of the other devices that are sensible on the supply voltage sinusoidal shape (e.g. measuring apparatuses, communication and control systems). The reactive power rises with longer control angle delays, so the rectifier is acting as time variable impedance which is furthermore nonlinear and causes the deformed current consumption.

To reduce these side effects the rectifiers are being supplemented by filters and compensators. The classical method of current harmonics reduction uses passive LC filters. These filters are usually constructed as capacitors and inductors series or parallel connected to the network. This means that the filter can not be designed in a general way, but must be designed for a given application. Each harmonic requires its own passive filter. Such a solution has advantages of simplicity and low cost. Modern alternative to the passive filter is application of the shunt active filters. The major disadvantage of these two methods is that additional circuits raise the costs and requirements on the material and space needed for the converter are increased.

1.2 PWM Rectifiers

The other possible reduction technique is application of a “network friendly” device, for example of the PWM rectifier. Such rectifier is realized by semiconductor devices that can be switched off (IGBTs). The rectifier is controlled by pulse width modulation. Rectifier controlled in this way consumes current with demanded waveform that is mostly sinusoidal. It works with given phase displacement between consumed current and supply voltage, enables control of power factor, and has minimal effects on the supply network.

Main features of PWM rectifiers are: bi-directional power flow, nearly sinusoidal input current, regulation of input power factor to unity, low harmonic distortion of line current (THD below 5 %), adjustment and stabilization of DC link voltage (or current), reduced capacitor (or inductor) size due to the continuous current. Furthermore, it can be properly operated under line voltage distortion and line frequency variations.

Two types of PWM converters, with a voltage source output and with a current source output can be used. First of them called boost rectifier (increases the voltage) operates at fixed DC voltage polarity, and the second one, called buck rectifier (reduces the voltage) operates with fixed DC current flow.

From these two types, the voltage type rectifier is being examined. The output voltage is smoother than in case of the current type. On the other side more powerful microcontroller is demanded for its control. Also the mean value of output voltage must be greater than the maximal value on the input side. Therefore, the output voltage with amplitude lower than on the input side can be obtained only by the increased reactive power consumption.

2. PWM Rectifier Realization

The PWM rectifier consists of 4 IGBTs connected in full bridge and includes input inductance and output capacitor; see Fig. 1 and Fig. 4. Supply voltage U_s and the voltage at the rectifier input U_r have sinusoidal waveforms separated by input inductance. Therefore the energy flow depends on the angle between these two phasors, see Fig. 2.

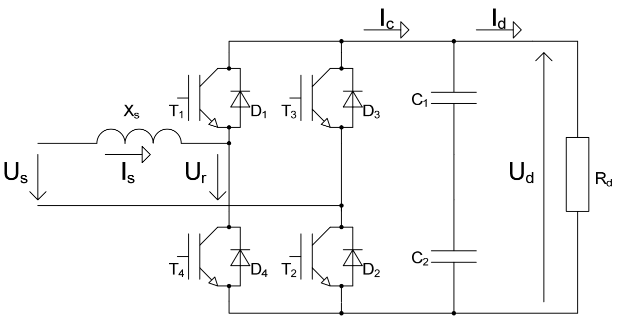

Fig. 1. PWM rectifier.

Then the power transferred from the supply to the input terminals of the rectifier is

$$P_{SR} = (U_s U_r / X_s)\sin\delta\,, \tag{1}$$

$$P_{SR} = U_s I_s \cos\phi\,. \tag{2}$$

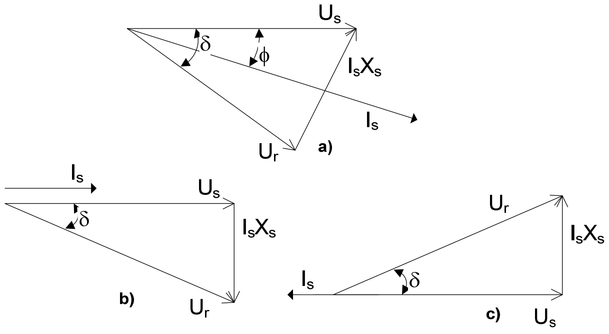

Fig. 2. Phasor diagrams.

From the phasor diagram in Fig. 2 and from the condition that the rectified voltage should be constant it results

$$I_s \cos\phi = U_r \sin\delta / X_s\,, \tag{3}$$

$$I_s \sin\phi = (U_s - U_r \cos\delta)/X_s\,. \tag{4}$$

To meet the expectations of power factor equal to unity and zero reactive power consumption the equations can be adapted to

$$I_s X_s = U_r \sin\delta\,, \tag{5}$$

$$U_s = U_r \cos\delta\,. \tag{6}$$

Phasor diagrams for such a working rectifier are shown in Fig. 2.

