Chapter 11

High Frequency Harmonics Emission in Smart Grids

Jaroslaw Luszcz

Additional information is available at the end of the chapter

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1. Introduction

The term 'smart grid', is nowadays very often used in many publications and so far has not been explicitly defined, however it refers mainly to such an operation of electricity delivery process that allows to optimize energy efficiency by flexible interconnection of central and distributed generators through transmission and distribution system to industrial and consumer end-users [1], [3], [11], [13], [15], [17]. This functionality of power delivery system requires the use of power electronic converters at generation, consumer and grid operation levels. Harmonic pollution generated by power electronics converters is one of the key problems of integrating them compatibly with the power grid, especially when its rated power is high with relation to the grid's short-circuit power at connection point [18], [19], [20].

Contemporary power electronics converters has already reached rated power of several MW and are integrated even at the distribution level directly to medium voltage (MV) grid. Power electronics technologies used nowadays in high power and MV static converter increase the switching frequency significantly due to the availability of faster power electronic switches which allows to increase power conversion efficiency and decrease harmonic and inter-harmonic current distortion in frequency range up to $2\,kHz$. This trend significantly increases harmonic emission spectrum towards higher frequencies correlated with modulation frequency of switching conversion of power. Therefore typical harmonic analysis up to $2\,kHz$ in many power electronics application requires to be extended up to frequency of $9\,kHz$ which is the lowest frequency of typical electromagnetic interference analysis interest. Numerous problems related to current and voltage harmonic effects on contemporary power systems are commonly observed nowadays, also in frequency range $2-9\,kHz$. Levels and spectral content of current distortions injected into electric power grids are tending to increase despite the fact that the acceptable levels are determined by numerous regulations [2], [3], [7], [9], [12], [14], [16].

In recent years many of grid-side PWM boost converters of relatively high rated power have been introduced into power grid because of many advantages, like for example:

current harmonics limitation, reactive power compensation and bidirectional power flow. Implementation of smart grids idea will conceivably increase this tendency because of the need for bidirectional flow control of high power in many places of distribution and transmission power grid.

Typical carrier frequencies used in AC-DC PWM boost converters are within a range from single kHz for high power application up to several tens of kHz for small converters. Important part of conducted emission spectrum generated by those types of converters is located in frequency range below 2 kHz normalized by power quality regulations and above 9 kHz normalized by low frequency EMC regulation (especially CISPR A band 9kHz-150kHz). In between those two frequency ranges typically associated with power quality (PQ) and electromagnetic compatibility (EMC) respectively, where a characteristic gap of standard regulations still exists, the conducted emission of grid-connected PWM converters can be highly disturbing for other systems. Current and voltage ripples produced by grid-connected PWM converters can propagate through LV grids and even MV grids, where converters of power of few MW are usually connected. Filtering of this kind of conducted emission will require a new category of EMI filters with innovative spectral attenuation characteristic which is difficult to achieve by just adaptation of solutions that are already in use for current harmonics filtering for PQ improvement and radio frequency interference (RFI) filters used for EMC assurance.

2. Harmonic emissions of non-linear loads into power grid

Harmonics content defined for currents and voltages is an effect of its non sinusoidal wave-shape. Power electronics switching devices used in power conversion process like diodes, thyristors and transistors change its impedance rapidly according to line or PWM commutation pattern and produce non sinusoidal voltages and currents which are required to perform the power conversion process properly. Unfortunately, these non sinusoidal currents, as a results of internal commutation process in a converter, are also partly injected into the power grid as an uninvited current harmonic emission. Non sinusoidal load currents charged from power grid produce voltage harmonic distortions in power grid which can influence all other equipment connected to that grid because of the existence of grid impedance. This mechanism results that non-linear current of one equipment can be harmful for other equipment supplied from the same grid and also for the grid itself, like e.g. transformers, transmission lines.

A frequency spectrum range of harmonic distortions introduced into power grid can be exceedingly wide, nevertheless the maximum frequency range which is usually analysed is defined by CISPR standard as $30MHz$. Between $9kHz$ and $30MHz$ two frequency sub-bands are defined as CISPR A up to $150kHz$ and CISPR B above $150kHz$ (Figure 1). These two frequency rages are well known as conducted electromagnetic interference (EMI) ranges, where harmonic components of common mode voltages or currents are limited to levels defined by a number of standards.

In general, despite some specific cases, amplitudes of harmonic distortions observed in typical applications decrease with the increase of frequency, stating from several or tens percent in frequencies close to the power frequency and reach levels of only microvolts or microamps for the end frequency of conducted frequency band $30MHz$. Unfortunately, even so small voltage and current amplitudes can be really harmful, disturbing, and difficult to

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filter because of relatively high frequency which results with easiness of propagation by means of omnipresent parasitic capacitive couplings.

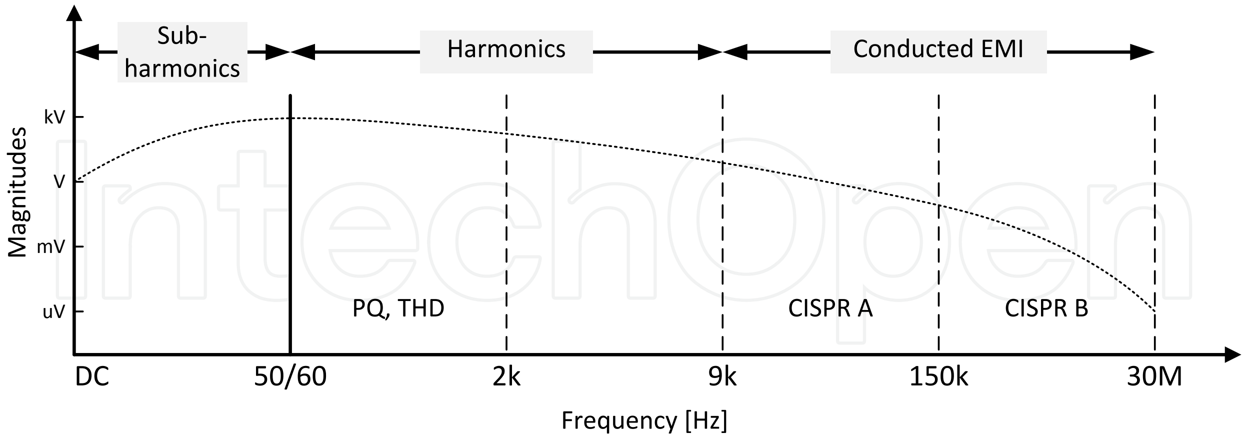

Figure 1. Harmonic distortions frequency sub-ranges.

On the other hand, typical harmonic distortion components which are usually recommended for analysing and solving PQ problems by standards are within frequency range up to $2kHz$. In this frequency range integer multiples of the fundamental power frequency ($50Hz$ or $60Hz$) harmonic components are defined usually up to 40^{th} order.

Consideration of conducted emissions and harmonic distortions in these frequency bands: one up to $2kHz$ and second $9kHz - 30MHz$, were sufficient enough in last years in applications with classic line-commutated rectifiers and switch mode DC power supplies which are also fed by this type of rectifiers. During the last decades, with the increase of the rated power of single power supplies and increasing number of power supplies used the increased difficulties with acceptable current harmonic emission levels arise and other technologies like PWM boost rectifiers have been intensively introduced. The PWM modulation carrier frequency used in such applications is often within the range of $2 - 9kHz$ or adjacent ranges, which results with the significant increase of harmonic emission in this frequency range what will be discussed in the next sections of this chapter.

3. Harmonic distortions emission of grid-connected power electronics converters

Harmonic distortion emission is commonly understood as harmonics produced by non-linear loads, usually power electronics converters in the frequency range up to $2kHz$ which are strongly related to some of the power quality indices. From this point of view (PQ) harmonic distortion emission in the frequency range above $2kHz$ can be named as high frequency harmonics emission. On the other hand, from the EMC point of view, the conducted EMI emission below $9kHz$ is usually defined as low frequency EMC conducted emission.

