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Harmonics in the current powering selected low and medium power devices and their impact on power losses

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The paper deals with the issues related to currents of higher harmonics occurring in low and medium power circuits, using the Mcad software. Furthermore, it presents the effect of current harmonics on the root–mean–square value of these currents, and thus on the current load of conductors, especially the neutral (zero) conductor. Subject to discussion are also the effects of higher current harmonics on the performance of the power grid.

KEYWORDS: electromagnetic compatibility of electric circuits, harmonics in current and voltage

1. Introduction

The applicable legal regulations concerning the transmission and use of electric energy provide the permissible (maximum) values of harmonics occurring in currents and voltages. However, when it comes to harmonics in voltages and currents, the regulations are not so unambiguous. When comparing the requirements of these regulations it is difficult to indicate which of them, whether those referring to voltage or to currents, are stricter. In operational practice, from the point of view of the formal meaning, a greater role is assigned to requirements concerning values of harmonics for voltages, which have been regarded as parameters that characterise the quality of electric energy. And so it is the electric energy supplier on whom an obligation is imposed to observe the values of harmonics in voltage. In principle, the legal regulations do not indicate who is responsible for observance of requirements for values of harmonic currents. In certain places, though not too specifically, there are mentions in the regulations that it is the manufacturer of equipment who should make sure that no current harmonics exceeding permissible values will appear in the current which powers a specific device. However, as opposed to the requirements for voltages, which are specified in the regulations of the relevant ministers, the requirements for current harmonics arise from the respective standards exclusively.

2. Permissible values of harmonics

A greater and greater problem in the power grids are harmonics in currents and voltages. The cause of these harmonics is, in the majority of cases, power electronics equipment. The highest permissible values of these harmonics are specified in the applicable regulations, i.e. standards and ordinances. At present, of utmost significance in the legal regulations are the harmonics in voltage, which are parameters that characterise the quality of electric energy. These are usually the values of harmonics in voltage which affect the current of the respective harmonics. Harmonics in voltages which sometimes force out currents with values that affect significantly the operation of the wiring system in circuits with capacitors are particular examples here. Capacitors are this particular case, in which the higher the harmonic order is, the higher current values due to a decreasing reactance value, may be reached. In many cases, in order to limit the currents in circuits with capacitors, it is necessary to activate special glands. According to the applicable regulations, voltage values for the respective harmonics are limited, irrespective of the fact that the comprehensive content of all harmonics is limited by introducing the notion of the so called THD coefficient. The value of this coefficient is specified for the respective classes of receivers. For receivers belonging to class 1, the value of this coefficient may not exceed 5%, for receivers of class 2 – 8% and for receivers of class 3 – 10%, whereby at the same time, the permissible voltage values for the respective harmonics must not be exceeded.

3. Specifics of issues related to harmonics for receivers of different classes

In power grids, the energy supplier is obliged to ensure the THD_u value as well as the voltage value of the respective harmonics required by the law. The value of current harmonics required by the law is treated differently. In lower power circuits, the manufacturer of devices or receivers is obliged to provide such equipment which will not force currents of the respective harmonics with values higher than those allowed by the legal regulations. In reference to the receivers, in which the phase current of the receiver is lower than or equal to 16 A, the regulations specify the maximum values of current for the respective harmonics. At the same time, the regulations specify that harmonics < 0.6 % of the supply current or < 5 mA are negligible. Because of current harmonics, receivers belonging to 4 classes – A, B, C and D – are distinguished. Receivers of class A comprise symmetrical three–phase receivers as well as all other receivers except those belonging to classes B, C and D. Class B includes portable tools, class C refers to lighting equipment, and class D groups equipment in which the shape of the time run of current is specific, and the receiver consumes power with a value not higher than 600 W.

For equipment of class A, the following maximum values apply to the respective current harmonics:

- for the third harmonic, the permissible value of harmonic current is 2.3 A,
- for the fifth harmonic, the permissible value of harmonic current is 1.14 A,
- for the seventh harmonic, the permissible value of harmonic current is 0.77 A,
- for the ninth harmonic, the permissible value of harmonic current is 0.40 A,
- for the eleventh harmonic, the permissible value of harmonic current is 0.33 A,
- for the thirteenth harmonic, the permissible value of harmonic current is 0.21 A,
- for harmonics ranging between 15 and 39, the permissible value of harmonic current is determined based on the $0.15 \cdot 15/n$ A formula.

