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Influence of Supply Voltage Quality on Harmonics Generated by AC Adjustable Speed Drives

***Abstract**. The paper presents results of computer simulations and experimental measurements for several topologies of AC adjustable speed drives fitted with selected devices for harmonics mitigation. Simulation models of the drive topologies have been developed using the program EMTP-ATP and tested under adjusted levels of supply voltage distortion. Both experimental measurements and simulations demonstrate high harmonic mitigation effectiveness of broad-band harmonic filter and active front end rectifier.*

***Streszczenie.** Artykuł prezentuje wyniki symulacji komputerowych oraz pomiarów doświadczalnych przeprowadzonych dla kilku układów napędowych prądu przemiennego o regulowanej prędkości, wyposażonych w wybrane urządzenia do łagodzenia wpływu harmonicznych. Modele symulacyjne badanych topologii układów napędowych zostały opracowane z wykorzystaniem oprogramowania EMTP-ATP i przetestowane w warunkach umożliwiających regulowanie stopnia odkształcenia napięcia zasilającego. Pomiary laboratoryjne jak również symulacje wykazały wysoką efektywność łagodzenia wpływu harmonicznych poprzez stosowanie szerokopasmowych filtrów harmonicznych oraz aktywnych prostowników. (**Wpływ jakości napięcia zasilającego na wyższe harmoniczne generowane przez układu napędowe prądu przemiennego o regulowanej prędkości**).*

Keywords: adjustable speed drives, current distortion, harmonics, voltage distortion.
Słowa kluczowe: układy napędowe o regulowanej prędkości, odkształcenia prądu, harmoniczne, odkształcenia napięcia.

Introduction

Semiconductor converters in structures of such devices as adjustable speed drives, UPS or data processing and electronics devices used in various technical applications represent sources of harmonic currents generated into the power network to which they are connected [1-4]. Standard AC adjustable speed drives utilize the input three phase six-pulse diode rectifier for the AC-DC conversion, therefore the drawn current is not harmonic with a high level of distortion if no harmonic mitigation technique is used. An example of this drive input current is shown in Fig. 1a.

To determine the spectrum of this current, harmonic analysis is applied. It enables to resolve a periodic function into a sum of sinusoidal waves – the Fourier series of the function. The input current can be expressed as:

$$i(t) = I_0 + \sum_{h=1}^{\infty} \sqrt{2} I_h \sin(h\omega t + \varphi_h) \tag{1}$$

where: I_0 – amplitude of the DC component (generally zero in the electrical power distribution), I_h – rms value of the h^{th} current harmonic, φ_h – phase angle of the h^{th} harmonic.

Simplified waveform of the input current is shown in Fig.1b. In this case, the current can be described, using the Fourier series, by the formula:

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

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

It can be determined from the equation (2) that only harmonics of these orders are present in spectrum of the current:

$$h = k \cdot p \pm 1 \tag{3}$$

where: k – 1,2,3…., p – rectifier pulse number.

This means harmonics of the following orders:

$$h = 5, 7, 11, 13, 17, 19, 23, 25, 29, 31...... \tag{4}$$

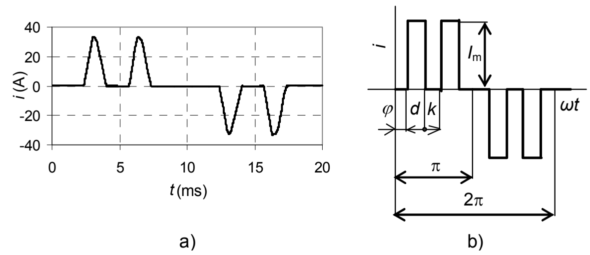

Fig.1. Input current waveform of adjustable speed drive with input six-pulse diode rectifier: *a)* measured, *b)* simplified

As seen in Fig. 1, the drive input current is heavily distorted. Its total harmonic distortion is calculated from the formula:

$$THD_i = \frac{\sqrt{\sum_{h=2}^{40} I_h^2}}{I_1} \cdot 100 \,. \tag{5}$$

Harmonic currents can have a negative impact on devices connected to the network. Their levels are affected by the following factors: short-circuit ratio at the point of the drive coupling to the network, type of converter and its loading, technique for harmonics mitigation and quality of supply voltage.

