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[1.]Vladimir ŠINIK, [2.]Željko DESPOTOVIĆ, [1.]Slavica PRVULOVIĆ,
[1.]Eleonora DESNICA, [1.]Jasmina PEKEZ, [1.]Jasna TOLMAČ, [1.]Ivan PALINKAŠ

HIGHER HARMONICS OF CURRENT CAUSED BY THE OPERATION OF ROLLING MILL

[1.]University of Novi Sad, Technical Faculty "Mihajlo Pupin", Zrenjanin, SERBIA
[2.]Institute "Mihajlo Pupin", Belgrade, SERBIA

Abstract: Three-phase controlled rectifiers have a wide range of applications, from small rectifiers to large. They are used for electro-chemical process, many kinds of motor drives, traction equipment, controlled power supplies, and many other applications. A simple analytic method of calculating higher harmonics of current generated by a three phase bridge rectifier at its network end is represented in this paper. This method is used for calculating higher harmonics of current with all inductance relationships of the circuits of the alternating and direct ends of a three phase bridge rectifier, at various rectifier loads and at various thyristor control angles.
Keywords: higher harmonics, rolling mill

INTRODUCTION

One of the most characteristic tendencies in the development of electromotive drives of cylindrical dwellings and their respective auxiliary drives is based on the large application of thyristor rectifiers for powering the armature and the excitation of their drive single-stroke engines. The installed power of thyristor rectifiers of some larger roller bearings reaches up to 100 MW and even more. Facilities equipped with industrial electronics components operate back to the electrical network [1-9]. The return operation of rectifier drive continuous rolling mills, which are the subject of this paper, manifested in the form of taking a reactive power from the network and network load with a higher harmonics current. Higher harmonics with network impedance create more harmonics in the network voltage. Distorted voltage has the adverse effect of the consumers who are supplied from such a network. Therefore, the method for the determination of harmonics in the current drawn from the network indicated consumers seems very current.

Rolling is a continuous process of metal processing, whereby the piece is passed between two rollers and changes its shape. The length increases, and reduces the cross-section. The rolls are placed in the roller housing and rotate around their longitudinal axis. When rolling, the piece is passed through the gap of the roller. Rollers rotate in the opposite direction (Fig. 1) [4].

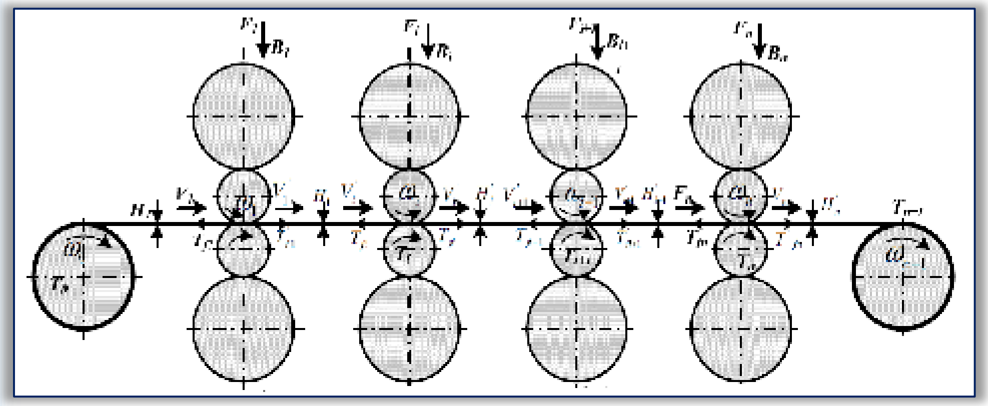

Figure 1. Scheme of multistage tandem strip for continuous cold rolling of sheet metal

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2. METHOD OF CALCULATING HIGHER HARMONICS OF CURRENT

The operation of a thyristor bridge rectifier is based on the switching operation of strong semiconductor components, so that, together with the consumer, it exhibits a non-linear load on the network. Such operation results in distorted waveforms of voltage and current, i.e. in higher harmonics of the network. The presence of higher harmonics in the network is considered to be "contamination" of the network and may cause undesired effects on electrical equipment and other consumers.

Considering a three phase bridge rectifier with the counter-electromotive force E as a load, there are analytic equations derived to calculate higher harmonics of current generated by the rectifier at its network end.

