The influence of the dead time duration and switching frequency on the input current distortion of voltage-source active rectifiers

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***Abstract* – This paper is focused on the influence combinations of the dead time duration and switching frequency on the drawn current from the grid by voltage-source active rectifiers. Newly the various definitions of the total harmonic distortion of the current are used. According to the EU standard the total harmonic distortion of the current is calculated up to the 50th harmonic; this definition of the total harmonic distortion shows anomalies for higher switching frequencies. The aim of this paper is to present occurrence of harmonics at frequencies above 2.5 kHz (out of EU standard) and to point out the case of voltage-source active rectifiers operation at a grid resonance frequency.**

Keywords-current harmonic, harmonic analysis; pulse width modulation; voltage-source active rectifier, total harmonic distortion.

I. Introduction

This paper follows the authors' previous publications which are focused on the harmonics of the current drawn from the grid by voltage-source active rectifiers. The calculations of the input current harmonics are based on the theory of a pulse width modulation that is presented in the publications [1] – [5]. With regard to these calculations the paper [6] proposes simple calculations of the input current harmonics values according to the equivalent circuit of the voltage-source active rectifier. From the literature it is obvious that the harmonics in the input current spectrum appear around the switching frequency and its multiples this is shown in equation (1) published in [6]. These harmonics values around the switching frequency are independent on the load of the active rectifier. This leads to the fact that the input current harmonics values are inappropriately expressed in the high relative values if the load is low percentage of the converter nominal load that is discussed in paper [7] and [8].

$$\begin{aligned} B_h &= 2(hm_F + 1)f_m \\ \Delta f_h &= hf_{sw} \pm f_m \end{aligned} \quad (1)$$

With regard to the equation (1) the harmonic order is dependent on the switching frequency; the paper [9] describes graphs showing the effect of the switching frequency on the input current harmonics and total harmonic distortion of the current. This publication discusses that the total harmonic distortion of the current is low in relation to the nominal load, if the switching frequencies are higher than 2 kHz. This fact shows that the total harmonic distortion of the current is necessary to express with respect to the nominal load, otherwise the results are misinterpreted and the suitability of pulse rectifiers can be assessed wrongly.

The paper [10] deals with the influence of the dead times duration of semiconductors switches used in power electronics. This publication describes analysis of the dead times and presents that the input current spectrum does not consist only of the harmonics according to the equation (1); other harmonics corresponding to the equation (2) appear in the input current spectrum, these harmonics are called characteristics harmonics:

$$h = kp \pm 1, \quad (2)$$

where h is a harmonic order, k is an integer and p is pulsation of a converter. The paper [10] shows the effect of the switching frequency and dead time duration on these characteristics harmonics.

The aim of the present paper is the simultaneous influence of the switching frequencies and the dead times durations on the whole current spectrum (over 2 kHz) and on the total harmonic distortion.

II. Waveforms of the Input Current and Their Harmonic Analysis

This part presents the waveforms of the input current i_a and its harmonics analysis if the switching frequency f_{sw} and the dead time duration t_d are set to two different values. The harmonic analysis are performed up to 10 kHz (up to the 200th harmonic), because one of the aims of the paper is to show the vision of this methodology which is out of EU standard [11] (this standard recommends to perform the harmonic analysis up to 2.5 kHz – the 50th harmonic). The methodology can be applied to converters with high performance and high switching frequency.

With regard to power switches properties and to the objective of the paper, the switching frequency f_{sw} is set to the low and high value, the dead time duration t_d is set to 0s and 6 μs:

a) f_{sw}=*1.5kHz* and t_d=*0s,*

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b) f_{sw}=1.5kHz and t_d=6μs,

c) f_{sw}=6kHz and t_d=0s,

d) f_{sw}=6kHz and t_d=6μs.

Figure 1 presents input current waveform if the switching frequency is low and the pulse width modulation is ideal. The input current follows the sine wave and it is distorted. Figure 2 shows harmonic analysis of the input current. The harmonics appear around the switching frequency and its multiples according to equation (1). The characteristics harmonics are not in the spectrum, because the pulse width modulation is ideal (t_d=0s).

Figure 1. Waveform of the input current i_a (f_{sw}=1,5kHz, t_d=0μs)

