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Simulation Models of Power Rectifiers in the EMTP-ATP Software

***Abstract**. The paper presents results of computer simulations of 6-pulse, 12-pulse and 18-pulse power rectifiers and their comparison to results from experimental measurements. To analyze their behaviour under various voltage quality conditions, simulation models have been developed using program EMTP-ATP. Performed simulations and measurements demonstrate a high effectiveness of the harmonic elimination of multi-pulse rectifiers. Nevertheless, it is affected by the quality of the supply voltage at the point of rectifier coupling as it is shown in the paper.*

Streszczenie.** Zaprezentowano rezultaty komputerowej symulacji 6-, 12- i 18-pulsowego prostownika mocy oraz przedstawiono porównanie wyników symulacji z eksperymentem. Do symulacji yżto program EMTP-ATP. **Symulacja prostownika mocy z wykorzystaniem programu EMTP-ATP

Keywords: EMTP-ATP, harmonics, power rectifier, simulation.
Słowa kluczowe: prostownik mocy, EMTP-ATP, symulacja.

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Introduction

Power semiconductor converters are widely used in structures of variable speed drives to control their speed and torque. The most common type of these drives is AC drive with induction motor fed by frequency converter. The converter utilizes an input rectifier, most often as three phase 6-pulse diode. Rectifiers produce harmonic currents, which are generated into the power network with a negative impact on it and connected devices. In this case the current drawn by the drive is non-sinusoidal with a high level of distortion [1-4]. To determine its spectrum, harmonic analysis is applied. It enables to resolve a periodic non-sinusoidal function into a sum of sinusoidal waves – the Fourier series of the function:

$$f(t) = \frac{a_0}{2} + \sum_{h=1}^{\infty} \left[a_h \cos(h\omega t) + b_h \sin(h\omega t) \right] \tag{1}$$

where: a_0, a_h, b_h – Fourier coefficients [1].

Simplified waveform of the drawn current by AC drive with 6-pulse rectifier is shown in Fig. 1. In this case, the Fourier coefficients a_0, a_h are equal to zero, so the waveform can be expressed as:

$$f(t) = \sum_{h=1}^{\infty} b_h \sin(h\omega t) \tag{2}$$

Computing the coefficient b_h for $k = \pi/3 - d$ gives:

$$\begin{aligned} b_h &= \frac{2}{\pi} \left(\int_{\frac{\pi}{2}-\frac{k}{2}-d}^{\frac{\pi}{2}-\frac{k}{2}} I_\mathrm{m} \sin(h\omega t) \mathrm{d}\omega t + \int_{\frac{\pi}{2}+\frac{k}{2}}^{\frac{\pi}{2}+\frac{k}{2}+d} I_\mathrm{m} \sin(h\omega t) \mathrm{d}\omega t \right) = \\ &= \frac{8}{h\pi} \cdot I_\mathrm{m} \cdot \sin\frac{hd}{2} \cdot \cos\frac{h\pi}{6} \cdot \sin\frac{h\pi}{2} \end{aligned} \tag{3}$$

Now, the input current according to the equation (2) is:

$$i(\omega t) = \sum_{h=1}^{\infty} \frac{8}{h\pi} \cdot I_\mathrm{m} \cdot \sin\frac{hd}{2} \cdot \cos\frac{h\pi}{6} \cdot \sin\frac{h\pi}{2} \cdot \sin(h\omega t) \tag{4}$$

where: h – harmonic order, d – rectifier diode operating angle, I_m – current magnitude.

It can be determined from the equation (4) and seen in Fig. 1 that only harmonics of these orders are present in spectrum of the current:

$$h = 5,7,11,13,17,19,23,25,29,31.... \tag{5}$$

This means harmonics satisfying this formula:

$$h = n \cdot p \pm 1 \tag{6}$$

where: n – 1,2,3…., p = 6 – rectifier pulse number.

As seen from the equation (6) the number of present harmonics depends on the number of pulses of the used rectifier – the rectifier with higher pulse number generates smaller number of harmonics, which means lower input current distortion with lower total harmonic distortion.

Harmonic Elimination Using Multi-Pulse Rectifiers

As seen in Fig. 1 the drawn current has a high level of distortion if no harmonic mitigation technique is used. There are various technical solutions for reducing harmonics in the area of variable speed drives [1-7]. One of them is using multi-pulse power rectifier, such as 12-pulse, 18-pulse or 24-pulse instead of the standard 6-pulse one. Multi-pulse rectifiers provide a good solution for harmonics suppression, because they are able to eliminate theoretically, or in practice to reduce by a significant way, some harmonics of important orders [6-9]. As can be determined from the equation (6) for power rectifier with pulse number equal to twelve only harmonics of these orders are present in the input current spectrum:

$$h = 11,13,23,25,35,37.... \tag{7}$$

which means that dominant harmonics of the 5th and 7th orders are eliminated.