Basic starting assumptions in this analysis were the following:

- the rectifier was fed from a symetrical sinusoidal three phase network; the network had the short circuit final strength; the operational and capacitance resistance of the network were neglected;
- the decrease of resistance in the thyristor conducting direction was neglected;
- higher harmonics were calculated in the stationary state;
- it was assumed that the thyristor current commutation was linear and that no more than two thyristors were involved in the commutation;
- the current of the transformer magnetization was neglected.

As for the three phase bridge rectifier with the counter-electromotive force E as a load, we shall derive now equations in order to calculate the value of higher harmonics of current generated by the rectifier at its network end. The parameters of the network and transformer are supposed to be reduced to the secondary phase voltage of the rectifying transformer U_S so that an appropriate scheme of the six-pulse three phase rectifier with the network may be represented as shown in Fig. 2. Thus Figure 2 shows: U_R, U_S, U_T -phase voltages of the rectifying transformer secondary, X_K -induction resistance of the phase containing the induction resistance of the network, electric lines and rectifying transformer reduced to its secondary end X -induction resistance at the direct end of the rectifying transformer including the inductance of the smoothing filter and the inductance of the consumer, Ra-active resistance at the direct end of the rectifier, u_1 and i_1- instantaneous values of the line voltage and filament current, i_d – instantaneous value of the direct current, and i_1 to i_6 – instantaneous values of thyristor currents 1 to 6.

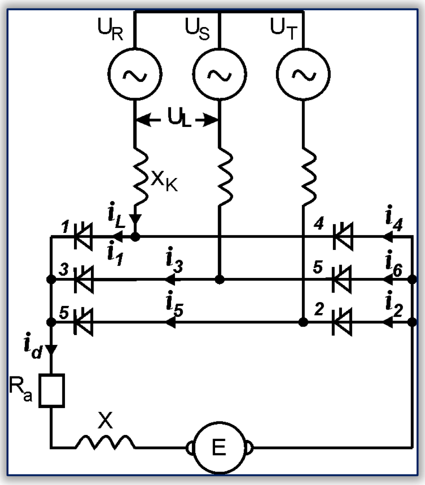

Figure 2. Scheme of the three phase bridge rectifier with reduced parameters of the rectifying transformer and the network at the secondary end of the rectifying transformer

If the rectifier load corresponds to the value of the intermittent current limit, the filament current time i_L may be represented as in Fig. 3.

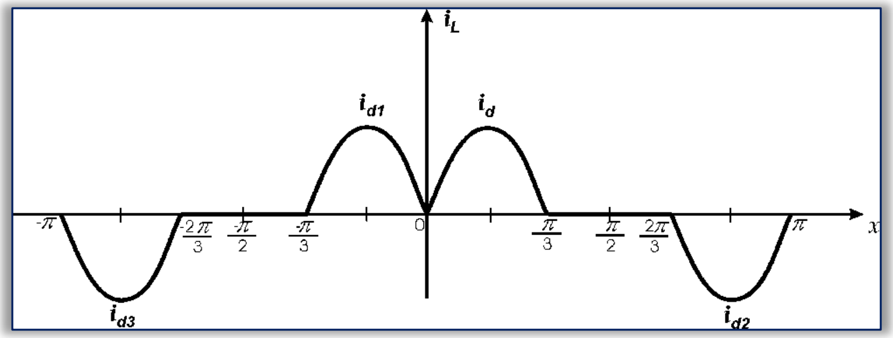

Figure 3. Flow of the current i_L of the three phase bridge rectifier with the load at the intermittent current limit

Let us perform a harmonic analysis of the completely smoothed current at the direct end of the three phase bridge rectifier with the flow of the filament current i_L shown in Fig. 4.