The frequency map of different harmonic emissions, usually considered as conducted type emissions which are mainly propagating by conduction process along power lines, is presented in Figure 2. From this prospective we can distinguish three primary types of harmonic distortion emission of typical sources which can be associated to particular power electronics converters topologies and technologies. These are:

- classic PQ frequency range up to $2kHz$, where the main sources of harmonic distortions are usually line commutated rectifiers used in single- and multi-phase topologies using as power switches diodes or thyristors,
- high frequency harmonic distortion emission in the frequency range $2-9kHz$, where mainly PWM boost rectifiers, as a relatively new topology, are generating harmonic components correlated to the used PWM carrier frequency which depending on the topology and rated power of the converter is usually located between a few kHz and tens of kHz,
- conducted EMI emission in frequency range ($9kHz - 30MHz$), which is primarily an effect of DC voltage conversion by switching mode methods where power transistor switching processes are key sources of high frequency conducted emission which can easily propagate also towards AC power lines.

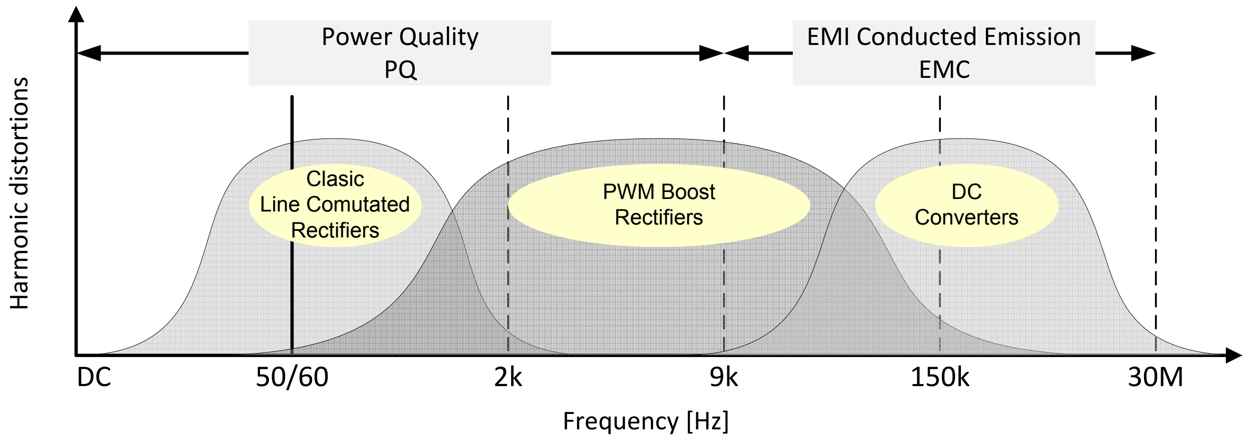

Figure 2. Characteristic distribution of harmonic emission spectra for different types of power electronics converters.

3.1. Low frequency harmonic emission of classic AC-DC converters

Classic, diode-based AC-DC converters (rectifiers) were successfully used for many years in multiple applications. Nowadays, because of extremely increasing number of such devices used in power system and significantly increasing its rated power, AC-DC converters for power of hundreds of kW are quite often used, its harmonic emission levels cannot be accepted by power grid operator demands. Significantly increasing problem of harmonic distortions in power grid led to legislation numerous of grid regulations which are set-up by grid operators and international standards. A typical configuration of six pulse three phase diode rectifier with DC link capacitor commonly used in medium power applications is presented in Figure 3 .

The exemplary input current waveform for this type of rectifier is presented in Figure 4 with correlation to input AC voltage. The maximum value of line current and its flow duration which is in six pulse rectifier always shorter than half cycle are accountable for the level of distortion. These parameters of current wave-shape are dependent of grid impedance and DC link capacitor parameters, especialy size, equivalent serial resistance (ESR) and equivalent serial inductance (ESL) In the evaluated case significant distortion of input current I_{AC} make a distortion effects slightly visible also at voltage waveform, where voltage deformations are correlated in time with the current pulses.

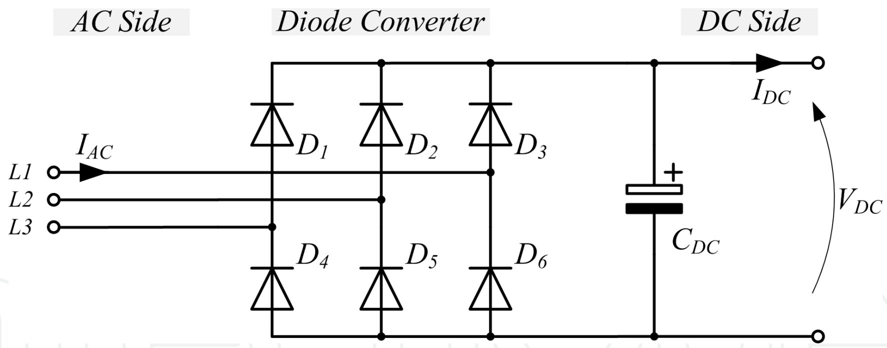

Figure 3. Six pulse diode rectifier with DC link capacitor.

The frequency domain representation of input current, calculated for 10 cycle period with rectangular widowing as a discrete Fourier transform (DFT) product [8] is presented as harmonic amplitudes I_k with $5Hz$ resolution in frequency range up to $2kHz$ in Figure 5 and up to $25kHz$ in Figure 6 . The characteristic harmonics for six-pulse rectifier are non nontriplen odd harmonics (5th, 7th, 11th, 13th etc.) and its amplitudes decrease with frequency

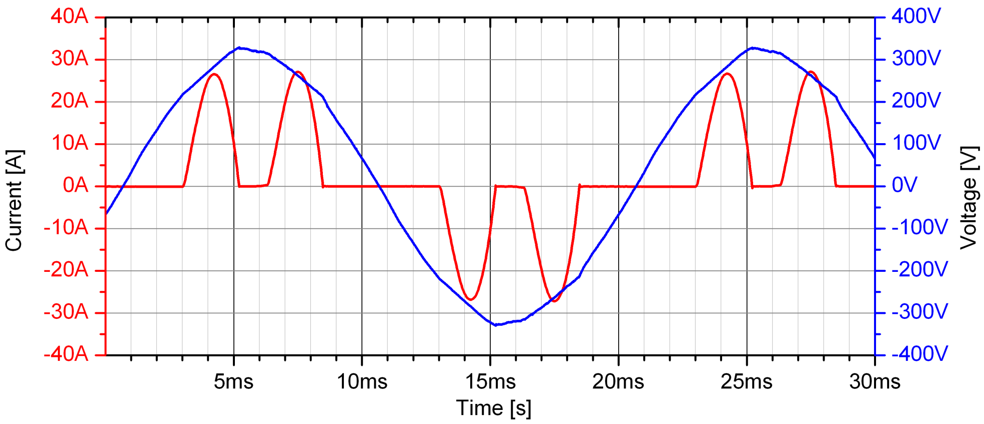

Figure 4. Six pulse diode rectifier - typical input current and voltage waveforms.

