MODELLING OF COMMUTATION PROCESS OF DIODE RECTIFIER BOTH IN CURRENT AND VOLTAGE MODES

J. Koscelnik, M. Benova, B. Dobrucky

Faculty of Electrical Engineering, University of Zilina.

Abstract

The paper shows selected results analysis of diode rectifierduring commutation process.The commutation process and the process between commutations of diode rectifierare investigated. The process is modelled in the current and voltage modes. There are used numerical methods because of result equations (e.g. for length of commutation) cannot be solved analytically due to transcendental nature. The resulting waveforms of the commutation process in MATLAB are presented as well.

1 Commutation process in diode rectifier

The commutation process in rectifier is defined as all processes due to current commutating from on branch of the rectifier and followingthrough a given valve to the other branch of the rectifier.During commutation two different voltages interact: the “primary” voltage, i.e. phase voltage of appropriate transformer winding (supply voltage) and self-induced voltage of the anode circuit [2].

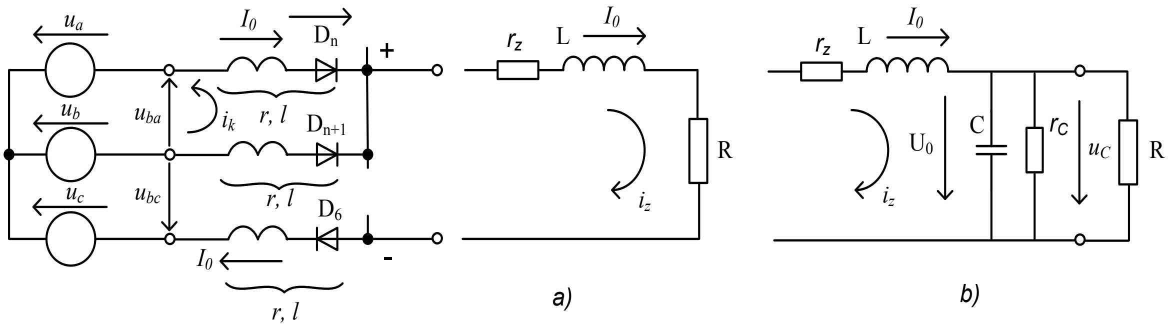

Figure 1: Commutation between two phases caused by internal inductances of the rectifier in current mode *a*) and voltage mode *b*)

Fig. 1 shows the basicschematicrepresentation of diode rectifier involvement in both modes. During the commutation the load current floating through the one pair of the diodes (D_n, D_6) is exchanged by other pair ones (D_{n+1}, D_6), [1]. It begins when voltage of incoming phase is higher than voltage of actual phase, and it is over when the commutating current i_k is reaching the load current i_z.

$$\mathrm{i_k(t_k) = i_z(t_k)} \tag{1}$$

So, it depend both on the time constant of the commutating circuit τ_k and of the load circuit τ_z

$$\tau_k = \frac{2l}{2r};\ \tau_z = \frac{2l+L}{2r+R} \tag{2}$$

where *l, r* are resistance and inductance (parameters) of diodes and *R,L* are resistance and inductance of load.

2 Commutation process of rectifier in current mode

In first step the currentis conducted by diodes D_1 and D_6. The voltagesources are notconsidered what is caused by superposition of thecurrent tosource. In the case of commutation the current i_k flows through the diodes D_n and D_{n+1} is

$$\mathrm{i_k(t)} = \frac{U_m^{ba}}{\lfloor Z_k \rfloor}\left[\sin(\omega t-\gamma)+\sin(\gamma).e^{-\frac{t}{\tau_k}}\right]+I_0.e^{-\frac{t}{\tau_k}} \tag{4}$$

where Um^{ba} is the maximal value of line voltage,$\lfloor Z_k \rfloor$ is the value of impedance during commutation, ω is angle velocity τ is time constant of the circuit ,γ is commutation angle.