The effort is to control the rectifier to consume harmonic current from the supply network being in phase with supply voltage. This can be achieved in many different ways of control. The easiest control algorithm uses pulse width modulation. To derive a rectifier controller we came from the equation which describes numerically the amplitude rectifier's input voltage first harmonic

$$U_{r(1)m} = \frac{z \cdot U_d}{\pi}\int_0^{2\pi}\left(\sin^2 x\right)dx = z \cdot U_d\,. \tag{7}$$

Then the modulation ratio z can be written as

$$z = \frac{U_{r(1)m}}{U_{dAV}}\,. \tag{8}$$

Another necessary variable to control is displacement angle δ. From the phasor diagram in Fig. 2b

$$\delta = arctg\frac{\omega L I_{s(1)m}}{U_{sm}}\,. \tag{9}$$

On the bases of the above mentioned equations the rectifier controller can be made. It is obvious that only two variables are needed for such rectifier control. During the displacement angle δ control, it is needed to consider the fact that if δ increases also the current through the inductance will increase. That is why the value of the displacement angle should not exceed 60°. The actual value and demanded value of output DC voltage is compared in voltage controller. The output of voltage controller is displacement angle δ which is at the same time input for the PWM modulator and for the modulation ratio counter block. The PWM modulator then generates directly four driving signals for IGBTs.

Block diagram of the realized rectifier control system is shown in Fig. 3. The control algorithm was realized on the bases mentioned above. As a power part four IGBTs act and as a controller microprocessor MOTOROLA 56F805 was chosen.

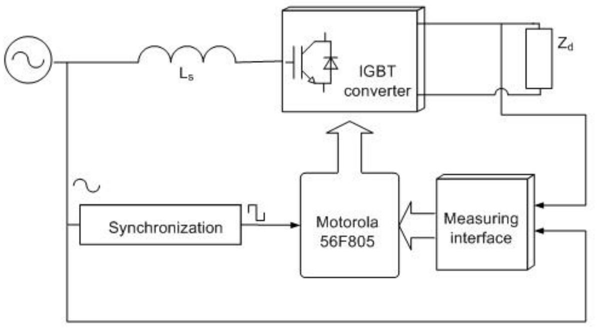

Fig. 3. Realized control system.

For the rectifier proper function it is necessary to know exactly when the network voltage crosses zero. So the synchronization circuit is needed. In general, there are two types of synchronization circuits – analog and software. Synchronization made by software, mostly phase sling, doesn’t need complicated analog circuits, but it loads microprocessor and decreases its power.

On the other side the analog circuit works faster and doesn’t need the power of the microprocessor, so the analog synchronization circuit was chosen. Voltage from supply goes through an isolating transformer and a low-pass filter to comparator inputs. The comparator generates rectangle signal which is then adjusted to the demanded amplitude by a resistor divider. This synchronization circuit looks very simple, but the output rectangle signal is heavily disturbed by IGBTs switching, so the SW synchronization looks like the better choose for future.

For proper operation of PWM rectifier a minimum DC-link voltage is required. Generally it can be determined by the peak value of line-to-line grid voltage. Defining the natural DC-link voltage value (as it is possible to obtain in case of not operating transistors) the freewheeling diodes constitute a standard diode bridge. Therefore, the boost nature of the active rectifier leads to

$$U_{DC\min} > \sqrt{2}\cdot \mathrm{u}_{\mathrm{s(RMS)}}\,. \tag{10}$$

If this condition is not fulfilled, the full control of the input current is not possible. Moreover, to keep the switching losses down, the DC-link voltage should be as low as possible. Typically, the reference value for the controlled DC-link voltage should be chosen about 10 % above the natural DC-link voltage. If unity power factor is required for PWM rectifier operation, it can be obtained in case of

$$u_r^2 = u_s^2 + u_L^2\,. \tag{11}$$

The voltage drop across the inductor (u_L) depends on reactance of the inductor at the input frequency and on the input current. The magnitude of the switching voltage vectors depends on the DC-link voltage level.

The inductor has to be designed carefully because low inductance will give a high current ripple and will make the design more depending on the line impedance. The high value of inductance will give a low current ripple, but simultaneously reduces the operation range of the rectifier. The voltage drop across the inductance has influence on the line current. This voltage drop is controlled by the input voltage of the PWM rectifier, but maximal value is limited by the DC-link voltage. Consequently, a high current (high power) through the inductance requires either a high DC-link voltage or a low inductance (low impedance). Therefore, after equation (11) transformation the maximum inductance can be determinate as

$$\frac{\sqrt{{u_r}^2 - {u_s}^2}}{\omega i_L} > L\,. \tag{12}$$

Fig. 4. Realized voltage type PWM rectifier.