For even harmonics, the following values of harmonic currents are applicable:

- for the second harmonic – 1.08 A,
- for the fourth harmonic – 0.43 A,
- For the sixth harmonic – 0.30 A,
- for harmonics from 8 to 40, the permissible value of the harmonic current is determined on the basis of the $0.23 \cdot 8/n$ A formula.

Table 1. Maximum values for the respective current harmonics for equipment from class D

Harmonic order	Maximum permissible values of currents for the respective harmonics converted into [W]	Maximum permissible values of harmonic current
3	3.4	2.3
5	1.9	1.14
7	1.0	0.77
9	0.5	0.4
11	0.35	0.33
$13 \leq n \leq 39$ (only uneven harmonics)	3.85/n	$0.15 \cdot 15/n$

For equipment of class B, for the respective current harmonics, the maximum values that are the same as for equipment of class A are applicable, with the value of the coefficient amounting to 1.5. For equipment of class C, for the respective current harmonics, the maximum values determined as the percentage ratio of the current permissible for the given harmonic and the first harmonic are applicable. The value of this ratio for the second harmonic is 2. For the third harmonic, the permissible value is determined as the product of 30 times λ, where λ is the circuit power factor. For the fifth harmonic, the permissible value is 10% and for the seventh harmonic, the permissible value is

7%, for the ninth harmonic – 5%, for all other harmonics up to 39, but only the uneven ones, the permissible value is 3%. Table 1 for equipment of class D specifies the maximum values for the respective current harmonics.

4. Exemplary calculations of current for receivers of different classes

In the case of equipment belonging to class A, while taking into account only significant harmonics with values given in Table 1, current in the supply conductor is determined by relation (1):

$$I_A = \sqrt{I_1^2 + I_3^2 + I_5^2 + I_7^2 + I_9^2 + I_{11}^2 + I_{13}^2 + I_2^2 + I_4^2 + I_6^2} \quad (1)$$

At the highest values of the respective harmonics, we get:
I_1 = 16 A, I_3 = 2.3 A, I_5 = 1.14 A, I_7 = 0.77 A, I_9 = 0.4 A, I_{11} = 0.33 A, I_{13} = 0.21 A, I_2 = 1.08 A, I_4 = 0.43 A, I_6 = 0.3 A.

$$I_A = 16.277 \text{ A}$$

Power loss ΔP for the given current value may be calculated by assuming the conventional resistance value of the R line section, and the value specified in the electricity supply contract as rated current, i.e. 16 A. Current in the conductor is the rated current plus harmonic currents, i.e. 16.277 A in total. Power loss for equipment of class A is the conventional resistance value, i.e. power loss $\Delta P_A = R{\cdot}265$ W.

In the case of equipment from class B, while taking into account only the significant harmonics with values given in table 1, at factor 1.5 as for class A, current in the supply conductor will amount to I_B = 24.4 A. Power loss on conventional resistance R will be $\Delta P_B = R{\cdot}595$ W.

For equipment of class C, while taking into account harmonics of the 9th order, with values given in table 1, current in the supply conductor will be as follows:

$$I_C = \sqrt{1{,}0^2 + 2^2 + (0{,}30 \cdot 0{,}8)^2 + 0{,}1^2 + 0{,}07^2 + 0{,}05^2 + 0{,}03^2}$$

$$I_C = 2{,}253 \cdot I_n$$

$$I_C = 36 \text{ A}$$

Power loss on conventional resistance R for equipment of class C is:

$$\Delta P_C = R \cdot 1296 \text{ [W]}$$

For equipment of class D, while taking into account harmonics of the 11th order, with values given in table 1, current in the supply conductor will amount to:

$$I_D = \sqrt{16^2 + 2{,}3^2 + 1{,}14^2 + 0{,}77^2 + 0{,}4^2 + 0{,}33^2 + 0{,}21^2}$$

$$I_D = 16{,}23 \text{ A}$$

and power loss:

$$\Delta P_D = R \cdot 264 \text{ W}.$$

While comparing the power loss values for all four cases of receivers (classes A, B, C and D), this is what we get:

$$\Delta P_A = R \cdot 265 \text{ W}.$$

$$\Delta PB = R \cdot 593 \text{ W}$$

$$\Delta P_C = R \cdot 36 \text{ W}$$

$$\Delta P_D = R \cdot 264 \text{ W}.$$

It is easy to notice that the highest value of power loss in the conductor that powers all four classes of receivers, caused by higher harmonic currents, is present in the case of receivers of class B, which comprises portable tools for which the highest values of current harmonics are allowed.