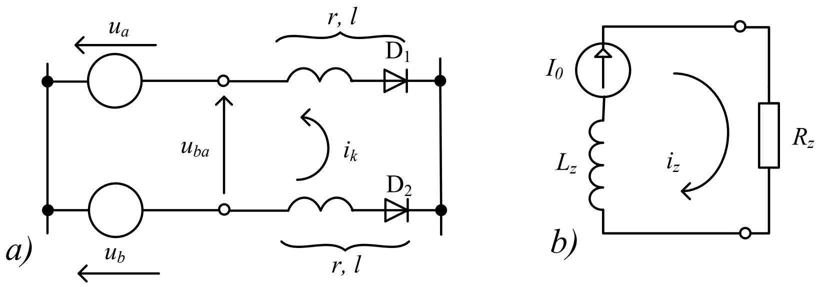

Figure 2: The circuit diagramsin the aftermath of the commutation current i_k a) and the load current i_z b) during commutation

The equation describes the current i_k according to situation of the circuit on Fig.2 b) will be created

$$\frac{di_k}{dt} = -\frac{r}{l} i_k(t) + \frac{1}{2l} u_{ba}(t) \tag{5}$$

where u_{ba} is the line voltage between phase *a* phase *b*.

Using Euler's explicit methodthe numerical solution is:

$$i_{k\,n+1} = \left(1 - h\frac{r}{l}\right) i_{k\,n} + h\frac{1}{2l} u_{ba\,n} \tag{6}$$

where *n* is interpolation, *h* is the size of interpolation step.

Forth is circuit applies:

$$i_z(t) = I_0 e^{-t/\tau_z} \tag{7}$$

where I_0 is the current through the inductance which is formed by *r,l.* (2). In spite of due to transcendental nature of the equation (1). Then it is necessary to use numerical (or graphical) solution.

$$L\frac{di_L}{dt} = -i_T R \rightarrow \frac{di_L}{dt} = -\frac{R}{L} i_T \tag{8}$$

The differential equations describing current mode, Fig. 2, is necessary to transform to the discrete form. Equations have been transformed by the Euler's explicit method to the discrete form

$$\frac{di_{Ln+1} - di_{Ln}}{h} = \frac{di_L}{dt} \tag{9}$$

Than the equation describes circuit of current mode in discrete form is:

$$i_{Ln+1} = -i_{Ln} - h\frac{R}{L} i_{Ln} = \left(1 - h\frac{R}{L}\right) i_{Ln} \tag{10}$$

where value *h* is size of every step and setting $i_{Ln} = i_0 + n.h$. So, one step of the Euler method is from i_{Ln} to i_{Ln+1}.

Then as a discrete form has been obtain the equals can be used for create graphical waveforms of commutation process of current mode in the MATLAB environment.

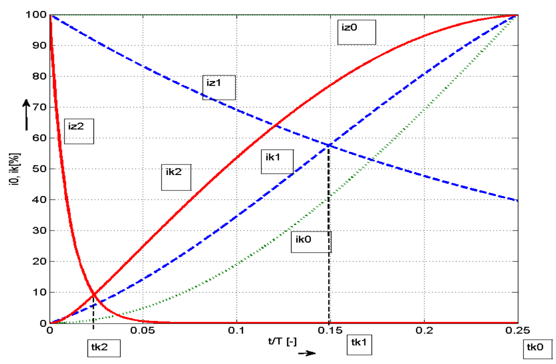

Figure 3: The dependenceof length of commutation on time constants τ_z in current mode

As an example on Fig. 4, the current waveforms measured in current mode.

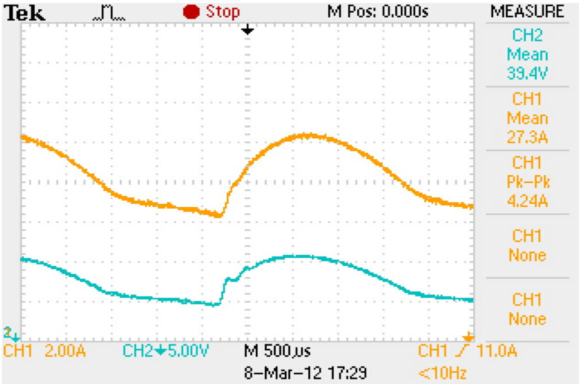

Figure 4:The current waveform (top) of 3-phase rectifier with commutation angle γ≅ 20 ° el. [3]

The commutation drop in rectified voltage depends directly on the reactance of commutation circuit and on rectified current (instantaneous value at the beginning of commutation).