3. Measured Results

To achieve comparable results in electromagnetic compatibility comparison of PWM rectifier and classical phase controlled rectifier, both rectifiers were tested under the same conditions. Test bed lay-out is shown in Fig. 5.

To provide the asked load torque $\mathrm{T_l}$, two coupled DC motors were used. The asked value of rectifier output DC voltage average value $\mathrm{U_{dAV}}$ was set and waveforms of input voltage u_1 (red), input current i_1 (blue), output voltage u_d (green), and output current i_d (violet) were taken and consecutively analyzed.

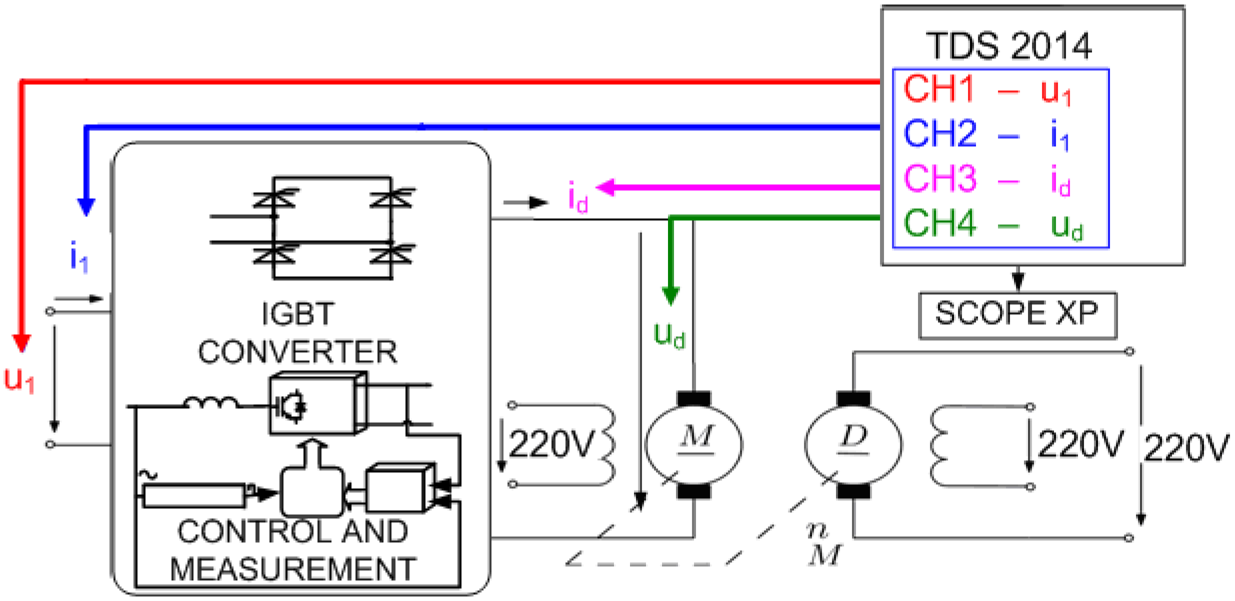

Fig. 5. PWM rectifier DC motor drive experimental test bed lay-out.

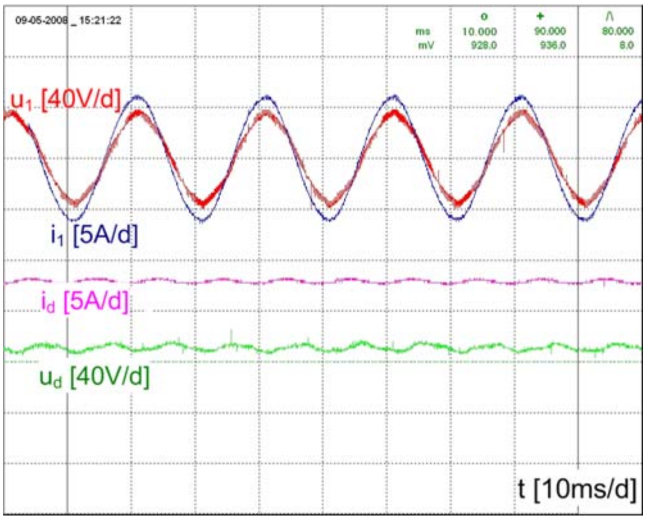

Fig. 6. PWM rectifier waveforms, $U_{dAV} = 65$ V, $T_l = 0$ Nm.