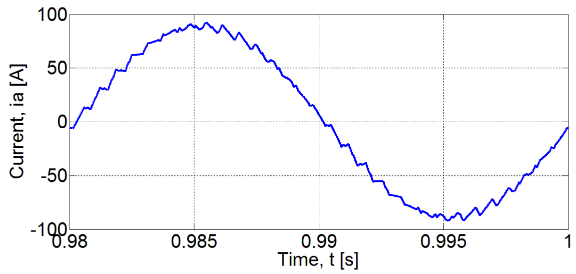


Figure 2. Harmonic analysis of the current i_a in Fig. 1

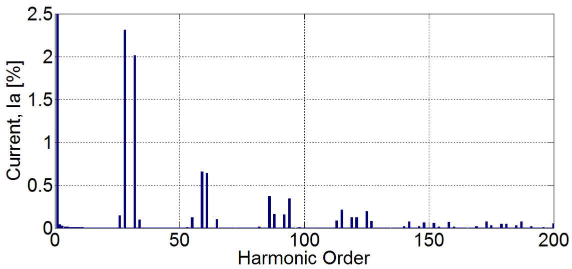


Figure 3 presents the input current waveform if the switching frequency is set to the above value and the dead time duration is set to 6 μs. Figure 4 shows the harmonic analysis of this waveform. It is obvious that the harmonics appear around the switching frequency and the dead times costs characteristics harmonic mainly the 5th harmonic. Figure 5 presents detail of the 5th harmonic that corresponds to the equation (2).

Figure 3. Waveform of the input current i_a (f_{sw}=1,5kHz, t_d=6μs)

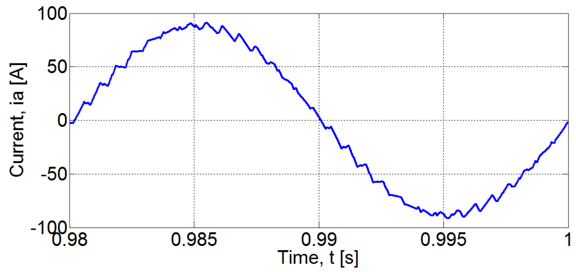


Figure 4. Harmonic analysis of the current i_a in Fig. 3

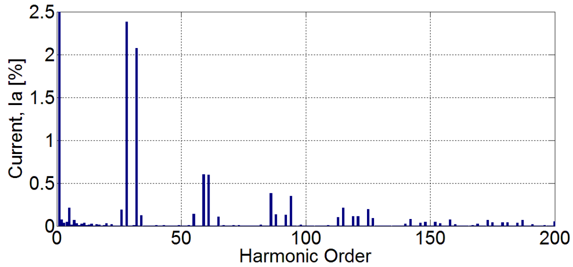
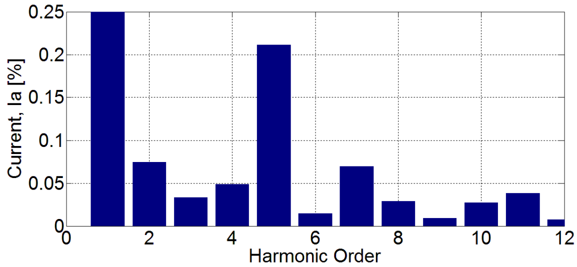


Figure 5. Detail on the 5th harmonic in Fig. 4



Figures 6 and 7 illustrate the input current waveform and its harmonic analysis if the switching frequency is high and the pulse width modulation is ideal. The current waveform is little distorted and harmonics in the input current spectrum appear only around the switching frequency.

Figure 6. Waveform of the input current i_a (f_{sw}=6kHz, t_d=0μs)

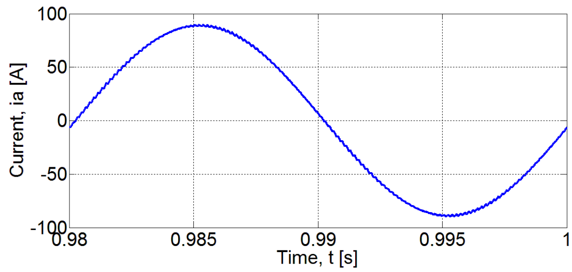
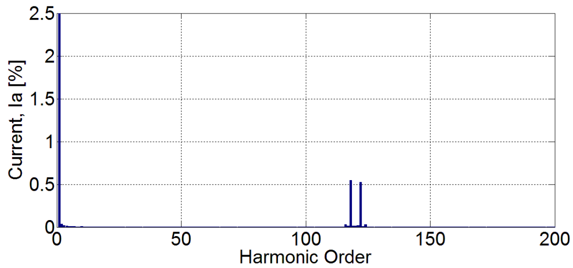


Figure 7. Harmonic analysis of the current i_a in Fig. 6



Figures 8 and 9 show the input current waveform and its harmonic analysis if the switching frequency is high and the dead time duration is set to 6 μs. The characteristics harmonics caused by the dead times and harmonics around the switching frequency appear in the input current spectrum. The highest current harmonic is the 5th harmonic. The dead time duration has a main effect on the current spectrum. The influence of the dead times is more significant than in figures 4 and 5 where the switching frequency is low.