In the paper, computer simulations and experimental measurements of several adjustable speed drive topologies have been performed under chosen levels of supply voltage distortion represented by the total harmonic distortion THD_v calculated in the same manner as the THD_i in the equation (5).

Tested topologies of AC adjustable speed drives

The adjustable speed drives draw non-harmonic currents out of the network with a high level of THD_i, which can exceed 100% if no harmonic filter is used. Various technical solutions are applied for harmonic mitigation aiming to reduce levels of THD_i, it is to reduce their negative impact on supply voltage quality and devices connected to the network [4-8]. In the paper drives fitted with 3% AC input reactor, broad-band harmonic filter and active front end rectifier (AFE) have been tested.

The tested adjustable speed drives have been fed by programmable three phase linear AC power source Pacific 3120AMX with adjusted levels of voltage total harmonic distortion THD_v equal to 0%, 2%, 4%, 6%, and 8% respectively. Three phase induction motor of rated power of 5.5 kW was braked using DC motor controlled by a thyristor rectifier, and supplied from frequency converter. Input currents and voltages have been measured and analyzed by a network analyzer. A diagram of the measured circuit is shown in Fig. 2.

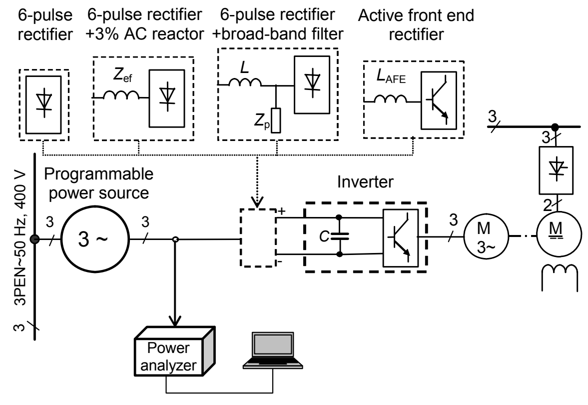

Fig.2. Diagram of the measured circuit

Simulation models of the drives with each of the chosen devices for harmonic mitigation have been developed using the EMTP-ATP program and their results compared to results brought out by their experimental measurements.

Simulation and experimental measurement results

Experimental measurements have been performed in our EMC laboratory. The AC adjustable speed drives have been fed by the programmable power source with the adjusted levels of voltage distortion mentioned in the previous section. The loading degree of the induction motor have been adjusted using the controlled rectifier of the DC drive, and its influence on the AC drive input current *THD* is shown in Fig. 3 under THD_v = 0%, and under THD_v = 4% in Fig. 5. Converter output frequency was adjusted to 50 Hz. Results from simulations of the tested drive configurations are shown in Fig. 4 and in Fig. 6 under the same levels of THD_v.

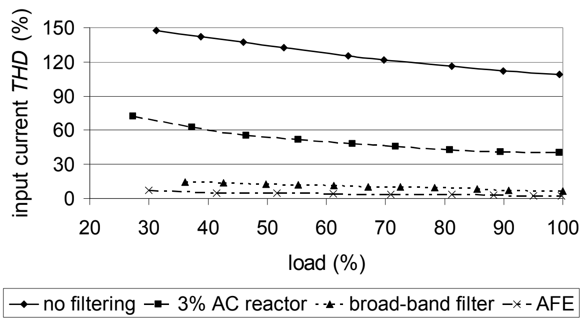

Fig.3. Input current *THD* versus load (THD_v = 0%, measured)