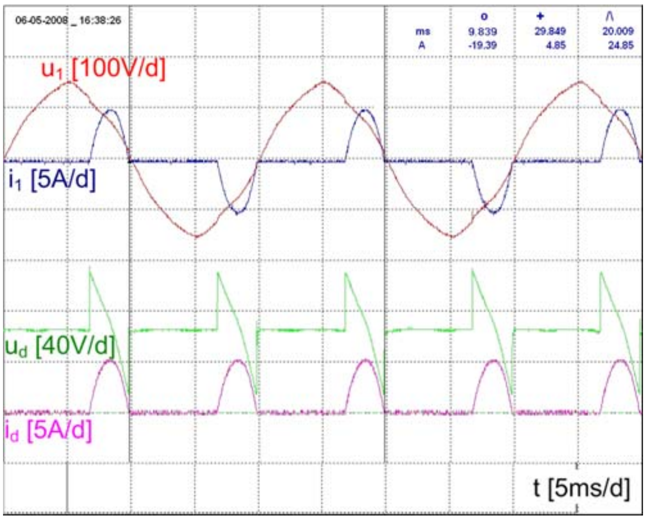

Fig. 7. Thyristor rectifier waveforms, $U_{dAV} = 65$ V, $T_l = 0$ Nm.

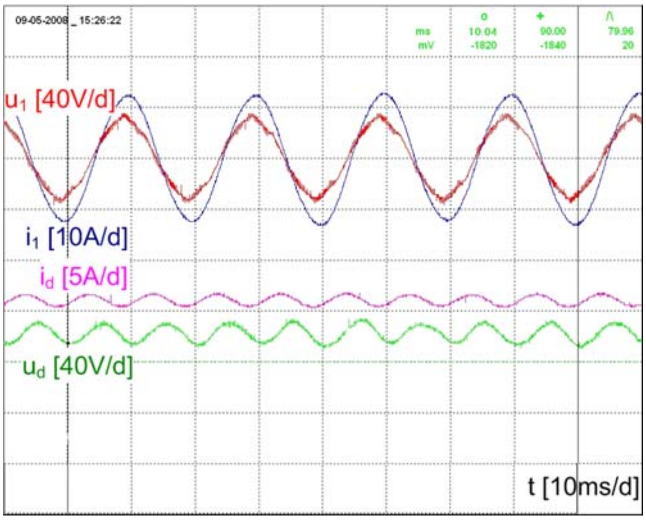

Fig. 8. PWM rectifier waveforms, $U_{dAV} = 65$ V, $T_l = 2.5$ Nm.

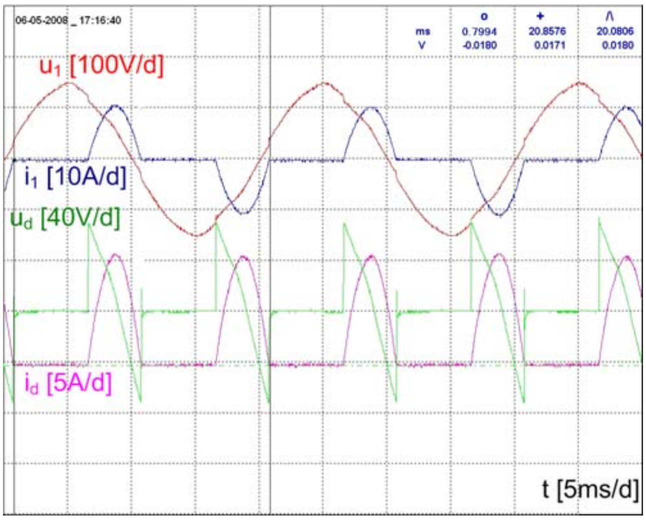

Fig. 9. Thyristor rectifier waveforms, $U_{dAV} = 65$ V, $T_l = 2.5$ Nm.

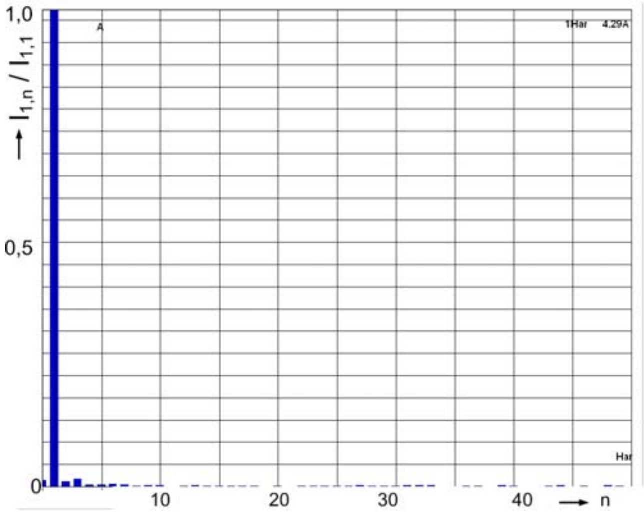

Fig. 10. PWM rectifier input current harmonic analysis, $U_{\mathrm{dAV}} = 65$ V, $T_{\mathrm{l}} = 0$ Nm.