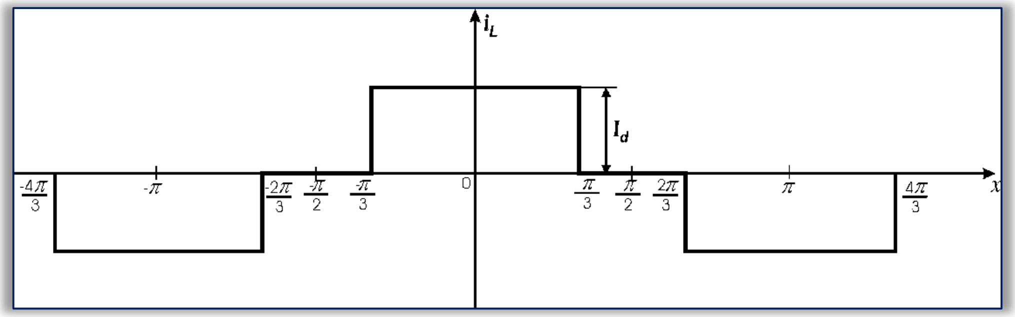

Figure 4. Flow of the filament current i_L of the three phase bridge rectifier with ideally smoothed direct current

In the literature [7], the relative values of higher current harmonics in the case of the last two images were derived.

When the three phase bridge rectifier load is greater than $I_{di\alpha}$ and when the effect of the thyristor commutation is neglected, the filament current i_L flows as shown in Fig. 5. It is obvious that such a flow of the current i_L is obtained by superpositioning the current flows shown in Fig. (3) and (4).

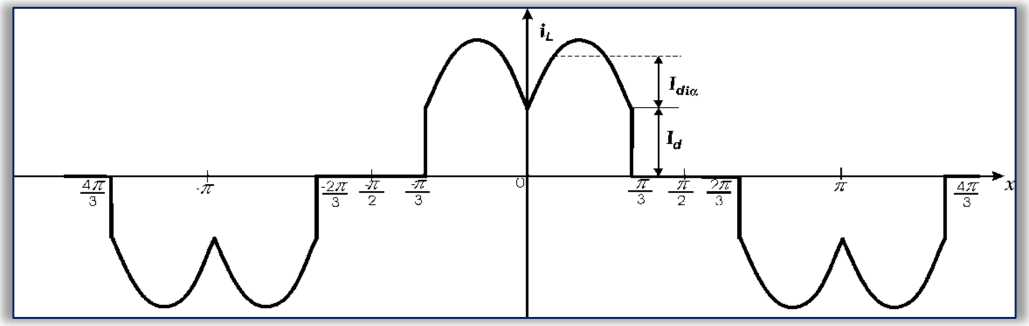

Figure 5. Flow of the filament current i_L of the three phase bridge rectifier with a load greater than $I_{di\alpha}$ and with the thyristor commutation effect neglected

In the literature [7], the relative values of the higher current harmonics in the case of the last two images were derived. Based on [7] and after certain transformations, the expression for the relative value of the harmonic n = 5, 11, 17, ... in = 7., 13., 19. .... becomes:

$$\bar{i}_{n\alpha(5.,11.,17.,...)} = \frac{-\frac{9.56}{n(n-1)}}{1+0.9814634\left(\frac{I_d}{I_{di\alpha}}-1\right)} - \frac{0.9812379\left(\frac{I_d}{I_{di\alpha}}-1\right)\frac{1}{n}}{1+0.9814634\left(\frac{I_d}{I_{di\alpha}}-1\right)} \tag{1}$$

$$\bar{i}_{n\alpha(7.,13.,19.,....)} = \frac{-\frac{9.56}{n(n+1)}}{1+0.9814634\left(\frac{I_d}{I_{di\alpha}}-1\right)} + \frac{0.981379\left(\frac{I_d}{I_{di\alpha}}-1\right)\frac{1}{n}}{1+0.9814634\left(\frac{I_d}{I_{di\alpha}}-1\right)} \tag{2}$$

In order to analyse the effect of the relative voltage of the rectifier phase short circuit u_k, the relationship of, X/X_K and the thyristor ignition control angle α, on higher harmonics generation in the filament current of the three phase bridge rectifier, we should perform certain transformations of equations (1) and (2).