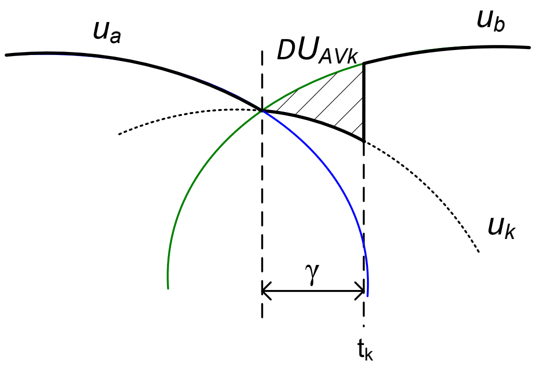

Figure 5: The commutation drop of rectifier voltage

The commutation voltage u_k is defined as

$$u_k = \frac{U_{AV}^{a}+U_{AV}^{b}}{2} \tag{11}$$

whereU_{AV}^{a} is average value of voltage phase *a* and U_{AV}^{b} is average value of voltage phase *b* and then

The average value of the output voltageU_{AVk} is [6]

$$U_{AVk}{}^{*} = \frac{3}{\pi}U_{max}^{ba} - \Delta U_{AVk} \tag{12}$$

Then commutation dropΔU_{AVk}

$$\Delta U_{AVk} = U_{AV}^{ba} - \frac{U_{AV}^{a}+U_{AV}^{b}}{2} \tag{13}$$

and consequently average value of rectifier current I_{AV} is

$$I_{AV} = \frac{U_{AVk}{}^{*}}{R} = \frac{3}{\pi}\frac{U_{max}^{ba}}{R} - \Delta U_{AVk} \tag{14}$$

Average value of the rectified current doesn't depend on load inductance, just on load resistance and commutation voltage drop. The commutation drop is, for negligible commutation time, equal zero.

Then

$$U_{AV} = U_{AV}^{*} - \Delta U_{AVk} = \frac{3}{\pi}U_m\{1 - \frac{\sqrt{3}}{2}[1 - \cos(\gamma)]\} \tag{15}$$

So,

$$I_{AV} = \frac{U_{AV}}{R} \tag{16}$$

3 Commutation process of rectifier in voltage mode

The schematic representation of the circuit in voltage mode is shown on the Figure 6. Compared to circuit of current mode the voltage mode circuit contains capacitor C (includes r_C) parallel connected to the load.

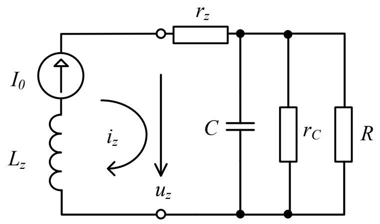

Figure 6: The circuitdiagramin the aftermath ofthe loadcurrentduringcommutation in voltage mode

The inductor L_z is the source of current I_0. Resistance of the inductor (r_z) and capacitor (r_C) may or may not bounder consideration. The current i_z is closing inside the circuit. By the circuit, fig. 4, the differential equations of the system may be created.

$$\frac{d}{dt}\begin{pmatrix} i_L \\ u_C \end{pmatrix} = \begin{pmatrix} -\frac{r_z}{L_z} & -\frac{1}{L_z} \\ 1/C & -\left(\frac{1}{r_C}+\frac{1}{R}\right)\frac{1}{C} \end{pmatrix}\begin{pmatrix} i_L \\ u_C \end{pmatrix} \tag{17}$$

Using numerical methods the discrete form may be obtained.

$$\frac{d}{dt}\bar{x}(t) = A\bar{x}(t) + B\bar{u}(t) \rightarrow \frac{\bar{x}_{n+1}-\bar{x}_n}{h} = A\bar{x}(t) + B\bar{u}(t) \tag{18}$$

Where A is the matrix of the system and B is the excitation matrix. The superposition of thecurrent tosourcecauses that the sources are notconsidered in circuit. So, the excitation matrix is not considered.

$$\bar{x}_{n+1} = \bar{x}_n + h\big(A\bar{x}(t)\big) \rightarrow \bar{x}_{n+1} = \Big(1 + h\big(A\bar{x}(t)\big)\Big)\bar{x}_n \tag{19}$$