As can be seen in Figs. 3-6, an increasing of motor loading causes a decrease of AC drive input current distortion. A dominant influence on the current distortion has the input rectifier of the frequency converter [5, 6]. If the standard six-pulse one is used, the levels of generated harmonics depend on the rectifier diode operating angle, as seen in Fig. 7 for the dominant harmonics of the 5^{th} and 7^{th} order derived from the equation (2) and expressed in p.u. of the fundamental. The applied method of a harmonic mitigation technique has the considerable effect on the reducing of harmonics, especially the broad-band harmonic filter and active front end rectifier as seen in Figs. 3-6. The level of the current distortion is also affected by supply voltage quality which can be also seen in these figures and more clearly in Figs. 8 and 9 where the dependence of current distortion on adjusted levels of THD_v is illustrated.

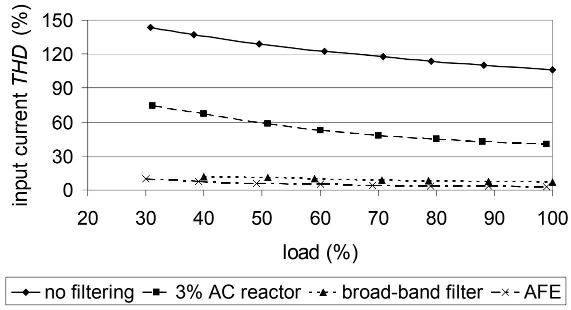

Fig.4. Input current *THD* versus load (THD_v = 0%, simulation)

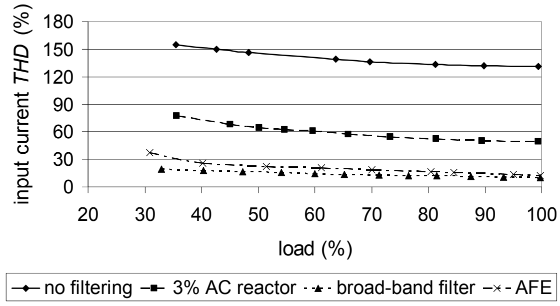

Fig.5. Input current *THD* versus load (THD_v = 4%, measured)

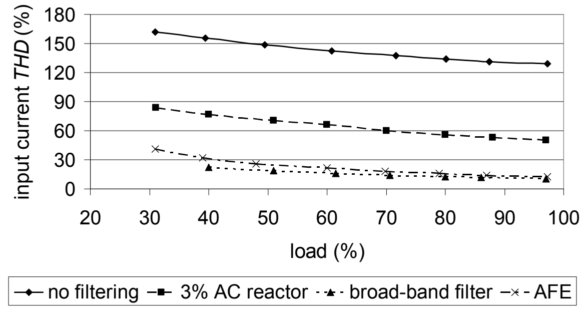

Fig.6. Input current *THD* versus load (THD_v = 4%, simulation)

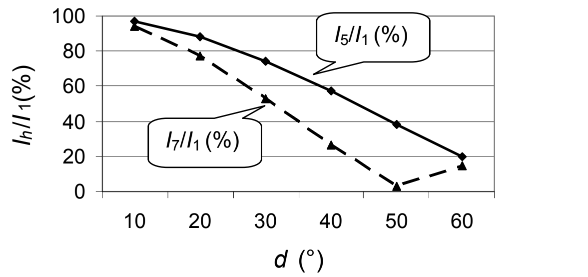

Fig.7. The 5^{th} and 7^{th} harmonic in p.u. versus diode operating angle

As can be also seen in Figs. 3-6 and 8-9, the results from simulations match the results from experimental measurements very well and therefore can be used to analyze the behaviour of the tested drive topologies under various levels of supply voltage distortion represented by the total harmonic distortion THD_v.