Figure 8. Waveform of the input current i_a (f_{sw}=6kHz, t_d=6μs)

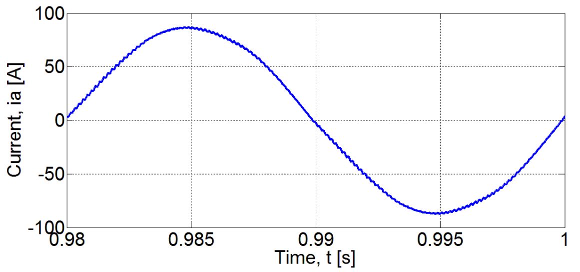


Figure 9. Harmonic analysis of the current i_a in Fig. 8

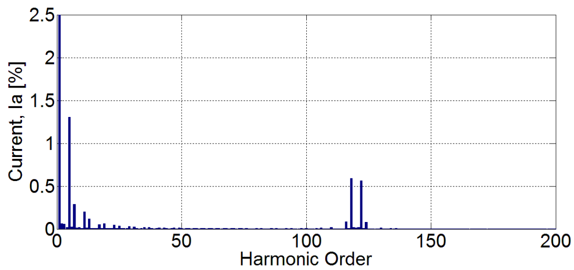


Figure 10. THDI calculated up to 50[th] harmonic according to the EU standard

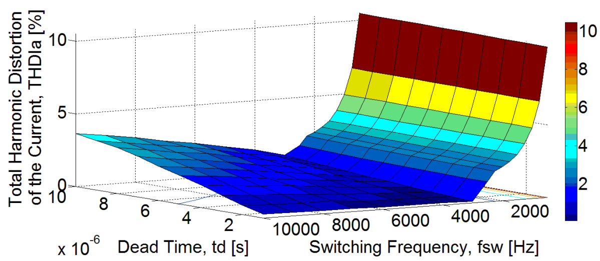
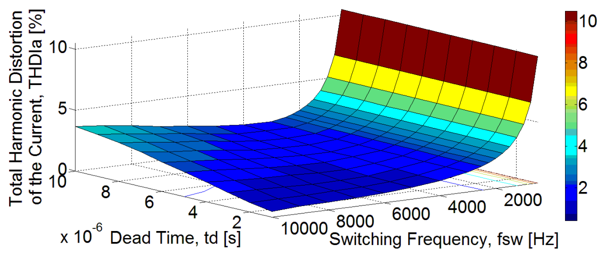


Figure 11. THDI calculated up to 200[th] harmonic



The above waveforms and harmonic analysis illustrate that the effect of the dead time duration is low, if the switching frequency is low too. The influence of the dead time duration is not negligible, if the switching frequency is high. Harmonics around the switching frequency and characteristics harmonics appear in the input current spectrum.

III. VALUES OF THE TOTAL HARMONIC DISTRTION OF THE CURRENT - THD_I

The calculations (3) that is used in literature as a symbol of the total harmonic distortion is calculated up to the 50[th] harmonic (H=50) in accordance with the EU standard [11]. This definition of the total harmonic distortion is used even when the switching frequency is higher than 2.5 kHz.

$$THD_I = \sqrt{\sum_{h=2}^{H}\left(\frac{I_h}{I_1}\right)^2} = \frac{\sqrt{\sum_{h=2}^{H} I_h{}^2}}{I_1} \quad (3)$$

This part of the paper discusses the calculations of the THD_I depending on the switching frequency and dead time duration if the two definitions of THD_I are applied. First, the THD_I is calculated up to 2.5 kHz (H=50) with regard to the EU standard recommendation [11] that is shown in figure 10. Second, the THD_I is calculated up to 10 kHz (H=200) that is illustrated in figure 11.

The frequency of 10 kHz is chose with regard to the possible switching frequency values of power active rectifiers. Figures 7 and 9 present that the harmonics higher than 2.5 kHz appear in the current spectrum. The aim of the THD_I calculation up to 10 kHz is to discuss the influence of the current harmonics frequencies according to the equation (1) that are higher than the 50[th] harmonic.

Figure 11 presents that the effect of the dead time duration is negligible if the switching frequency is low (up to 2 kHz); the total harmonic distortion of the current THD_I drops to 2%. In this case the total harmonic distortion of the current can be calculated according to the EU standard up to the 50[th] harmonic. If the switching frequency is higher, the influence of the dead time duration is greater especially for the dead time duration higher than 5 μs and for the switching frequencies higher than 6 kHz.

IV. CONCLUSION

The paper deals with the effect of the dead time duration on the harmonics values of the current drawn from the grid by voltage-source active rectifiers. If the switching frequency of the active rectifier switched by pulse width modulation is high, the dead time duration costs an increase in the values of the input current harmonics and of the total harmonics distortion of the current.

The paper shows that the increase of the total harmonic distortion of the current and current harmonics can be significant with regard to the increasing switching frequency of the semiconductors elements and high converters performance. It is important to consider the appropriate definition of the total harmonic distortion of the current. The paper can be support for revision of the standard dealing with the high-frequency range of the current and voltage harmonics.

This contribution also points to the danger of these input currents (especially high switching frequencies) if the voltage harmonics emergence is investigated when active rectifiers operate at a grid resonance frequency.

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