5. Issues of harmonics in relation to the grid classes

The sources of higher harmonics of currents are receivers with non–linear current–voltage characteristics or receivers of other types. Among the sources of current harmonics occurring in the power system, it is possible to distinguish:

- electronic and power electronic devices,
- devices with magnetic cores, e.g. transformers,
- arc devices.

Whether, for instance, transformers are significant sources of harmonics is dependent on the voltage in the grid. At increased voltages, transformers can be significant sources of current harmonics.

As an example, values of the respective harmonics occurring in the transformer during the welding process are given:
I_1 = 20 A, I_3 = 12 A, I_5 = 4 A, I_7 = 0.7 A, I_9 = 0.6 A, I_{11} = 0.33 A, I_{13} = 0.11 A, I_2 = 7.98 A, I_4 = 5.3 A, I_6 = 2.7 A.

Current in the conductor is calculated according to formula (1), and the calculated value of the current is 25.7 A.

In the case of lower power receivers, at present, the most important sources of harmonics are discharge light sources. However a single source does not constitute a significant disturbance for the grid, the large number of these sources are an important risk for the grid. However, the greatest risks for the grid, when higher harmonics of currents are considered, are converters characterised by high THD values. IT hardware or equipment as well as such appliances as TV sets cannot be excluded as sources of higher harmonics. Their impact on the power grid is particularly visible during an evening load peak. A large number of these devices are of significant importance for current harmonics in the grid. Many electric energy receivers tolerate higher current harmonics, however it is always necessary to pay attention to their detrimental effects. This, in particular, refers to the control and measuring devices.

Complications in the operation of capacitor banks used to improve the power factor often appear because of current harmonics, whereby it must be remembered that power losses are dependent on the resultant current in the conductor. Capacitors are usually designed in such a manner as to withstand (thermally) currents with values which are 1.3 or 1.5 times higher than rated currents. Of course, the higher the value of currents which the capacitors withstand, the higher their price is.

As an example, the values of harmonics in currents reaching the capacitor connected to the three–phase low voltage grid in the three–wire system are given. An assumption is made that in order to compensate the reactive power, the capacitance of the capacitor per phase in the case of the star connection amounts to $C = 52$ μF.

Currents for two grid classes are presented; for each of the classes, different values of permissible harmonic voltages are applicable.

For the grid of class 2, the permissible percentage harmonic voltages are as follows: for the fifth harmonic, the permissible voltage value is 6%, for the seventh harmonic, the voltage value is 5%, for the eleventh harmonic – 3.5%, for the thirteenth harmonic – 3% and for the seventeenth harmonic – 2%. The given values correspond to voltage values which force harmonic currents: for the fifth harmonic – 13.87 V, for the seventh harmonic – 11.56 V, for the eleventh harmonic – 8.09 V, for the thirteenth harmonic – 6.94 V and for the seventeenth harmonic – 4.62 V. These voltage values force the following harmonic currents:

- the first harmonic forced by voltage with the rated value – 3.77 A,
- the fifth harmonic forced by voltage with the value of 13.87 V – 1.13 A,
- the seventh harmonic forced by voltage with the value of 11.56 V – 1.32 A,
- the eleventh harmonic forced by voltage with the value of 8.09 V – 1.45 V,
- the thirteenth harmonic forced by voltage with the value of 6.94 V – 1.47 A
- the seventeenth harmonic forced by voltage with the value of 4.62 V – 1.28 A,

for the sixth harmonic, the current value is 0.30 A, while for harmonics from 8 to 40, the permissible harmonic current value is determined by the following formula: $0.23 \cdot 8/n$ A.

RMS value for current is I = 4.81 A.