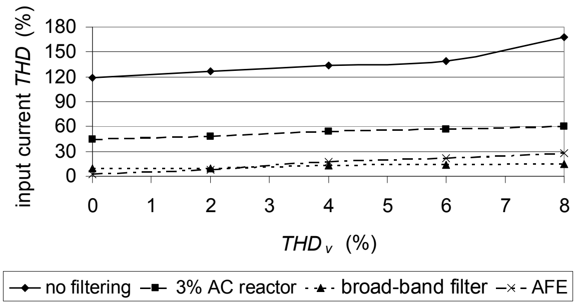

Fig.8. Input current *THD* versus THD_v (75% load, measured)

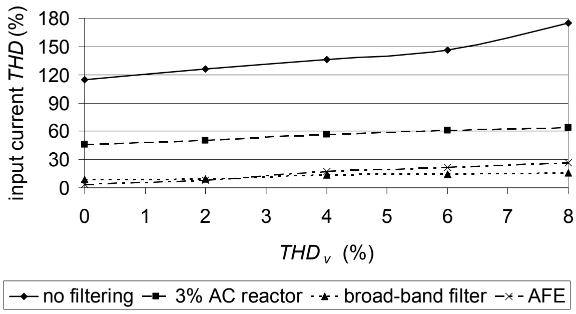

Fig.9. Input current *THD* versus THD_v (75% load, simulation)

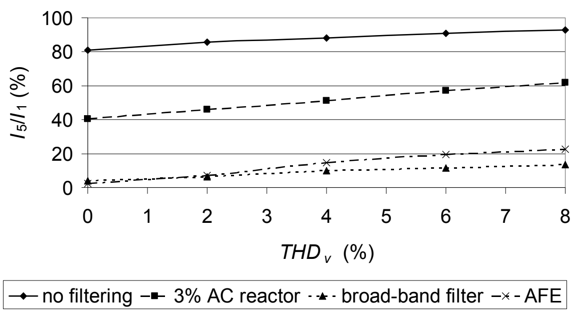

Fig.10. The 5[th] harmonic versus THD_v (75% load, simulation)

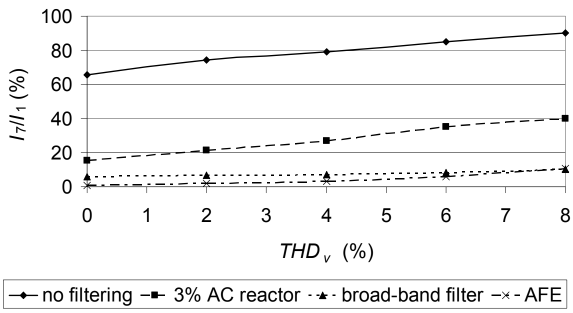

Fig.11. The 7[th] harmonic versus THD_v (75% load, simulation)

The influence of voltage distortion on input current *THD* is negative for each tested drive configuration. As seen in Figs. 8 and 9, the broad-band harmonic filter is least sensitive to voltage distortion and markedly reduces harmonic currents in the whole range of THD_V. AFE is also very effective even if its sensitivity to supply voltage distortion is higher. Harmonics of the 5[th] and 7[th] order in the spectrum of input drive current have a significant influence on the level of current distortion, so their dependence on the adjusted levels of supply voltage distortion THD_v is shown in Figs. 10 and 11, where they are expressed in p.u. of the fundamental. Higher levels of THD_v mean higher levels of voltage harmonics in the spectrum of supply voltage causing the increasing corresponding current harmonics.

Conclusion

Frequency converters used in structures of the adjustable speed drives and operating in various technological applications represent significant sources of harmonic currents resulting in a negative impact on quality of supply voltage and operation characteristics of devices connected to the power network. The levels of harmonics are affected in different ways. In the paper, the influence of drive loading and levels of THD_V of supply voltage on harmonic currents is presented. To reduce them, various technical solutions of variant levels of harmonic mitigation effectiveness are accepted and implemented into structures of the adjustable speed drives. This paper provides the comparison of the 3% AC input reactor, broad-band harmonic filter and active front end rectifier with the case if no filtering is used in the drive structure. As seen in figures, the broad-band harmonic filter and active front end rectifier provide the significant reduction of drive-generated harmonics in the wide range of drive loading and supply voltage distortion.

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