To achieve this elimination two 6-pulse rectifiers are used and connected to the three-winding transformer with phase shift between its secondary phase voltages of 30 degrees. As seen in Fig. 2 the transformer Dd0y1 is used. To eliminate harmonics of more orders 18-pulse rectifier is used. In this case only harmonics of these orders are theoretically in the input current:

$$h = 17,19,35,37.... \tag{8}$$

so the dominant harmonics of the 5th, 7th, 11th and 13th orders are eliminated, which means considerably lower input current distortion. In this case three 6-pulse rectifiers are connected to the four-winding transformer with phase shift of 20 degrees between secondary phase voltages as it can be seen in Fig. 2. So considering equations (5)-(8) this formula can be derived:

$$h = 6 \cdot n \cdot r \pm 1 \tag{9}$$

where *r* – number of connected 6-pulse rectifiers.

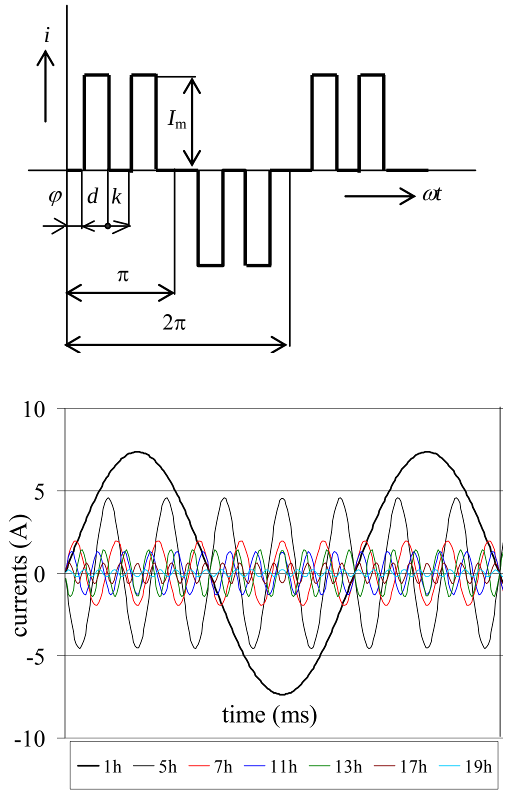

Fig.1. Simplified waveform of current drawn by AC drive with 6-pulse rectifier and its harmonic analysis

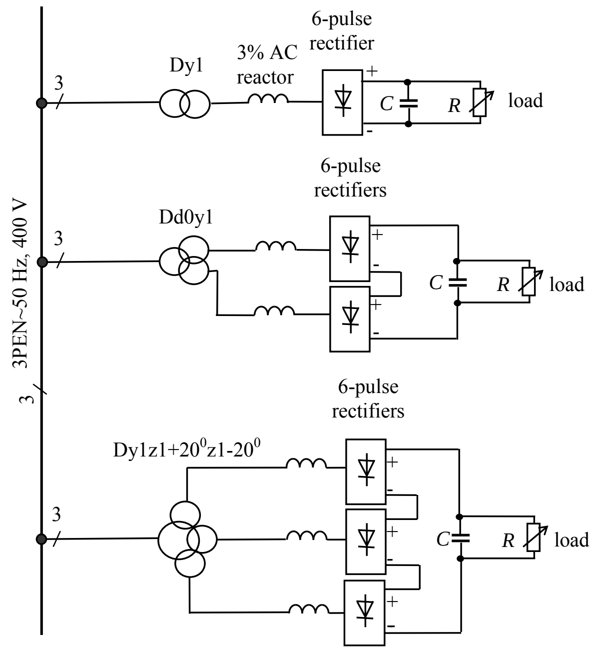

Fig.2. Diagram of simulated circuits

In our EMC laboratory, these special transformers are in operation with a drive assembly:

Twelve-pulse:

Dd0y1/Yd11y0 (primary winding with a tap for star, secondary winding with 200 V tap for series connection)
Nominal power: 20 kVA
Nominal primary voltage: V_{1n}=3 x 400 V, delta + tap for 231 V, star
Nominal primary current: I_{1n}=29.73 A, delta + tap for 17.16 A, 11.5 kVA, star
Nominal secondary voltages: V_{21n}=V_{22n}=3 x 200–400 V, delta, star
Nominal secondary currents: I_{21n}=I_{22n}=14.5 A (10 kVA)
Open circuit test: exciting current: I_{exc}=6.38%, excitation losses: P_{exc}=140 W
Short circuit test: short-circuit impedance: Z_{sc}=2.85%, short-circuit losses: P_{sc}=550 W

Eighteen-pulse:

Dy1z1+20^{0}z1-20^0/Yy0z0+20^{0}z0-20^0 (primary winding with a tap for star)
Nominal power: 6.93 kVA
Nominal primary voltage: V_{1n}=3 x 400 V, delta + tap for 231 V, star
Nominal primary current: I_{1n}=10 A, delta + tap for 5.77 A, 4 kVA, star)
Nominal secondary voltages: V_{21n}=V_{22n}=V_{23n}=3 x 133.3V
Nominal secondary currents: I_{21n}=I_{22n}=I_{23n}=10 A
Open circuit test: exciting current: I_{exc}=4.92%, excitation losses: P_{exc}=60 W
Short circuit test: short-circuit impedance: Z_{sc}=2.0%

The level of current distortion is often described as the total harmonic current distortion:

$$THD_i = \frac{\sqrt{\sum_{h=2}^{40} I_h^{\,2}}}{I_1} \cdot 100 \tag{10}$$

which represents the ratio of the effective value of harmonics (from 2nd up to 40th order) to that of the fundamental one.

Using EMTP–ATP Software for Power Rectifier Simulations

The EMTP-ATP (Electromagnetic Transient Program – Alternative Transient Program) is simulation software of the electrical power networks and power electronics, which has been used for simulations of tested power rectifiers. The designed circuit can be drawn in a graphics environment of a graphical pre-processor ATPDraw and saved as ACP file. In this manner designed circuits of 6-pulse and 12-pulse rectifiers have been simulated. After running their simulation circuits ATP data file and accompanying next files are generated. One of them is a file with compressed graphical data, which is possible to browse using graphical post-processor PLOTxy. Waveforms of quantities measured in the drawn electrical circuit can be plotted and their harmonic analyze performed.

As mentioned above, in the structure of multi-pulse rectifiers special multi-winding transformers are used to provide the required harmonic eliminations. As regards the 12-pulse rectifier, transformer with Dd0y1 connection was chosen to present some results of its simulation model. A representation of this transformer has been developed using supporting routine BCTRAN, which can be activated directly in ATPDraw, and inserted into rectifier simulation model with relevant transformer parameters. Data from the excitation test and from three short-circuit tests are also necessary to enter into the BCTRAN dialog window. After inserting all required data and running the BCTRAN a representation of the transformer is developed and inserted into a final ATP data file of the proposed circuit model.

There are two 18-pulse rectifiers with Dy1z1+20^{0}z1-20^0 transformer and with Dd0diii0+20^{0}diii0-20^0 transformer in our laboratory, whereas results of the first one are presented in this paper. The required phase shift of 20 degrees between secondary phase voltages is not possible to achieve by standard transformers, so it is necessary to divide two of three secondary windings into two unequal parts. This special transformer cannot be modelled in the graphical pre-processor ATPDraw due to higher number of windings. So user has to write a program and enter it into ATP file of the BCTRAN component according to the EMTP-ATP rule book 19-C. Besides the excitation test fifteen short-circuit tests have to be done and data from them entered as BCTRAN data in the BCTRAN ATP file. After inserting all required data and running this file a representation of the transformer is developed, which is inserted by user into a final ATP data file of the complete circuit model of the 18-pulse rectifier.

Some results of simulations are presented in Fig. 3, Fig. 4, and Fig. 5, respectively. In Fig. 3 waveforms of the input current (primary current of the rectifier transformer) in one phase are shown with THD_i=48.9% (6-pulse rectifier with 3% input AC reactor), THD_i=9.2% (12-pulse) and THD_i=4.7% (18-pulse) at distorted voltage with THD_v of 4%, which is a common value in university laboratory power networks. The positive effect of both multi-pulse rectifiers on current quality is evident. Percentage of dominant harmonics in primary current of multi-pulse rectifiers is presented in Table 1. As seen, the test results under supplying the rectifier circuits with the nearly sinusoidal voltage with THD_v=0.25% from the three-phase AC power source ASX 3120 connected to the supply network, and from simulations under purely sinusoidal voltage match the theoretical assumption fairly well, especially in the case of the twelve-pulse rectifier. As can be also seen the reduction of concerned harmonics is affected supplying rectifiers from the network with distorted voltage. The values of the monitored harmonics are mostly increased due to their presence in the spectrum of supply voltage.