Than the final matrix of the system is:

$$\begin{pmatrix} i_L \\ u_C \end{pmatrix}_{n+1} = \left[\begin{pmatrix} 1 & 0 \\ 0 & 1 \end{pmatrix} + h\begin{pmatrix} -\frac{r_z}{L_z} & -\frac{1}{L_z} \\ 1/C & -\left(\frac{1}{r_C}+\frac{1}{R}\right)\frac{1}{C} \end{pmatrix}\right]\begin{pmatrix} i_L \\ u_C \end{pmatrix}_n \tag{20}$$

After the system matrix in discrete form has been obtained the graphical waveform in MATLAB environment may be created.

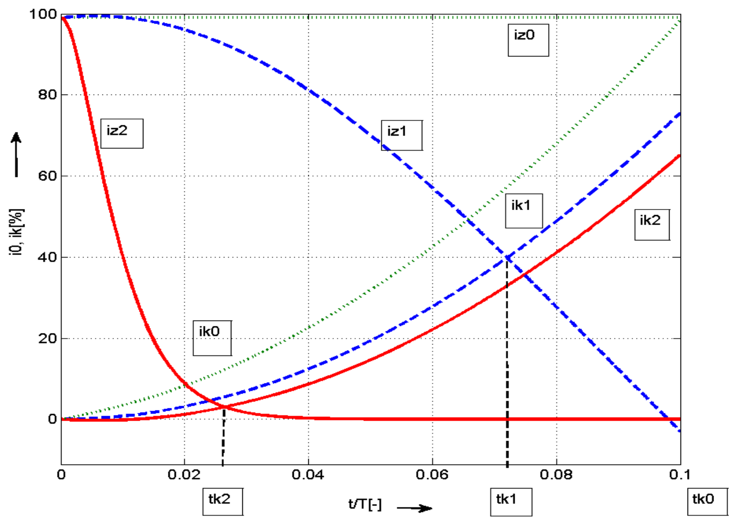

Figure 7: Depending of length of commutation on time constants τ_z in voltage mode

The average value of the output voltage is

$$U_{AVk}{}^{*} = \frac{3}{\pi} U_{max}^{ba} - \Delta U_{AVk} \tag{21}$$

and consequently average value of rectifier current is

$$I_{AV} = \frac{U_{AVk}{}^{*}}{R} = \frac{3}{\pi}\frac{U_{max}^{ba}}{R} - \Delta U_{AVk} \tag{22}$$

The commutation of the rectifier underway always between pair of diodes from the same group. The distance between commutations is 60°.

Thecalculation of the commutation drop in voltage mode of the rectifier has the same procedure as in the current mode.

4 The discussion of therectifier analysisresultsworked-out

The dependenceof the commutation drop of the time constant of both modes is given in Table 1 and Table 2..

Table 1: THE DEPENDENCE OF THE COMMUTATION DROP AND TIME CONSTANT OF CURRENT MODE

ΔU_{AVk}~f(t_k)	**t_{k0}**	**t_{k1}**	**t_{k2}**
t_k	*0,250*	*0,149*	*0,023*
ΔU_{AVk}	*93,717*	*37,002*	*0,928*

Table 2: THE DEPENDENCE OF THE COMMUTATION DROP AND TIME CONSTANT OF VOLTAGE MODE

ΔU_{AVk}~f(t_k)	**t_{k0}**	**t_{k1}**	**t_{k2}**
t_k	*0,100*	*0,071*	*0,022*
ΔU_{AVk}	*17,1448*	*8,509*	*0,703*

The graphical dependence of the commutation drop to the time constant of both modes is given in Figure 8.