If the relationship between the induction resistance of the direct circuit X and the induction resistance of the phase of the rectifier commutating circuit X_K is marked by "n", i.e. $n = X/X_K$ ~ , then the current $I_{di\alpha}$ determined by equation in [2], [7], may be expressed as follows:

$$I_{di\alpha} = 0.0931\frac{U_{di0}}{X_K(n+2)}\sin\alpha \tag{3}$$

If U_{dio} is expressed using the voltage U_s, in accordance with equation in [7], the current $I_{di\alpha}$ determined by equation (3) may be expressed as follows:

$$I_{di\alpha} = \frac{3\cdot 0.0931\sqrt{6}}{\pi}\frac{U_S\sin\alpha}{X_K(n+2)} = 0.217769\frac{U_S\sin\alpha}{X_K(n+2)} \tag{4}$$

The parameter X_K contained in equation (4) is determined by the following equation:

$$X_K = \frac{U_S u_k \sqrt{3}}{\sqrt{2} I_d} \quad \text{ie.} \quad I_d = \frac{U_S u_k \sqrt{3}}{\sqrt{2} X_K} \tag{5}$$

In accordance with equation (5) it follows that the relationship of $I_d / I_{di\alpha}$ contained in equations in [7], may be expressed as follows:

$$\frac{I_d}{I_{di\alpha}} = \frac{U_S u_k \sqrt{3}}{\sqrt{2} X_K} \frac{X_K (n+2)}{0.217769 U_S \sin\alpha} = 5.624 \frac{u_k (n+2)}{\sin\alpha} \tag{6}$$

Using equation (6) and equations (1) and (2), the relative values of the higher harmonics of h = 5., 11., 17.,… may be calculated as follows:

$$\bar{i}_{h\alpha(5.,11.,17.,...)} = \left| \frac{-\frac{9.56}{h(h-1)}}{1+0.981\cdot\left[5.624\frac{u_k(n+2)}{\sin\alpha}-1\right]} - \frac{\frac{1}{h}\cdot 0.981\cdot\left[5.624\frac{u_k(n+2)}{\sin\alpha}-1\right]}{1+0.981\cdot\left[5.624\frac{u_k(n+2)}{\sin\alpha}-1\right]} \right| \tag{7}$$

and the relative values of the higher harmonics of h = 7., 13., 19.,… may be calculated as follows:

$$\bar{i}_{h\alpha(7.,13.,19.,...)} = \left| \frac{-\frac{9.56}{h(h-1)}}{1+0.981\cdot\left[5.624\frac{u_k(n+2)}{\sin\alpha}-1\right]} + \frac{\frac{1}{h}\cdot 0.981\cdot\left[5.624\frac{u_k(n+2)}{\sin\alpha}-1\right]}{1+0.981\cdot\left[5.624\frac{u_k(n+2)}{\sin\alpha}-1\right]} \right| \tag{8}$$

The last equations (7) and (8) may be used for calculating higher harmonics of the filament current of the three phase bridge rectifier, if the effect of commutation on the value of generated higher harmonics is taken into account together with the factor f (h,u). In this particular case equations (7) and (8) have the following form:

$$\bar{i}_{h\alpha(5.,11.,17.,...)} = \left| \frac{-\frac{9.56}{h(h-1)}}{1+0.981\cdot\left[5.624\frac{u_k(n+2)}{\sin\alpha}-1\right]} - \frac{f(h,u)\frac{1}{h}\cdot 0.981\cdot\left[5.624\frac{u_k(n+2)}{\sin\alpha}-1\right]}{1+0.981\cdot\left[5.624\frac{u_k(n+2)}{\sin\alpha}-1\right]} \right| \tag{9}$$

$$\bar{i}_{h\alpha(7.,13.,19.,...)} = \left| \frac{-\frac{9.56}{h(h+1)}}{1+0.9814634\left[5.624\frac{u_k(n+2)}{\sin\alpha}-1\right]} + \frac{f(h,u)\frac{1}{h}0.981379\left[5.624\frac{u_k(n+2)}{\sin\alpha}-1\right]}{1+0.9814634\left[5.624\frac{u_k(n+2)}{\sin\alpha}-1\right]} \right| \tag{10}$$

The factor of the effect of commutation on the value of generated harmonics of current f(h,u) in the last two equations may be calculated in accordance with the following equation :

$$f(h,u) = \frac{\sin(h\frac{u}{2})}{h\frac{u}{2}} \tag{11}$$

where $u = \arccos(\cos\alpha - u_k) - \alpha$, ($u$ – angle of commutation). Assuming that the commutation is linear and that the direct current of the rectifier is ideally smoothed, the effective relative value of higher harmonics of current generated by the rectifier at its network end may be calculated using the following equation:

$$\frac{I_h^I}{I_1^I} = \frac{1}{h}\frac{\sin(h\frac{u}{2})}{h\frac{u}{2}} = \frac{1}{h} f(h,u) \tag{12}$$

3. RESULTS OF THE ANALYSIS

In order to compare the corresponding values of higher harmonics of current at the rectifier network end calculated in accordance with equations (7),(8), (9),(10) and (12), Fig. 6, Fig 7, Fig.8, shows the simultaneous flows of the functions $I_h / I_1 = f(\alpha)$ (obtained by the given equations) for various parameters of X/Xk and u_k in the function of the thyristor ignition angle.