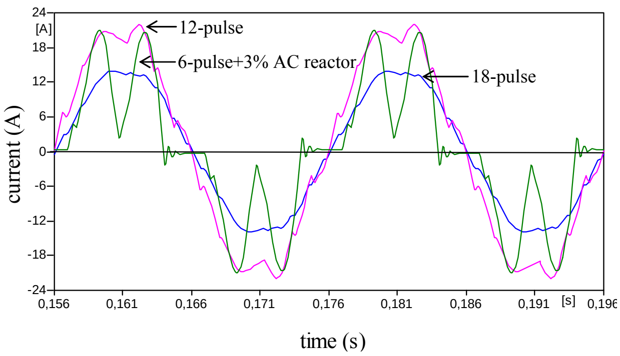

Fig.3. Input current waveforms (simulated, nominal load, THD_v=4%)

The dependence of input current THD_i on load current for both simulations and experimental measurements is shown in Fig. 4. As seen they match very well up to rectifier load of c. 50%, or c. 40% for eighteen-pulse rectifier. As regards the lowest rectifier loads, the differences are rather higher, which is caused by a higher influence of magnetizing inductance.

Table 1. Percentage of dominant harmonics in primary current of multi-pulse rectifiers (nominal loading)

	THD_v (%)	I_{hf} / I_{1f} (%)					
		12-pulse		18-pulse			
		5th	7th	5th	7th	11th	13th
Theory	0.0	0	0	0	0	0	0
Sinusoidal source	0.25	0.8	0.4	2.8	0.7	0.6	0.6
Supply network	4.0	6.6	3.8	4.9	2.1	0.3	0.2
Simulation	0.0	0.1	0.0	1.1	0.4	0.2	0.2

Simulation results under adjusted levels of THD_v and under nominal load of tested rectifiers are presented in Fig. 5 from which an influence of supply voltage quality on the ability of tested devices to reduce harmonics can be seen. Higher levels of THD_v mean higher levels of voltage harmonics in the spectrum of supply voltage causing the increasing corresponding current harmonics.

As expected, the 18-pulse rectifier is most effective and is least sensitive to voltage distortion, when values of THD_i are in the range of c. 3% under THD_v=0% to 4.7% under THD_v=4%. 12-pulse rectifier is also very effective even if its sensitivity to supply voltage distortion is moderately higher with THD_i being less than 10% under supply voltage THD_v of 4%. Finally, the result of 6-pulse rectifier with 3% input AC reactor is shown with considerably higher levels of THD_i being above 40% for all set values of THD_v. Nevertheless, in the case if no filtration technique for harmonics reduction is used, the input current THD_i can highly exceed 100%, so using the input reactor itself also brings quite effective solution widely used in various technical applications.

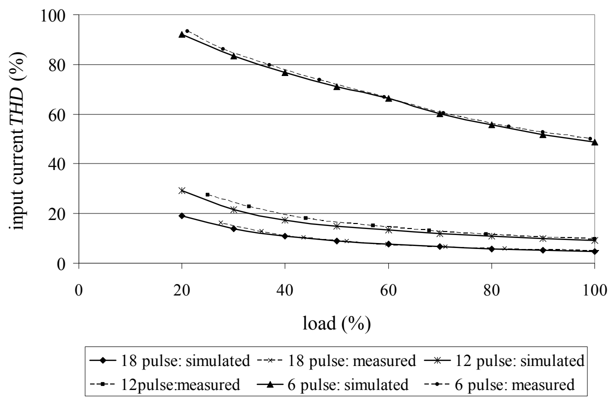

Fig.4. Input current *THD* versus load (simulated and measured, THD_v = 4%)

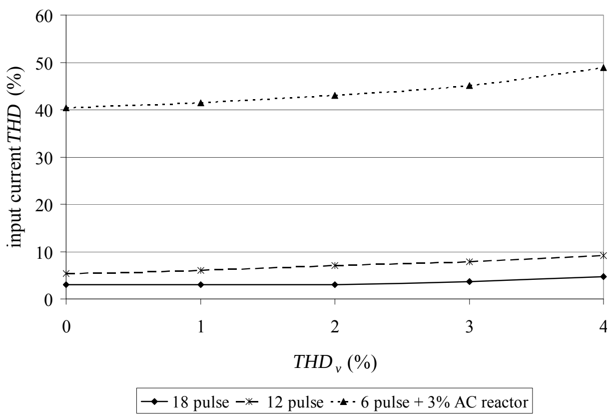

Fig.5. Input current *THD* versus adjusted levels of THD_v (simulated, nominal load)

Conclusion

This paper provides the presentation of some results generated from the simulation models of the 6-pulse, 12-pulse and 18-pulse power rectifiers and their comparison to the results from experimental measurements. As can be seen in Fig. 4, the results from the simulations match the results from the measurements quite well and can be used to analyze the behaviour of the tested multi-pulse rectifier topologies under various levels of supply voltage distortion. As seen the level of distortion of input current is considerably reduced by multi-pulse rectifiers in comparison with the standard 6-pulse one. Nevertheless, it is affected by the level of rectifier loading and the quality of supply voltage at the point of rectifier coupling, and voltage unbalance and a design of the multi-pulse rectifiers as well.

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