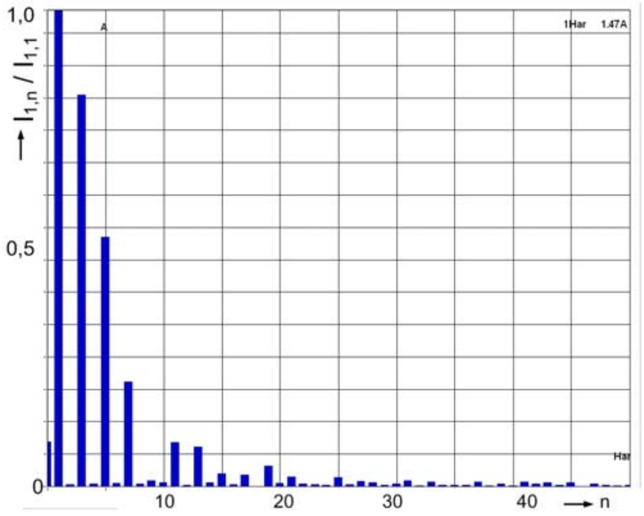

Fig. 11. Thyristor rectifier input current harmonic analysis, $U_{\mathrm{dAV}} = 65$ V, $T_{\mathrm{l}} = 0$ Nm.

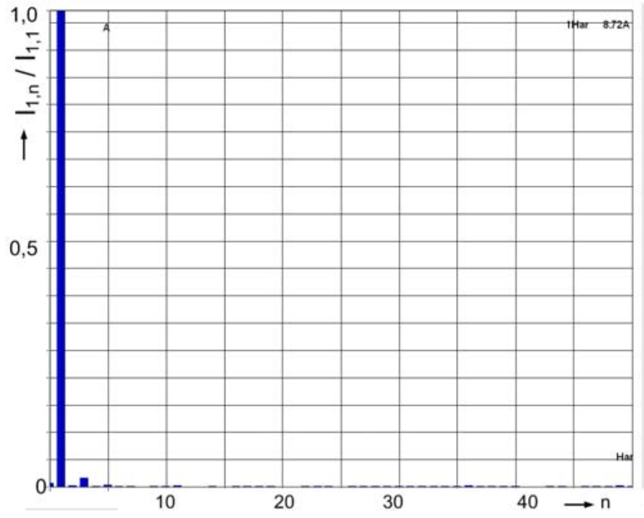

Fig. 12. PWM rectifier input current harmonic analysis, $U_{\mathrm{dAV}} = 65$ V, $T_{\mathrm{l}} = 2.5$ Nm.

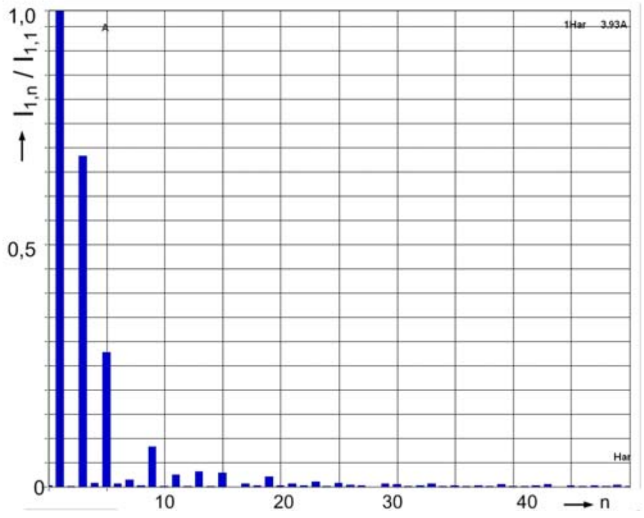

Fig. 13. Thyristor rectifier input current harmonic analysis, $U_{\mathrm{dAV}} = 65$ V, $T_{\mathrm{l}} = 2.5$ Nm.