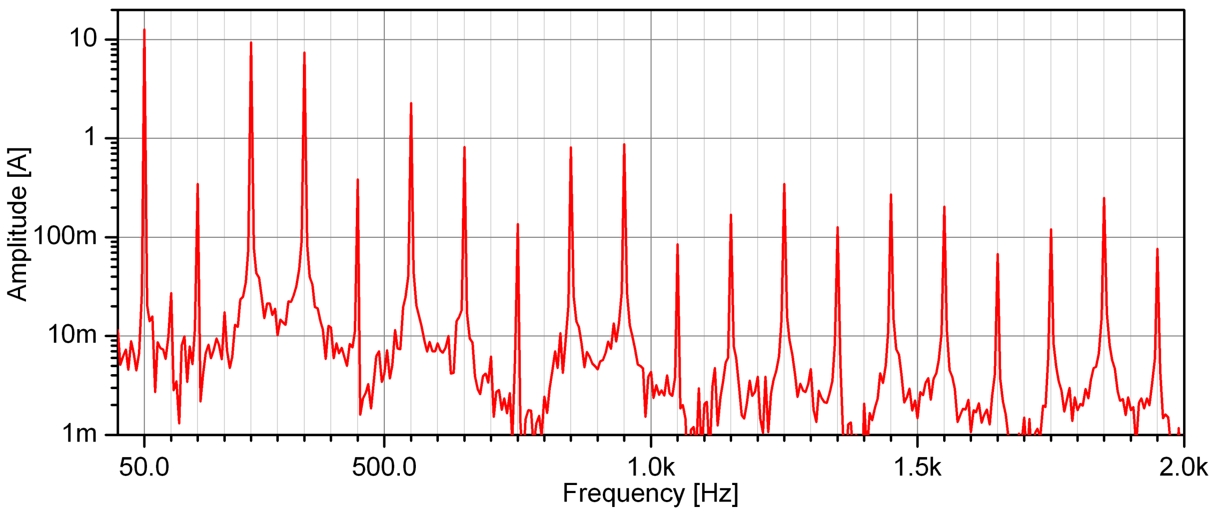

Figure 5. Six pulse diode rectifier - typical input current harmonics spectrum up to 2kHz.

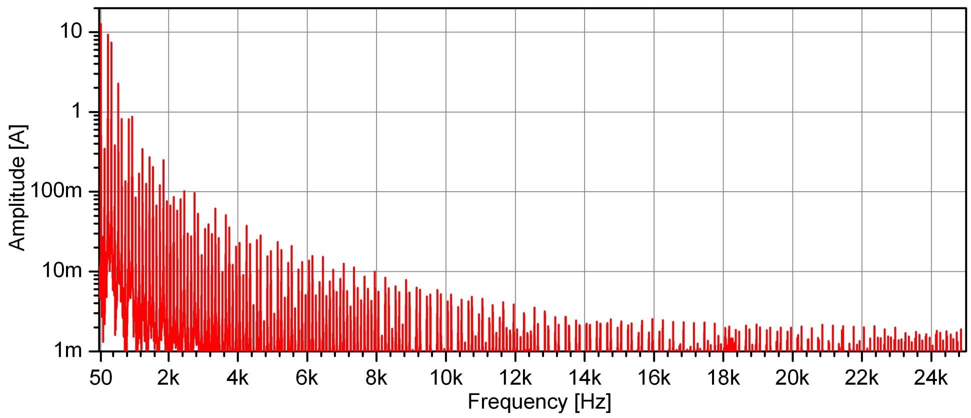

Figure 6. Six pulse diode rectifier - typical input current harmonics spectrum up to 25kHz.

The total harmonic distortion (THD) content of input current can be calculated using formula (1) where each harmonic group I_n is determined according to formula (2) . In the analysed example presented in Figure 4 the obtained THD was over 95%. To reduce so high harmonic emission number of passive filtering techniques can been introduced. AC reactors (L_{AC}) and DC chokes (L_{DC}) (Figure 7) are typically used and allow to decrease input current THD below 30%. Adequate input current waveform and its frequency domain representation for diode rectifier with passive filtering are presented in Figure 8, 9 and 10.

$$THD(I) = \frac{\sqrt{\sum_{n=2}^{40} I_n^2}}{I_1} \tag{1}$$

$$I_n = \sqrt{\frac{{I_{k-5}}^2}{2} + \sum_{i=k-4}^{k+4} I_i^2 + \frac{{I_{k+5}}^2}{2}} \tag{2}$$

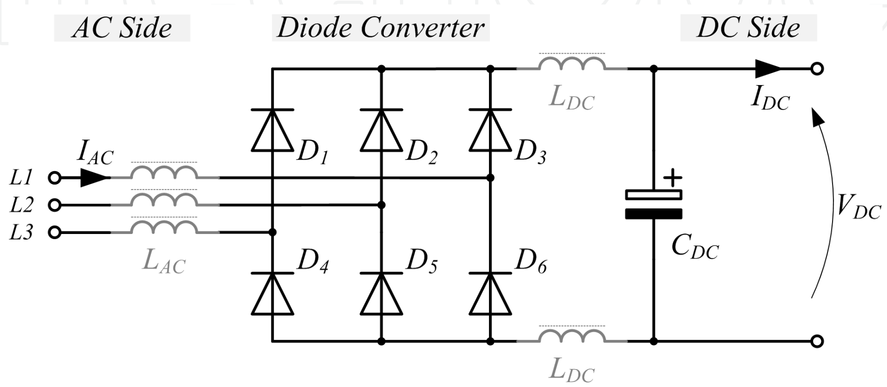

Figure 7. Six pulse diode rectifier with passive filtering of line current harmonic distortions.

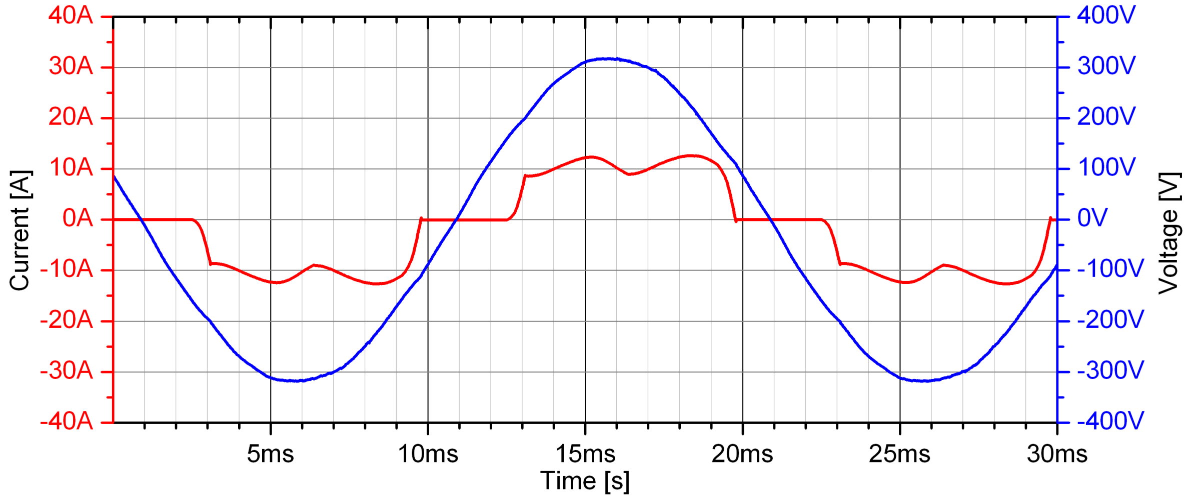

Figure 8. Six pulse diode rectifier with passive filtering - input current and voltage waveforms.