The ratio of rated current of the capacitor, which amounts to 3.77 A, to current supplying the bank is 4.81/3.77 = 1.27 < 1.3. The ratio of 1.3 provides information that the capacitor withstands the flow of harmonics with calculated values. It follows from the above, that the capacitor may operate in the grid without an additional protection.

For the grid of class 3, the permissible percentage harmonic voltages are as follows: for the fifth harmonic, the permissible voltage value is 8%, for seventh harmonic, the voltage value is 7%, for eleventh harmonic – 5%, for the thirteenth harmonic – 4.5%, and for the seventeenth harmonic – 4%. The given percentage values correspond to voltage values which force harmonic currents: for the fifth harmonic – 18.5 V, for the seventh harmonic – 16.18 V, for the eleventh harmonic – 11.56 V, for the thirteenth harmonic – 10.4 V, and for the seventeenth harmonic – 9.25 V. These voltage values force the following harmonic currents:

- the first harmonic forced by voltage with the rated value – 3.77 A,
- the fifth harmonic forced by voltage with the value of 18.5 V – 1.51 A,
- the seventh harmonic forced by voltage with the value of 16.18V – 1.85 A,
- the eleventh harmonic forced by voltage with the value of 11.56 V – 2.08 A,
- the thirteenth harmonic forced by voltage with the value of 10.4 V – 2.21 A
- the seventeenth harmonic forced by voltage with the value of 9.25 V – 2,57 A.

RMS value for current is I = 5.98 A.

The ratio of current reaching the bank (5.98 A) to the rated current of the capacitor (3.77 A) is 5.98/3.77 = 1.58 > 1.3. The ratio 1.58 > 1.3 provides information that the capacitor does not withstand the flow of harmonic currents with calculated values. It follows from the above, that the capacitor may not operate in the grid without an additional protection, i.e. e.g. an additional gland. The operating conditions of the capacitor in the grid of class 1 do not need to be checked because as the permissible values of harmonics are lower for class 1 than for class 2, the capacitor will meet the conditions set by the legal regulations.

Following the above discussion, it appears that the calculation of voltage drops is complicated to a great extent by higher harmonics in currents. This problem is even more complex when the cooperation of many non–linear receivers needs to be taken into account. Usually, the issue of voltage drops is simplified, by calculating them in the same manner as in the case of an ordinary circuit, i.e. without harmonics.

6. Permissible values of harmonics in currents for selected medium power devices

In contrast to the requirements for voltages, which are set in ordinances of the relevant ministers, the requirements for current harmonics result from the relevant standards exclusively.

In low voltage circuits, with currents higher than 16 A, (medium power devices), permissible harmonic values are given for three different operational situations. The first case refers to symmetrical three–phase loads, the second case also refers to symmetrical three–phase loads in specific conditions, and the third case refers to non–symmetrical three–phase loads. A significant difference between symmetrical and non–symmetrical three–phase circuits consists in the fact that the four–wire power supply system with a neutral conductor was assumed for the non–symmetrical circuit. Thus, in the case of the non–symmetrical circuits, the occurrence of third harmonics and their multiples was taken into consideration, while they were not taken into consideration in the symmetrical circuits for obvious reasons. The permissible harmonic values are particularly high, especially in comparison with the fifth or seventh harmonic. The permissible values of the so called THD factor are also relatively high. What is important in the standard referring to harmonics in currents is that for all the given harmonic values, a reference to the parameter marked as R_{sce}, that is, the conventional ratio of value at short–circuit, is applicable

$$R_{sce} = \frac{S_{sc}}{S_{equ}}$$

where:

$$S_{sc} = \frac{U_n^2}{Z}$$

whereby

$$S_{equ} = 3U_f I_{equ\,max}$$

is the conventional value of apparent power, for the maximum value of equivalent current I_{equ}.

Permissible values of current harmonics and THD for the three above–mentioned operational situations are listed in Tables 2 – 4. The article presents the effect of current harmonics on the rms value of these currents, and thus the load current of conductors for which the cross–section was probably not selected, taking into consideration the high values of harmonics.