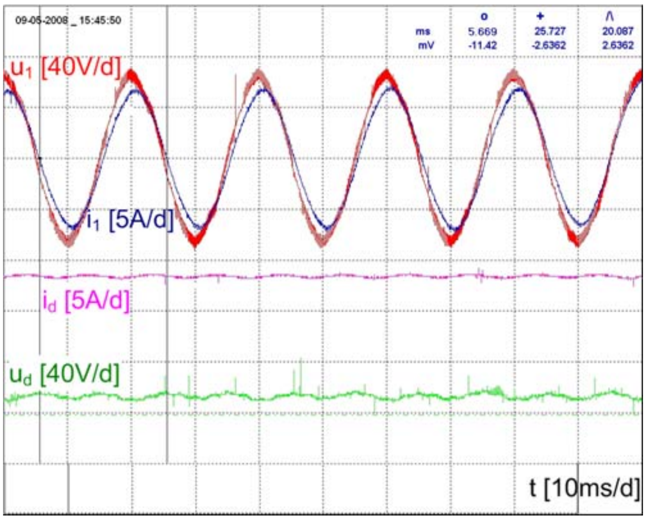

Fig. 14. PWM rectifier waveforms, $U_{\mathrm{dAV}} = 100$ V, $T_{\mathrm{l}} = 0$ Nm.

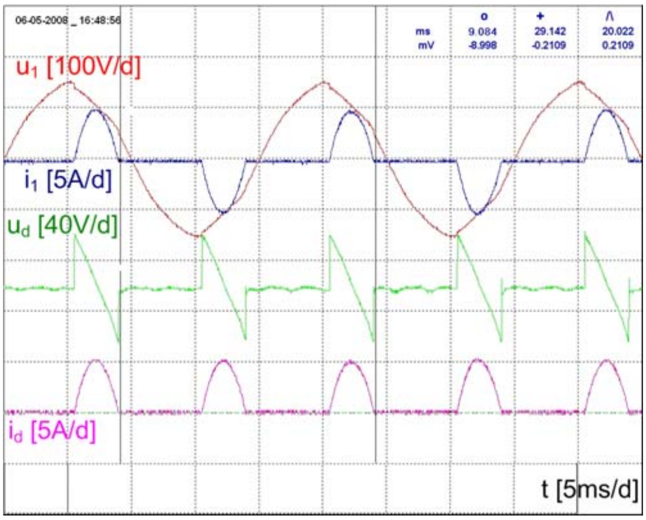

Fig. 15. Thyristor rectifier waveforms, $U_{\mathrm{dAV}} = 100$ V, $T_{\mathrm{l}} = 0$ Nm.

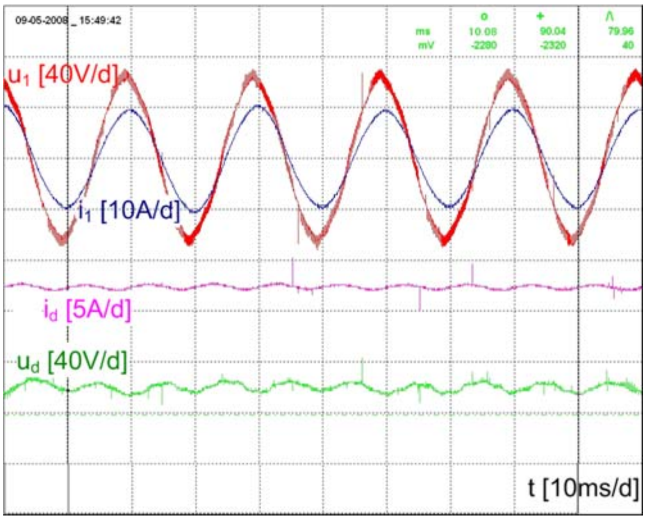

Fig. 16. PWM rectifier waveforms, $U_{\mathrm{dAV}} = 100$ V, $T_{\mathrm{l}} = 2.5$ Nm.

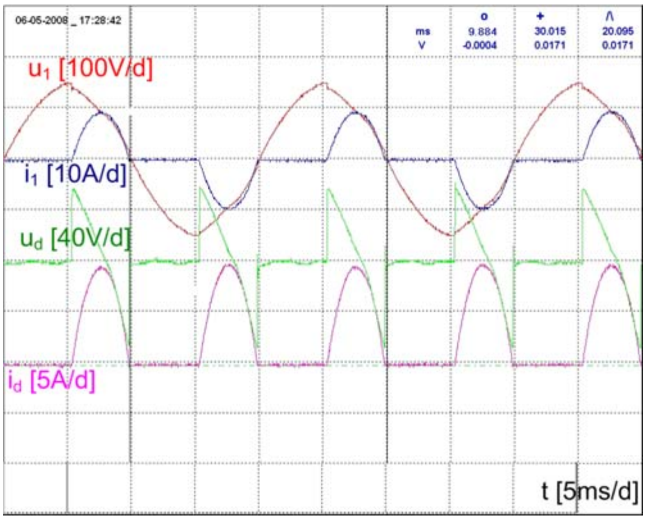

Fig. 17. Thyristor rectifier waveforms, $U_{\mathrm{dAV}} = 100$ V, $T_{\mathrm{l}} = 2.5$ Nm