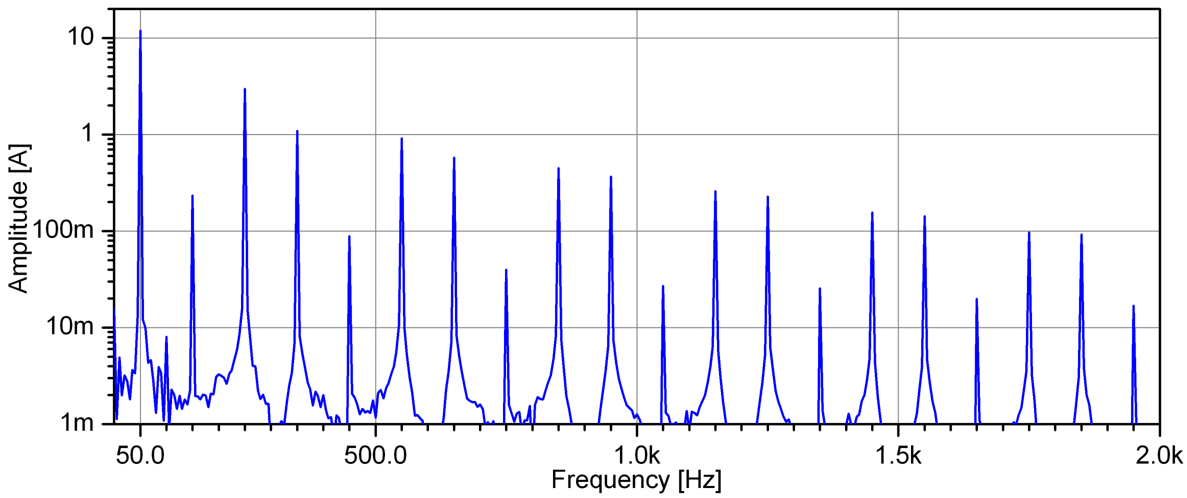

Figure 9. Six pulse diode rectifier with passive filtering - input current harmonics spectrum up to 2kHz.

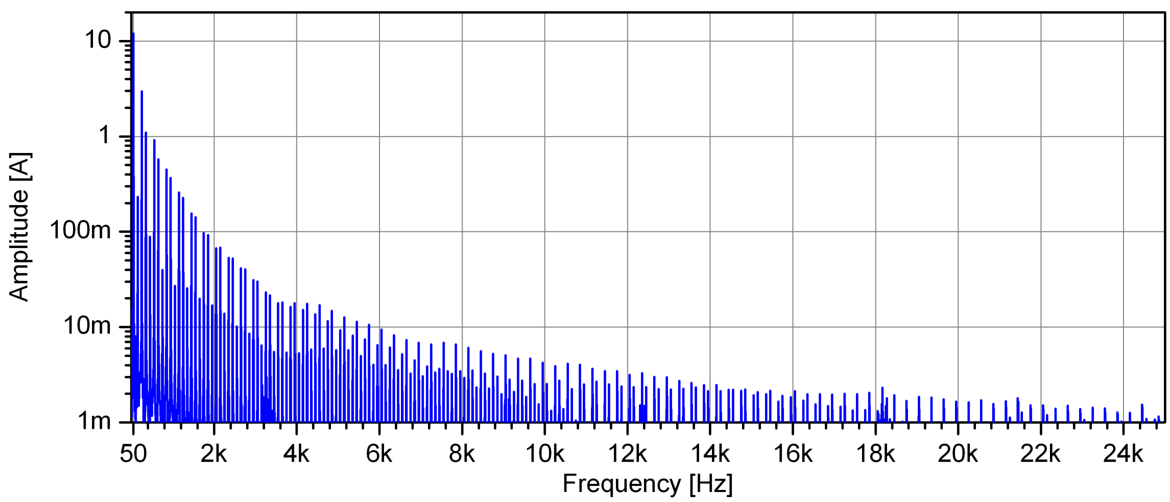

Figure 10. Six pulse diode rectifier with passive filtering - input current harmonics spectrum up to 25kHz.

3.2. High frequency harmonic emission of modern AC-DC converters

Severe limitations of the line current harmonic performance improvement possibilities of classic diode rectifiers stimulate introducing fully controlled switches in AC-DC converters. Accompanying significant increase of IGBT transistor performance during the last decade allows to obtain successful implementation of PWM boost AC-DC three phase converter topology in many applications where harmonic distortion emission has to be limited. PWM boost type AC-DC converters besides line current harmonic distortion significant reduction in frequency range up to $2kHz$ have a number of other advantages [4], [5], [10], like for example:

- ability to transform energy bidirectionally, which significantly increases the range of applications especially in energy saving purpose and renewable and distributed energy systems,
- possibility to control line current phase, which allows to maintain reactive power consumption within required limits and also stand-alone operations as a power factor correction system,
- autonomous operation as a harmonic distortion compensator for other non-linear loads working in the power grid.

PWM boost rectifier basic topology is based on the six pulse power transistors bridge which is connected to power grid through AC line reactor (Figure 11). AC line reactor L_{AC} allows to control line current freely using suitable PWM strategies, which results in a possibility to considerably decrease the line current harmonic emission level in frequency range below $2kHz$. Essential problem, tightly related to the current harmonic distortion emission in the frequency range close and above PWM modulation carrier frequency are input current ripples which are an effect of line and DC bus voltage commutations over the AC line reactor inductance L_{AC} (Figure 12).

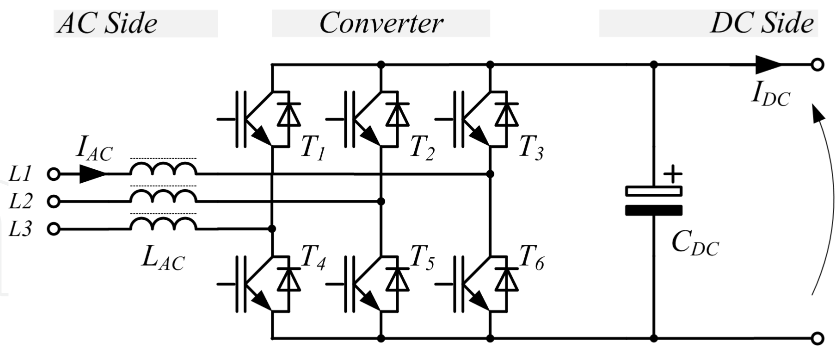

Figure 11. Three-phase grid connected PWM boost converter topology.

The exemplary line current waveform obtained using this method is presented in Figure 13, where nearly sinusoidal current can be seen with low harmonic content in frequency band below $2kHz$ (Figure 14), however with some noticeable distortions in higher frequency range which are an effect of existing limitations of the used PWM control method. To minimize the PWM carrier frequency related harmonic emission low pass filtering methods are used,usually based on the LCL filter topology. Nevertheless, the harmonic emission effect correlated with PWM carried frequency is observable in most of applications (Figure 15). The

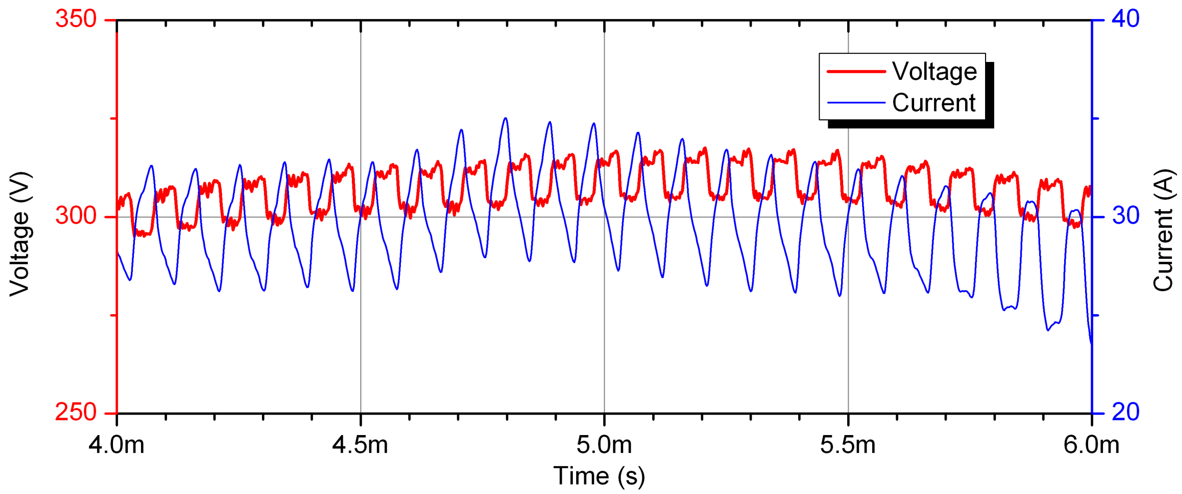

Figure 12. Line current and voltage ripples generated by PWM boost converter

maximum emission is observed around modulation frequency which in the tested converter was set to 15kHz. In higher frequency range, close to integer multiples of PWM carrier frequency harmonic products of modulation are usually also observed. Perfect elimination of this PWM-related emission is not possible and became more difficult to realize by using passive filters with the increase of frequency. An example of input current and voltage waveforms and its harmonic content in frequency domain representation recorded in PWM boost converter are presented in Figure 13, 14 and 15.