Table 2. Permissible values of current harmonics for the case of the symmetrical three–phase system

Value R_{sce}	Value of harmonics in % of rated current				THD (%)
	I_5	I_7	I_9	I_{13}	
33	10.7	7.2	3.1	2	13
66	14	9	5	3	16
120	19	12	7	4	22
250	31	20	12	7	37
> 350	40	25	15	10	48

Table 3. Permissible values of current harmonics for the case of the symmetrical three–phase system (in specific situations)

Value R_{sce}	Value of harmonics in % of rated current				THD (%)
	I_5	I_7	I_{11}	I_{13}	
33	10.7	7.2	3.1	2	13
> 120	40	25	15	10	48

Table 4. Permissible values of current harmonics for the case of the non–symmetrical three–phase system

Value R_{sce}	Value of harmonics in % of rated current						THD (%)
	I_3	I_5	I_7	I_9	I_{11}	I_{13}	
33	21.6	10.7	7.2	3.8	3.1	2	23
66	24	13	8	5	4	3	26
120	27	15	10	6	5	4	30
250	35	20	13	9	8	6	40
> 350	41	24	15	12	10	8	47

7. Discussion of effects of higher harmonics in currents

The comparison of the permissible values of the respective harmonic currents listed in Tables 2 and 4 shows that the highest currents can be expected at the level higher by about 15% than the basic harmonic current. As an example, the calculated values of currents in conductors were provided for the permissible values (levels) of harmonics according to table 5 – for the value of

$$R_{sce} > 350$$

For the given values of harmonic currents, (41, 24, 15, 12, 10 and 18 respectively) the percentage of current in the conductor is:

$$I = \sqrt{1{,}0^2 + 0{,}41^2 + 0{,}24^2 + 0{,}15^2 + 0{,}12^2 + 0{,}10^2 + 0{,}08^2}$$

and will increase to I = 1.131% of the first harmonic current.

For the case according to table 3, in which harmonic currents amount to (40, 25, 15, 10) respectively, the % current in the conductor is:

$$I = \sqrt{1{,}0^2 + 0{,}40^2 + 0{,}25^2 + 0{,}15^2 + 0{,}10^2}$$

and amounts to:

$$I = 1{,}12$$

i.e., it will increase to 1.12 % of the first harmonic current, and power losses will increase to 1.24 of losses at rated current.

Taking into account the harmonics up to the 13th order, with values given in table 3, current in the supply conductor will constitute 1.131% of rated current. This value is the highest among other possible values. The permissible values according to table 1 give the highest value of current equal to 1.12% of rated current, i.e. a bit less than in the case given in table 3. From the point of view of power losses, these values can be considered relatively high, as power loss in the conductors is proportionate to the square of current, which, at current $1.13I_n$ gives 1.279 R. This means that the heating up of the conductor is increased by almost 30%. In circuits where high values of harmonic currents or voltages are expected, it is always necessary to take into account the possibility of simultaneous occurrence of current and voltage harmonics forced by current harmonics. This means that with the occurrence of voltage harmonics, it is, at the same time, necessary to take into account the fact that these voltages force other current harmonics. All the harmonic currents sum up, causing the heating up of the conductors by all the occurring harmonics. A particularly difficult situation may be faced in circuits in which there are capacitors that, at higher harmonic orders, force large values of currents, as the reactance of capacitors decreases at higher harmonic orders. The rule assumed in the regulations for harmonics in voltage is that the higher the harmonic order is, the lower the permissible value of harmonic voltage is. In this way, the currents were limited mainly in the circuits with capacitors.

As has been mentioned, in the case of power grids, it is necessary to pay attention to additional power losses in the power line caused by higher harmonics of currents and by an increase in the currents caused by the transmission of reactive power, which is related to transmission of active power that is important for the operation of electric devices, especially electric engines. As a consequence of these additional power losses, the efficiency of the power system decreases. This article, based on the example of an induction motor with the power of 10 kW, presents the values of these additional power losses.

In the case of an power with the rated power of 10 kW, with the assumption that the motor efficiency is $\eta = 0.88$, the active power drawn from the grid amounts to 11360 W. It has been assumed that the power factor of the grid is 0.809. For these values of the power factor and efficiency, the current drawn by the engine from the grid, which is the rated current, is described by the following equation:

$$I_n = \frac{P_n}{\sqrt{3}U_n 0{,}809 \cdot 0{,}88}$$

Rated current for engine $I_n = 20.27$ A.