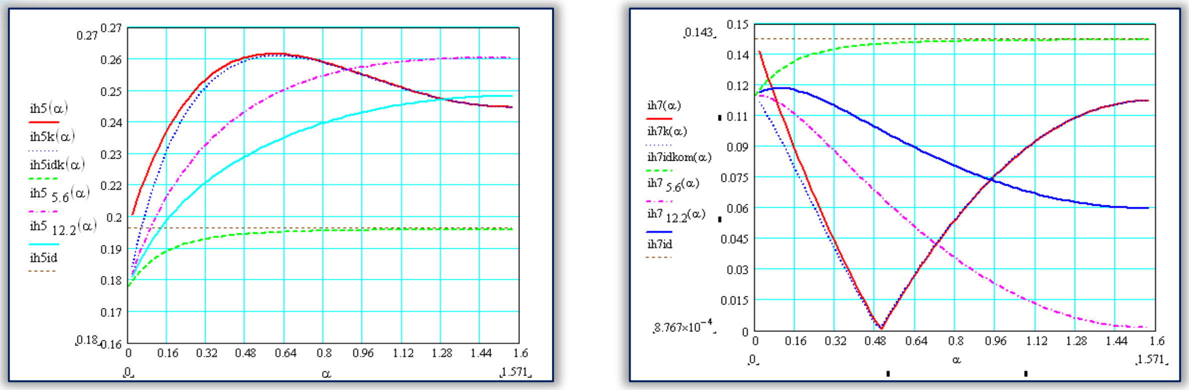

Figure 6. Flows of the relative values of the harmonics of current of 5., 7., ranges at the network end of the three phase bridge rectifier in the function of the thyristor ignition angle, the various parameters of u_k=0.05 and the relationship of X / X_K =(1.6.,5.6.,12.2.)

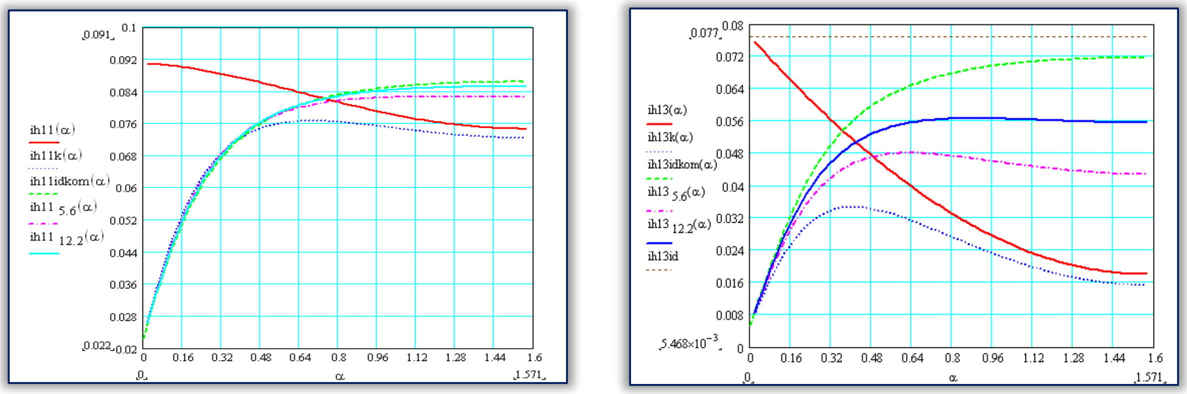

Figure 7. Flows of the relative values of the harmonics of current of 11., 13., ranges at the network end of the three phase bridge rectifier in the function of the thyristor ignition angle, the various parameters of u_k=0.05 and the relationship of X / X_K =(1.6.,5.6.,12.2.)