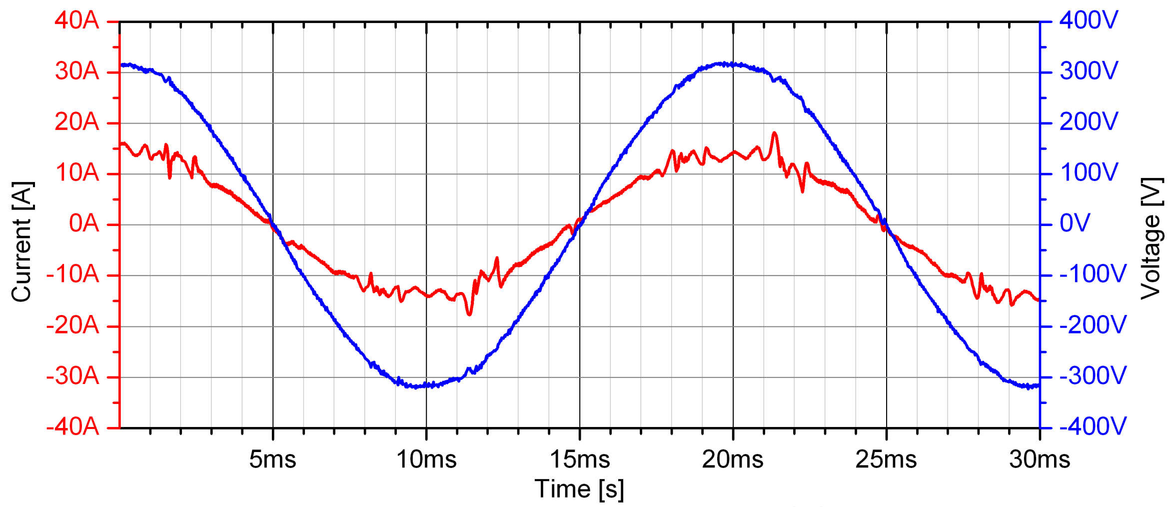

Figure 13. PWM boost converter – input current and voltage waveforms.

3.3. Comparison of line current harmonic distortion of diode and PWM boost rectifiers

Detailed comparison of current harmonic distortion emission has been done for three phase six pulse diode rectifier and PWM boost converter with the three phase IGBT transistor bridge. Both converters has been tested in similar supply condition and using similar load, which allows to minimize the influence of line impedance and DC load level on the obtained results. Comparison of input current harmonic distortion emission should be carried out

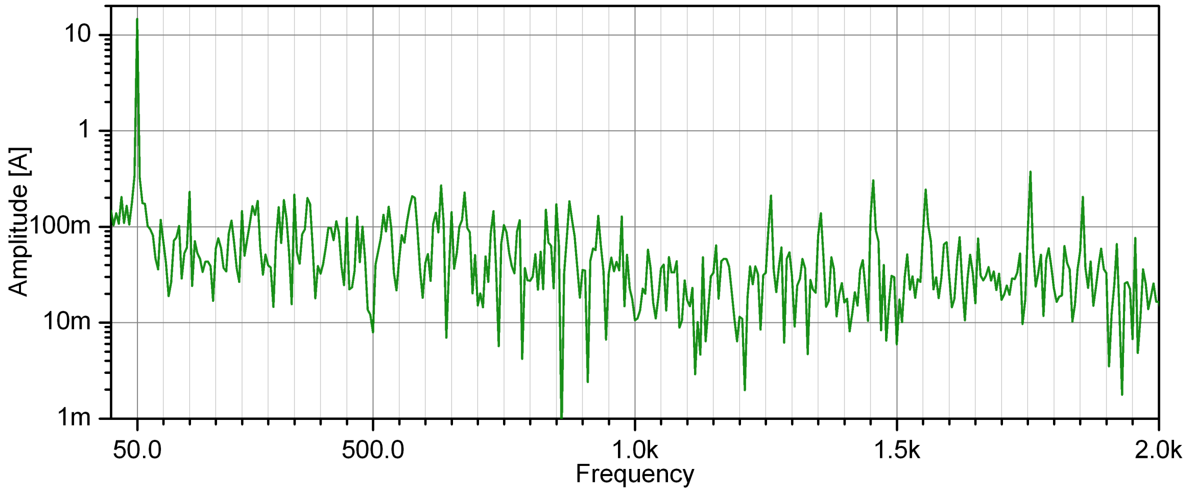

Figure 14. PWM boost converter – input current harmonics spectrum up to 2kHz.

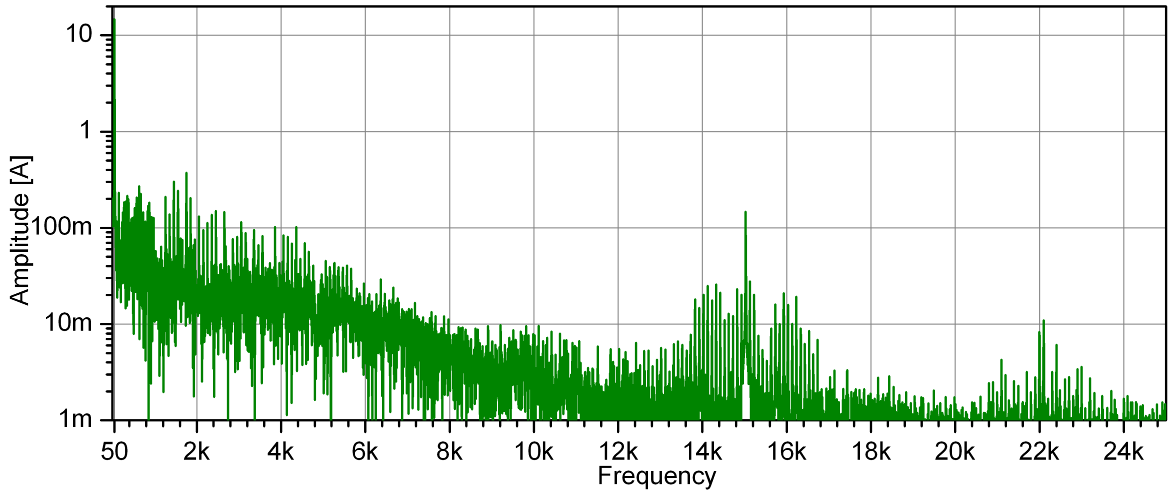

Figure 15. PWM boost converter – input current harmonics spectrum up to 25kHz.

separately for different frequency sub-ranges presented in Figure 1 and 2, because of different evaluation methods which have to be used in each particular sub-range.