At this active power, the engine draws reactive power from the grid – $Q_{1n} = 8256$ vars. In order to decrease the current, it is necessary to decrease the consumed reactive power. An assumption is made that the power factor will be increased up to the value recommended by the legal regulations. For value $tg\varphi = 0.4$, one receives $\cos\varphi = 0.929$. The reactive power will be compensated by using the capacitor with the reactive power $Q_k = 4000$ vars. In such a case, the reactive power drawn from the grid will decrease to $Q_1 = Q_{1n} - Q_k$, i.e. $Q_1 = 4.257$ kvars, which corresponds to the capacitance of the capacitor $C_k = 79.6$ µF. After the reactive power compensation, the current drawn by the engine from the grid will decrease to $I = 17.5$ A. The ratio of current after compensation to current before compensation is 0.864. Power loss in conductors that power the engine as a result of reactive power compensation will decrease by 25%.

The reduction of power losses as a result of reactive power compensation will not suffice to compensate the power losses caused by harmonics occurring in the current that supplies the capacitor as a result of harmonics in voltage. Currents from voltage harmonics were calculated with the assumption of permissible voltage values for class 2 according to table 1.

Rated current of the capacitor is determined for the rated capacitance, rated voltage and rated frequency. Thus, the rated current of the capacitor is I_{nk} = 5.77 A. The said current is the first current harmonic of the current supplying the capacitor. The fifth current harmonic of the current supplying the capacitor is described by the following equation:

$$I_{h5} = \frac{u_{h5} U_f}{X_{ck5}}$$

where: u_{h5} is the permissible value of the fifth harmonic of voltage.

The capacitor reactance for the fifth harmonic is presented by the following equation:

$$X_{ck5} = \frac{1}{2\pi \cdot 5 f_n C_k}$$

Fifth harmonic current I_{h5} = 1.73 A.

Consecutive harmonic currents are calculated in a similar manner. The seventh harmonic current is calculated according to the following formula:

$$I_{h7} = \frac{u_{h7} U_f}{X_{ck7}}$$

and amounts to I_{h7} = 2.02 A.

In a similar manner, current is calculated for the eleventh harmonic I_{h11} = 2.22 A, thirteenth harmonic I_{h13} = 2.25 A and seventeenth harmonic I_{h17} = 1.96 A. Despite the fact that, in principle, the harmonics in circuits should be calculated up to the fortieth harmonic, in the case of harmonics in circuits with capacitors, it suffices to take into account the values up to the seventeenth harmonic. Current in the circuit, taking into account the listed harmonics, presents the following relation:

$$I = \sqrt{I_{h1}^2 + I_{h5}^2 + I_{h7}^2 + I_{h11}^2 + I_{h13}^2 + I_{h17}^2}$$

and its value is I = 7.37 A.

The calculated current in relation to the current without harmonics, i.e. the first harmonic current will be 7.37/5.77 = 1.28.

8. Power losses in circuits, with consideration of higher current harmonics

As power losses depend on the square of this ratio, this will be $1.28^2 = 1.63$. This means that the power losses, as a result of harmonics in current will increase by as many as 63%. It is easy to notice, that additional power losses forced by harmonics in the current, amounting to 63%, are higher than the power losses decreased as a result of reactive power compensation, amounting to 25%.

A particularly dangerous operational situation occurs for the case of the four–wire three–phase system, especially for R_{sce} > 350, when the permissible value of the third harmonic current is determined at the level of 41% of the first harmonic. In the situation of the non–symmetrical load, the third harmonic current may be present in the neutral conductor, resulting from the totalization of third harmonic currents coming from three phases. In particularly unfavourable circumstances, the algebraic totalization of these three may occur, which will cause the flow in the neutral current conductor with the value of 123% of the first harmonic current, i.e. the rated current.

9. Conclusions

Higher harmonic currents and voltages make the operation of the grid and the electric devices significantly more complicated. The main reasons for this are increased power losses and difficulties in calculating voltage drops. Therefore, the applicable legal regulations limit the permissible values of both currents and voltages of higher harmonics in both low and high voltage electric circuits.

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