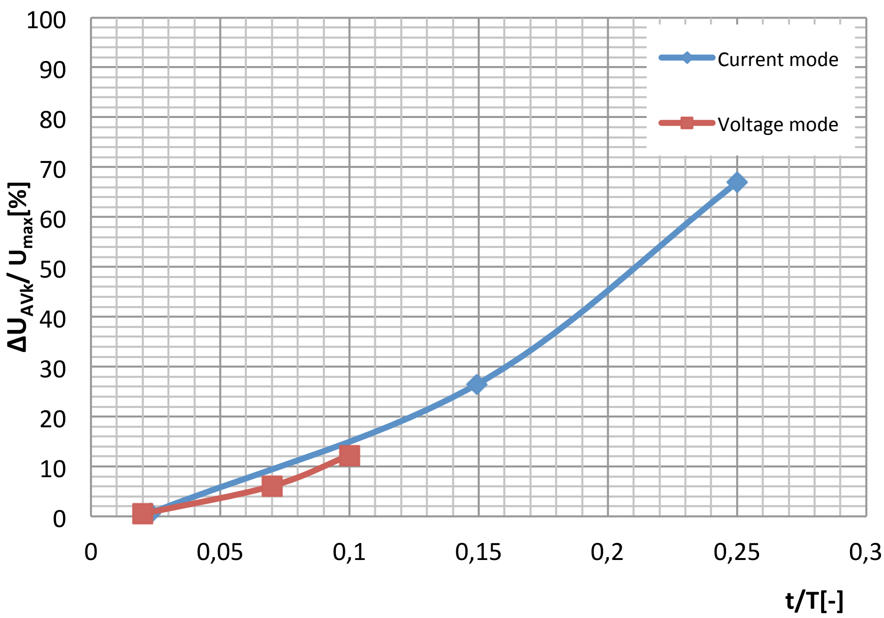

Figure 8: dependence of the commutation drop of the time constant of both modes

The Fig. 8 shows graphical dependence of the commutation drop of the time constant. On the vertical axes it ratio of commutation drop and the maximum voltage and on the horizontal axes is time constant. The waveform can be seen that with increasing commutation time the commutation drop increases.

Note: In the casethat the current value i_z is constant and time constant τ_z is "infinitely large "the commutation time analytically may be calculate.

Acknowledgment

The authors wish to thank to Slovak grant agency VEGA for project no. 1/0943/11.

References

[1] Huo, F. L.; Ye, H.,*Power Electronics: Advanced Conversion Technologies*, Boca Raton: CRC Press, Taylor&Francis Group, 2010, pp. 29–64.

[2] Sikora, A., Kulesz, B.,*Influence of Diode Commutation Processes on Rectifier Transformers Operation*, Proc. of XIX Int'l Conf. on Electrical Machines - ICEM 2010, Roma, Italy, 2010, pp...

[3] Dobrucký, B., Kúdelčík, J., Vavrúš V., Rafajdus,P.,*Transient Analysis of Power Cable for Ultra-Deep Geothermal Wells*, Proc. of LVEM'12 Int'l Conf. on Low Voltage Electrical Machines, Brno (CZ), Oct. 2012, pp. CD-ROM.

[4] Ráček, V., Solík, I.,*Power Semiconductor Systems II-III* (in Slovak: "Výkonové polovodičové systémy II-III"), Bratislava, NALC Publisher, 1993, Chap. II.3, pp. 14-35.

[5] Vondrášek, F.: *Power electronic II*, (in Czech: "Výkonová elektronika, svazek *II*"), Plzeň, ZČU Plzeň, 1994,Chap.IV,pp. 25-90, ISBN 80-7082-137.

[6] Bečka, J.,*Rectifying Technique Handbook* (in Czech: "Příručka usměrňovací techniky"), Prague, SNTL Publisher, 1971, Chaps. III-IV, pp. 46-109.

JurajKoscelník
Department of Mechatronics and Electronics, Faculty of Electrical Engineering, University of Zilina, Address: Univerzitna 1, SK-010 26 Zilina, Slovakia, Tel.: +421-41-513 1604,
e-mail: juraj.koscelnik@fel.uniza.sk

Mariana Beňová
Department of Electromagnetic Field and Biomedical Engineering, Faculty of Electrical Engineering, University of Zilina, Address: Univerzitna 1, SK-010 26 Zilina, Slovakia, Tel.: +421-41-513 2119,
e-mail: mariana.benova@fel.uniza.sk

BranislavDobrucký
Department of Mechatronics and Electronics, Faculty of Electrical Engineering, University of Zilina, Address: Univerzitna 1, SK-010 26 Zilina, Slovakia, Tel.: +421-41-513 1602,
e-mail: branislav.dobrucky@fel.uniza.sk