3.3.1. Frequency range up to 40^{th} *harmonic order*

Typical analysis, important from the total harmonic distortion (THD) limitations point of view, consider frequency range up 40^{th} harmonic order of power frequency (in $50Hz$ system it is up to $2kHz$). In this frequency range classic line commutated rectifiers generate dominating characteristic harmonics orders $n * (p \pm 1)$ correlated with number of pulses p depending on rectifier topology. According to this rule, for six pulse rectifiers harmonics of order H5, H7 and H11, H12 and H17, and 19 etc. are dominating (Figure 16 blue line).

The use of PWM boost conversion technology allows to decrease harmonic emission for this specific orders significantly (about tens of times for H5 and H7, about ten times for H11, H13 and H17, H19). Unfortunately, use of PWM boost conversion technology introduces extra harmonic components emission for frequencies values in between integer multiples

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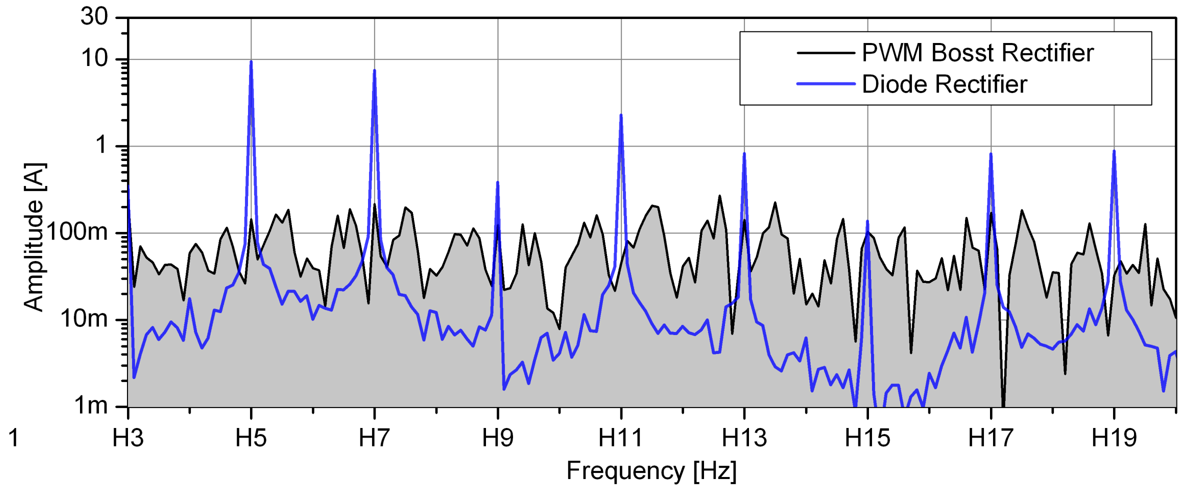

Figure 16. Harmonic emission of three phase six pulse diode rectifier with comparison to PWM boost converter emission

of power frequency: inter-harmonics (Figure 16 grey area). Detailed calculation results are presented in Table 1, where the decrease of harmonics content from 97% down to 3.5% and increase of inter-harmonics from 2% up to 10% are listed. The final effect of obtained harmonic reduction using PWM boost technology is the decrease of THD from 97% to 11% whereas inter-harmonic content is considerable: around 10%.

AC-DC Converter topology	Harmonics	Inter-harmonics	THD	PWHD
Diode rectifier	97%	2%	97%	48%
Diode rectifier with passive filtering	29%	0.5%	29%	28%
PWM boost converter	3.5%	10%	11%	34%

Table 1. Comparison of current harmonic distortion emission spectra of different AC-DC converters topologies

Higher order harmonic distortion of line current is particularly important in several applications because of its disturbing potency in power grid. To asses the certain limitation levels in standard [6] partial weighted harmonic distortion (PWHD) is extra defined using formula (3). According to this rule, harmonics above 14^{th} order up to 40^{th} order are considered with the weighting factor increasing with harmonic order. The best performance in terms of PWHD index, have been observed for diode rectifier with passive filters: only 28% (Table1). For the PWM boost converter and diode rectifier without passive filter PWHD index is substantially higher: 43% and 48% respectively.

$$PWHD(I) = \frac{\sqrt{\sum_{n=14}^{40} nI_n^2}}{I_1} \tag{3}$$

3.3.2. Frequency range $2 - 9kHz$

Harmonic distortions in frequency range up to $9kHz$ are characterized in standard [8] as a result of grouping of harmonics DFT product obtained for 5 cycles of observation within $200Hz$ sub-bands using rectangular window. Proposed grouping method results with 35 sub-bands (groups) H_g, $200Hz$ wide each with the center frequencies of the band starting from $2.1kHz$ up to $8.9kHz$. Grouping algorithm is represented by formula 4.

$$H_{g(200Hz)} = \sqrt{\sum_{k=g-90Hz}^{g+100Hz} {I_k}^2} \tag{4}$$

For the purpose of comparison of current harmonic emission of the diode rectifier and PWM boost converter the FFT analysis has been done according to [8]. To demonstrate more clearly the effect of harmonic emission character the raw DFT product in frequency range $2 - 9kHz$ is presented in Figures 17 and 18.

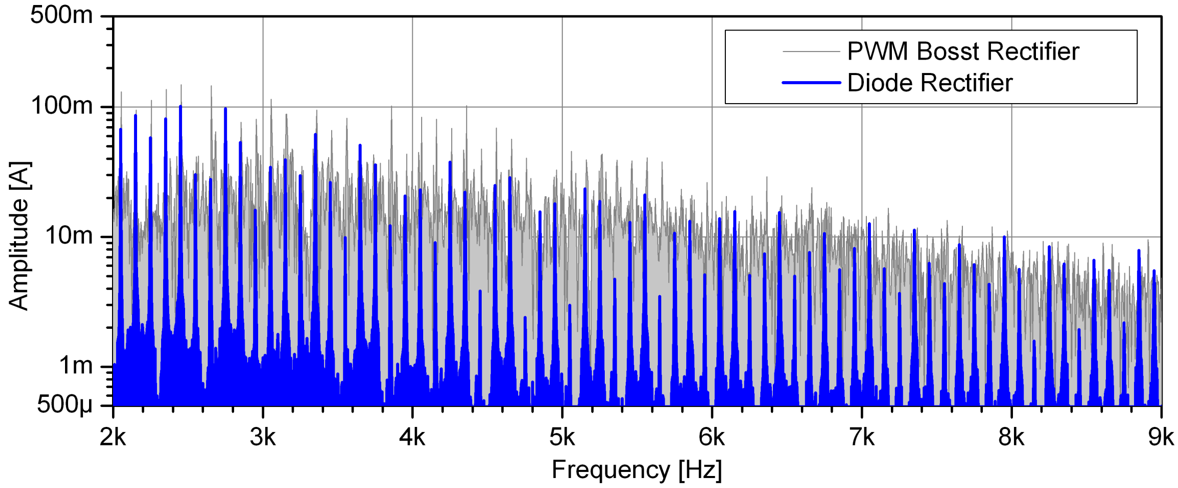

Figure 17. Comparison of harmonic emission of three phase six pulse diode rectifier and PWM boost converter in frequency range $2 - 9kHz$.