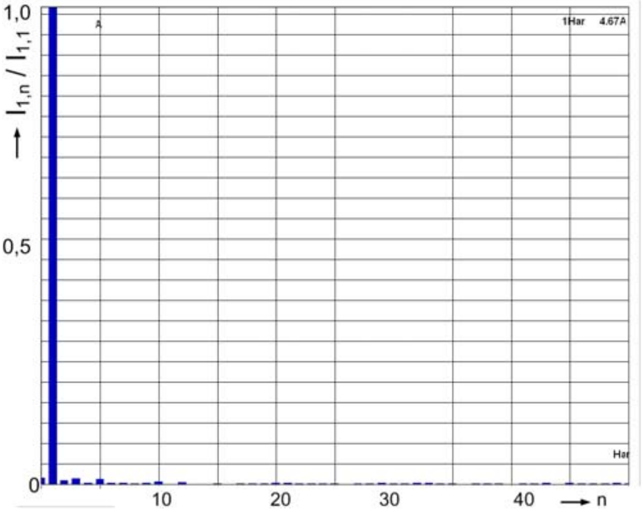

Fig. 18. PWM rectifier input current harmonic analysis, $U_{\mathrm{dAV}} = 100$ V, $T_{\mathrm{l}} = 0$ Nm

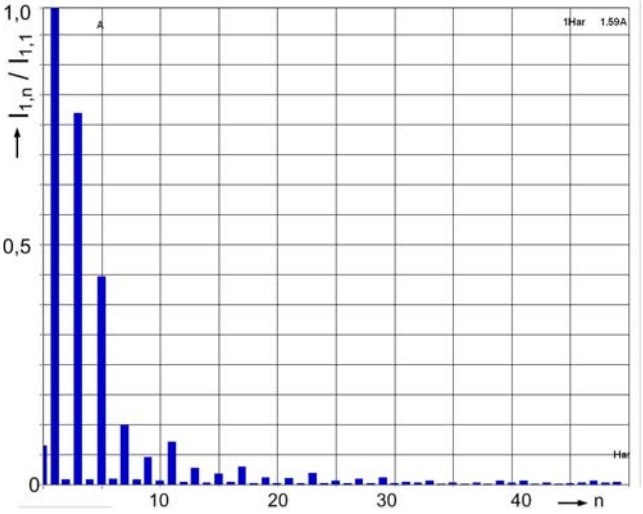

Fig. 19. Thyristor rectifier input current harmonic analysis, $U_{\mathrm{dAV}} = 100$ V, $T_{\mathrm{l}} = 0$ Nm.

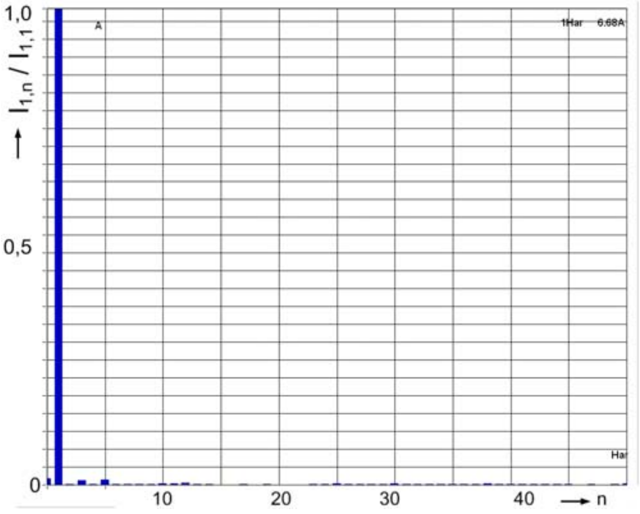

Fig. 20. PWM rectifier input current harmonic analysis, $U_{\mathrm{dAV}} = 100$ V, $T_{\mathrm{l}} = 2.5$ Nm.