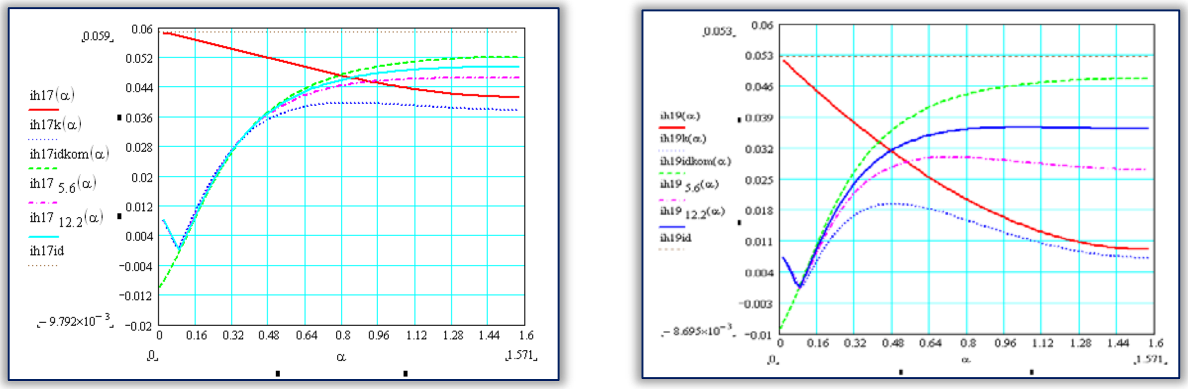

Figure 8. Flows of the relative values of the harmonics of current of 17., 19., ranges at the network end of the three phase bridge rectifier in the function of the thyristor ignition angle, the various parameters of u_k=0.05 and the relationship of X / X_K =(1.6.,5.6.,12.2.)

______ (red) – relative value of a h-range harmonic of current (without taking into account the thyristor commutation) obtained by equations (7) and (8) with u_k =(0.05) and n = 1.6

……… (blue) – relative value of a h-range harmonic of current (taking into account the thyristor commutation) obtained by equations (9) and (10) with u_k =(0.05) and n = 1.6

-------- (green) – relative value of a h-range harmonic of current with the assumption of linear commutation and ideally smoothed direct current of the rectifier obtained by equation (12)

-·-·-·- (pink) – relative value of a h-range harmonic of current in the function of the thyristor ignition angle (α) taking into account the thyristor commutation for n = 5.6 and u_k =(0.05)

_____ (blue) – relative value of a h-range harmonic of current in the function of the thyristor ignition angle (α) taking into account the thyristor commutation with n = 12.2 and u_k =(0.05)

…….. (black) – relative value of a h-range harmonic of current obtained by the following equation:

$$\frac{I_h}{I_1} = \frac{1}{h} \tag{13}$$

In accordance with the analysis of the flows of functions $I_h / I_1 = f(\alpha)$ shown in Fig. 6, Fig. 7, Fig. 8, it can be concluded that:

— The value of the inductance L in the output circuit of the rectifier has a significant effect on the value of the generated harmonics of current of 5., 7., 11., 13., 17., 19.,... ranges.
— The effect of the thyristor commutation (with the assumption that I_d is ideally smoothed current and that the thyristor current has a linear flow during the commutation) on decreasing the generated harmonic value grows with u_k, ie. with the increase of the rectifier power.
— The effect of the thyristor commutation on decreasing the generated harmonics value grows with the increase of the harmonic range h, particularly when the values of the thyristor ignition angle are low.
— By the increase of the inductance at the rectifier direct end, the value of the harmonic of current of range 5 decreases.

In all the cases of the given relationships X / X_K, the value of the harmonic of current of range 5 is greater than 20 % of the fundamental harmonic in major part of the change of the thyristor ignition angle (α).

With three phase bridge rectifiers having $u_k \leq 0.05$, the harmonic of current of range 5 may be calculated accurately enough by equation (7). With three phase bridge rectifiers having $u_k \geq 0.05$, the effect of the thyristor commutation should be taken into account when calculating the value of the harmonic of current of range 5, ie. the calculation should be done by equation (9).