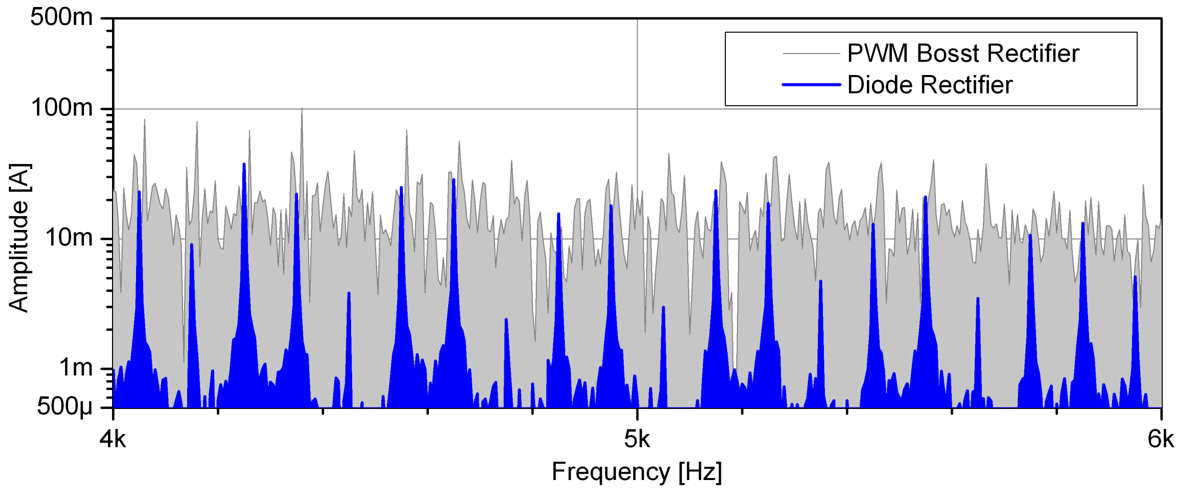

Figure 18. Comparison of harmonic emission of three phase six pulse diode rectifier and PWM boost converter - more detailed view at some exemplary frequency sub-range.

The obtained results show that the use of PWM boost converter do not change significantly current harmonic amplitudes for the frequencies close to integer multiples of the fundamental power frequency with relation to diode rectifier results, they are roughly at similar level. However, inter-harmonic emission for PWM boost converter is more or less at the same level as harmonics (Figure 18), whereas for diode rectifier inter-harmonic levels were in average at least more than ten times lower, which results with increase of power spectrum density in the whole frequency band. By employing the grouping method of harmonic content proposed in standard [8] the total power of harmonic emission within each of 200Hz wide frequency sub-range can be calculated using formula 4 . This standardized analysis shows a significant increase of total spectral power emission of PWM boost rectifier in relation to diode rectifier (Figure 19), whereas the maximum individual amplitudes of DFT product for both converters are at similar level (Figures 17 and 18).

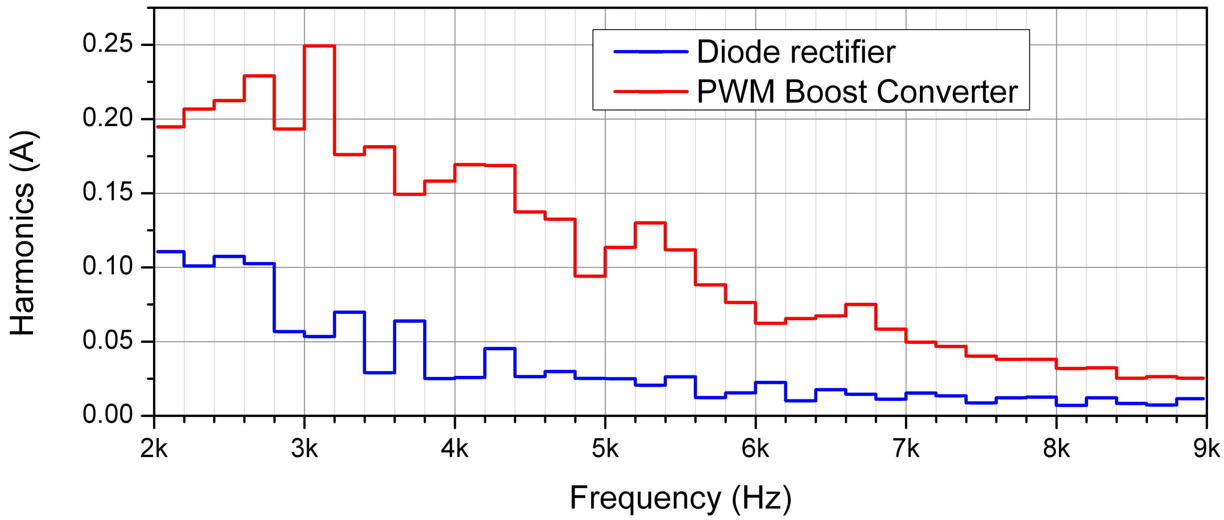

Figure 19. Comparison of harmonic emission of diode rectifier and PWM boost converter.

3.3.3. PWM carrier frequency range

Values of PWM carrier frequency used in typical applications are mainly correlated with converter's input voltage and its rated power. In contemporary applications of PWM boost rectifiers modulation frequency values are usually in a range of few kHz for high power converters (above hundreds of kW) up to tens of kHz low power converters (below kW). This frequency range is located just above power quality frequency range and includes significant part of CISPR A range (Figure 1). PWM carrier frequency and its integer multiples define frequency sub-rages, where increased current harmonic emissions usually appear. There are known different method of decreasing this emission, nevertheless it is difficult to eliminate them entirely by for example passive filtering.

In the evaluated converter modulation carrier frequency was set to 15kHz and more than ten times higher current harmonic amplitudes in analysed DFT product has been observed for this frequency, and about few times higher for frequencies close to PWM carrier frequency, between 13kHz and 15kHz (Figure 20). For analysing DFT product in accordance to CISPR 16 standard within CISPR A frequency band, 200Hz resolution band width should be used. Power spectral density (PSD) calculated according to this rule is presented in Figure 21. The obtained results show that harmonic emission in this frequency range is significantly higher in relation to diode rectifier converter.

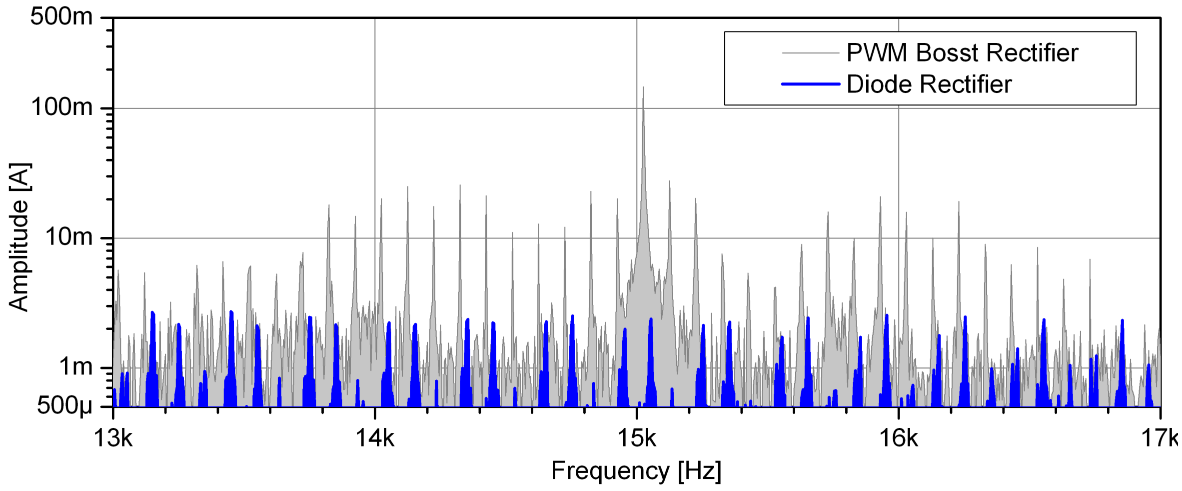

Figure 20. Current harmonic distortion of PWM boost converter in the frequency range close to PWM carrier frequency with comparison to classic diode rectifier distortions.