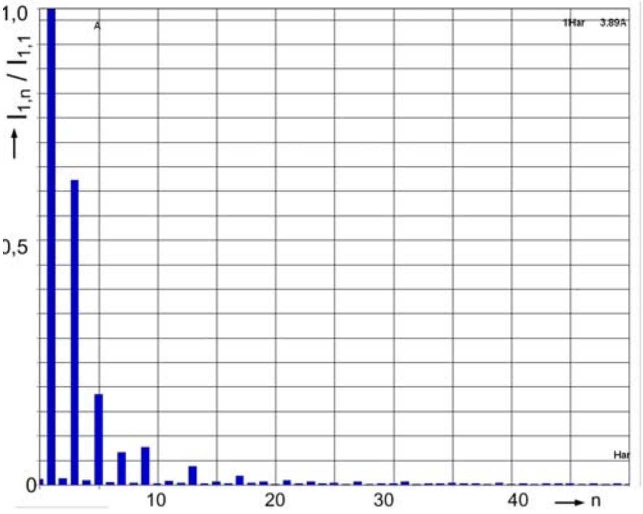

Fig. 21. Thyristor rectifier input current harmonic analysis, $U_{\mathrm{dAV}} = 100$ V, $T_{\mathrm{l}} = 2.5$ Nm.

	PWM RECTIFIER		**THYRISTOR RECTIFIER**	
	T_l = 0 Nm		**T_l = 0 Nm**	
U_{dAV} (V)	**THD (%)**	**ν (%)**	**THD (%)**	**ν (%)**
65	**2.30**	**99.97**	**98.43**	**70.37**
100	**2.13**	**99.98**	**91.08**	**73.93**
	T_l = 2.5 Nm		**T_l = 2.5 Nm**	
U_{dAV} (V)	**THD (%)**	**ν (%)**	**THD (%)**	**ν (%)**
65	**2.10**	**99.97**	**75.67**	**79.74**
100	**1.76**	**99.98**	**67.80**	**82.77**

Tab. 1. Comparison of the consumed current harmonic analysis evaluation for various U_{dAV} and T_l.

To evaluate the consumed current quality, the coefficients *THD* (total harmonic distortion) and ν (fundamental harmonic content) were counted and compared in all measured cases

$$THD = \frac{\sqrt{\sum_{2}^{\infty} I_{(n)}^{2}}}{I_{(1)}} , \qquad (13)$$

$$\nu = \frac{I_{(1)}}{I} \qquad (14)$$

where I is the input current RMS (root mean square) value.

Figs. 6, 8, 14, 16 show the PWM rectifier waveforms and Figs. 7, 9, 15, 17 display the thyristor rectifier waveforms for various U_{dAV} and T_l values. Figs. 10, 12, 18, 20 and Figs. 11, 13, 19, 21 depict the corresponding input current harmonic composition.

Tab. 1 summarizes the counted harmonic coefficients for different voltages U_{dAV} and two motor loads. Essential differences between the rectifiers can be seen. *THD* of the PWM rectifier is circa 2 %; *THD* of the thyristor rectifier depends on the load and is about 80 %.

4. Conclusions

Utilization of PWM rectifiers eliminates the problems caused by using of phase controlled rectifiers. The PWM rectifier can assert itself for its good behavior in many applications, for example as an active filter, or as an input rectifier for indirect frequency converter. This application appears mainly in traction vehicles where the AC voltage from trolley wire is rectified firstly and then from the rectifier output the traction inverters and the other auxiliary converters are fed. Traction vehicles equipped with PWM rectifier do not consume reactive power, do not last the supply network with harmonics, and the recuperation is possible.

Another mentioned possible usage of the converter is as an active filter. Active front-end would have the capacitor on the output. The rectifier would be controlled in order to consume the current that contains all harmonics, as the device, its negative effect should be suppressed. The current consumed by the rectifier would be in the opposite phase to the current consumed by the device, so the harmonics consumption from supply should be created.

Measured properties of the realized one phase thyristor rectifier and realized voltage type PWM rectifier were compared. The thyristor rectifiers due to their phase control load supply grid with higher harmonics and consume reactive power. These side effects of phase control cannot be ignored and must be suppressed or compensated. The modern way is to apply the rectifier with pulse width modulation instead of the thyristor rectifier. Such PWM rectifier consumes current of demanded shape and with demanded phase shift between input current first harmonic and supply voltage first harmonic so that the power factor can be regulated to the unity. Both rectifiers were tested under the same conditions and comparison of the tests results is summarized.

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Radovan DOLEČEK was born in 1971. He received M.Sc. degree (1999) in Electric Transport Equipment and Ph.D. degree (2006) in Electric Transport Equipment, both from the University of Pardubice. Nowadays he works as an assistant professor at the University of Pardubice. He is interested in simulations and EMC measurement.