— Except in the case of the intermittent current limit ($X / X_K = 1.6$, $u_k = 0.05$), the value of the harmonic of current of range 7 generated in the network by the three phase bridge rectifier is lower than the value obtained with the assumption of ideally smoothed direct current (I_7,/I_1 = 1/7 = 0.1428).
— Except in the case of X/X_k = 1.6 and u_k = 0.05, with all rectifiers, the obtained value of the harmonic of current of range 7, calculated with the assumption of linear commutation and smoothed direct current (I_7,/I_1 = 1/7 . f (7, u), is greater than the corresponding values obtained by equations (8) and (10).
— Except in the case of X/X_k = 1.6 and u_k = 0.05, the value of the generated harmonic of current of range 7 increases with the increase of the inductance at the rectifier direct end.
— With all rectifiers, the value of the harmonic of current of range 11, calculated by equation (7), is lower than the value I_{11}/I_1 = 1/11 obtained with the assumption of ideally smoothed direct current of the rectifier.
— The value of the generated harmonic of current of range 11 decreases with the increase of the rectifier u_k.
— With the increase of the inductance value L in the rectifier direct circuit, and with the given values of u_k and α, the value of the harmonic of current of range 11 changes slightly.
— With all rectifiers, the value of the harmonic of current of range 13, calculated by equation (8), is considerably lower than the value I_{13}/I_1 = 1/13 obtained with the assumption of ideally smoothed direct current of the rectifier.
— Except in the case of the limit of the intermittent current I_d, the value of the generated harmonic of current of range 13 increases with the increase of the inductance at the rectifier direct end.

The higher harmonics of current of ranges 17 and 19 have the same law as the harmonics of current of ranges 11 and 13.

4. CONCLUSION

In the given analytic method of calculating and analysing higher harmonics of current at the network end of a three phase bridge rectifier, a simple mathematical instrument is used. The contribution of this work is that it adequately shows the effect of the network inductance and final inductance at the direct end of the rectifier, which may be used for calculating higher harmonics of current with any relationships of L/L_K in the function of the thyristor control angle α.

Using derived equations and taking into account (or not taking into account) the thyristor commutation for calculating higher harmonics of current at the network end of the three phase bridge rectifier and then comparing them with those measured in the rectifying drive, it is possible to confirm the accuracy and justifiability of the proposed method of calculating higher harmonics of current.

Note:

This paper is based on the paper presented at IIZS 2019 – The 9th International Conference on Industrial Engineering and Environmental Protection, organized by Technical Faculty "Mihajlo Pupin" Zrenjanin, University of Novi Sad, in Zrenjanin, SERBIA, in 03–04 October, 2019.

References

[1] I.V. Žeželenko: »Viššie garmoniki v sistemah elektrosnabženija prompredprijatij« , »Energija« Moskva 1974.
[2] V.Šinik, "Improving Performance in Automatic Powerless Power Systems", Master thesis, Faculty of Electrical Engineering, Sarajevo, June, 1991
[3] Ž. Janda, One class of three-phase rectifiers with sinusoidal current using injection of higher current harmonics, Doctoral dissertation, Belgrade 2004.
[4] N. Jevtić. Dynamic Simulation of Electrohydraulic Servosystems for Adjusting Rolling Gaps on Five-Way Tandem Rail in Smederevo Iron, Doctoral Dissertation, University of Novi Sad Technical Faculty "Mihajlo Pupin" Zrenjanin 2013
[5] B. Kovač., »The reduction of harmonics distortion by resonant filters«, VI Conf in Power Electronics, Subotica, jun 1986, pp. 291-296.
[6] E. Schonholzer., A. Graham.: »Line harmonics of Converters with DC-motor Loads » IEEE Tran. on ind. Applic., No. 1, Jan/Feb 1983., pp. 84-93
[7] A.Gavranovic.,«Higher Harmonics of Current Caused by the Operation of Rolling Mill Continuous Rectifying Electric-Motor Drives«, Doctoral dissertation, Faculty of Electrical Engineering, Zagreb 1981.
[8] V. Katic, "Power Quality-higher harmonics", Faculty of Technical Sciences Novi Sad, Novi Sad 2002nd
[9] D. Graovac,"Universal system for power quality correction", Ph.D. Thesis, Faculty of Technical Sciences, Novi Sad, 2000.

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