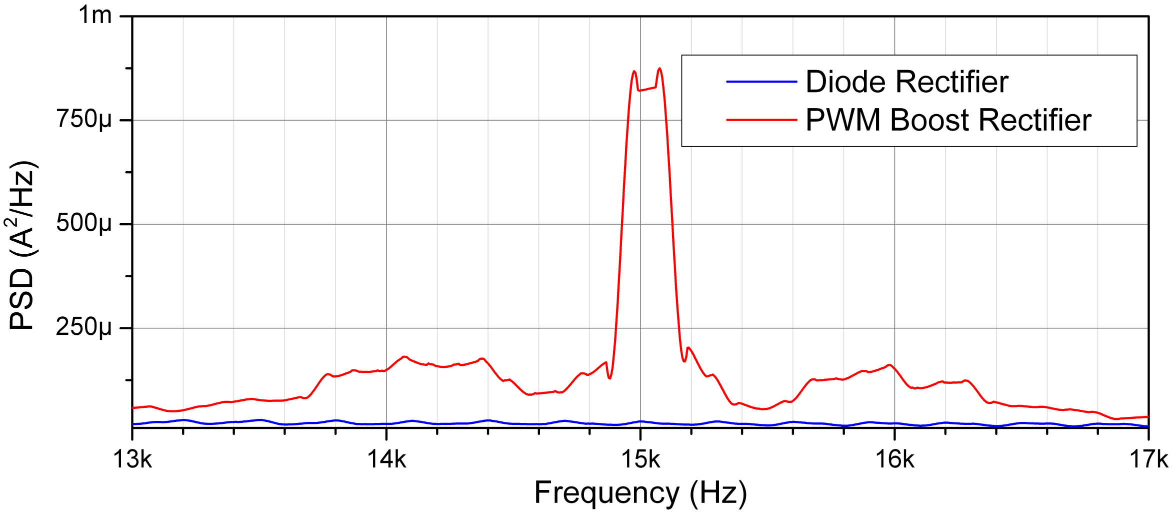

Figure 21. Power spectral density of current harmonic calculated for $200 Hz$ resolution badnwidth.

4. Conclusions

PWM boost AC-DC converters are increasingly used in contemporary application because of its considerable advantages, like bidirectional power transfer with unity power factor operation and low level of low order harmonic distortions emission. Systematic significant increase of the overall power quota converted from AC to DC and from DC to AC in the power system make these advantages more meaningful from the power quality point of view. This development trends also introduce some unfavourable effects, like increased emission in higher frequency ranges, which are presented in this chapter.

Increased harmonic emission in the frequency range between $2kHz$ and $9kHz$ as an effect of pulse width modulation method used for line current control in PWM boost converters becomes a fundamental problem to solve in such converters connected directly to the power grid. In recent years increased number of investigations focused on arising compatibility challenges in frequency band $2 - 9kHz$ has been reported and some new standardization methods has been initially proposed.

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Results of investigations presented in this chapter demonstrate that line current and voltage ripples, as an effect of PWM modulation carrier frequency in PWM boost converters, can induce compatibility problems in numerous applications which usually cannot be easily solved by using conventional passive harmonic-filters or radio frequency interference (RFI) filters. Harmonic emission filtering in this frequency band require new specific types of filters to be used.

Author details

Jaroslaw Luszcz

Faculty of Electrical and Control Engineering, Gdansk University of Technology, Gdansk, Poland

References

[1] Benysek, G. [2007]. *Improvement in the Quality of Delivery of Electrical Energy using Power Electronics Systems*, Power Systems, Springer-Verlag.

[2] Bollen, M. & Hassan, F. [2011]. *Integration of Distributed Generation in the Power System*, Wiley-IEEE Press.

[3] Bollen, M., Yang, Y. & Hassan, F. [2008]. Integration of distributed generation in the power system - a power quality approach, *Harmonics and Quality of Power, 2008. ICHQP 2008. 13th International Conference on*, pp. 1 –8.

[4] Cichowlas, M., Malinowski, M., Kazmierkowski, M. & Blaabjerg, F. [2003]. Direct power control for three-phase pwm rectifier with active filtering function, *Applied Power Electronics Conference and Exposition, 2003. APEC '03. Eighteenth Annual IEEE*, Vol. 2, pp. 913 –918 vol.2.

[5] Cichowlas, M., Malinowski, M., Kazmierkowski, M., Sobczuk, D., Rodriguez, P. & Pou, J. [2005]. Active filtering function of three-phase pwm boost rectifier under different line voltage conditions, *Industrial Electronics, IEEE Transactions on* **52**(2): 410 – 419.

[6] *IEC 61000-3-4 (1998): Electromagnetic compatibility (EMC) - Part 3-4: Limits - Limitation of emission of harmonic currents in low-voltage power supply systems for equipment with rated current greater than 16 A* [1998]. International Electrotechnical Commission Std.

[7] *IEC 61000-3-6 (2008): Electromagnetic compatibility (EMC) - Part 3-6: Limits - Assessment of emission limits for the connection of distorting installations to MV, HV and EHV power systems* [2008]. International Electrotechnical Commission Std.

[8] *IEC 61000-4-7 (2009): Electromagnetic compatibility (EMC) - Part 4-7: Testing and measurement techniques - General guide on harmonics and interharmonics measurements and instrumentation, for power supply systems and equipment connected thereto* [2009]. International Electrotechnical Commission Std.

[9] *IEEE Standard 519 (1992): Recommended Practices and Requirements for Harmonic Control in Electrical Power Systems* [1993]. The Institute of Electrical and Electronics Engineers.

[10] Liserre, M., Dell'Aquila, A. & Blaabjerg, F. [2003]. An overview of three-phase voltage source active rectifiers interfacing the utility, *Power Tech Conference Proceedings, 2003 IEEE Bologna*, Vol. 3, p. 8 pp. Vol.3.

[11] M. H. J. Bollen, J. Z. e. a. [2010]. Power quality aspects of smart grids, *International Conference on Renewable Energies and Power Quality (ICREPQ'10) Granada (Spain)*.

[12] McGranaghan, M. & Beaulieu, G. [2006]. Update on iec 61000-3-6: Harmonic emission limits for customers connected to mv, hv, and ehv, *Transmission and Distribution Conference and Exhibition, 2005/2006 IEEE PES*, pp. 1158 –1161.

[13] Olofsson, M. [2009]. Power quality and emc in smart grid, *Electrical Power Quality and Utilisation, 2009. EPQU 2009. 10th International Conference on*, pp. 1 –6.

[14] Smolenski, R. [2009]. Selected conducted electromagnetic interference issues in distributed power systems, *Bulletin of the Polish Academy of Sciences: Technical Sciences* Vol. 57(no 4): pp.383–393.

[15] Smolenski, R. [2012]. *Conducted Electromagnetic Interference (EMI) in Smart Grids*, Power Systems, Springer.

[16] Strauss, P., Degner, T., Heckmann, W., Wasiak, I., Gburczyk, P., Hanzelka, Z., Hatziargyriou, N., Romanos, T., Zountouridou, E. & Dimeas, A. [2009]. International white book on the grid integration of static converters, *Electrical Power Quality and Utilisation, 2009. EPQU 2009. 10th International Conference on*, pp. 1–6.

[17] Strzelecki, R. & Benysek, G. [2008]. *Power electronics in smart electrical energy networks*, Power Systems, Springer-Verlag.

[18] Tlusty, J. & Vybiralik, F. [2005]. Management of the voltage quality in the distribution system within dispersed generation sources, *Electricity Distribution, 2005. CIRED 2005. 18th International Conference and Exhibition on*, pp. 1 –4.

[19] Vekhande, V. & Fernandes, B. [2011]. Bidirectional current-fed converter for integration of dc micro-grid with ac grid, *India Conference (INDICON), 2011 Annual IEEE*, pp. 1 –5.

[20] Wasiak, I. & Hanzelka, Z. [2009]. *Integration of distributed energy sources with electrical power grid*, Vol. 57, Bulletin of the Polish Academy of Sciences - Technical Sciences, pp. 297–309.
URL: *http://bulletin.pan.pl/(57-4)297.pdf*