Journal of Engineering and Applied Sciences 11 (Special Issue 1): 2939-2945, 2016
ISSN: 1816-949X

Local Fourier Transformation Application for Mathematic Modeling of Synchronous Machine Valve Actuator

A.I. Fedotov, E.I. Gracheva, E.A. Fedotov and N.V. Chernova
Kazan State Power Engineering University, Kazan, Russia

Abstract: The study describes the application technique of Fourier mathematical device for local transformation in relation to the description of transient processes in the electrical circuits containing controlled rectifiers. It was shown that this transformation allows to perform the transition from a variable structure system to a permanent structure system of a discrete species using the example of a synchronous machine valve exciter. The presented results of numerical calculations showed the discrete model adequacy.

Key words: Fourier Local Transformation (FLT), mathematical model, valve exciter, synchronous machine, transient process, electric technical facility

INTRODUCTION

Problem formulation: Modern synchronous machines with the power of several megawatts and more have valve actuators. During the mathematical modeling of transient electromagnetic processes in such Electric Machinery Valve Systems (EMVS) the accuracy of the obtained results will be determined primarily by the combination representation adequacy of discrete operating elements (actuator valves) and a synchronous machine, where a continuous transformation of energy takes place.

A classic technique for the solution of a joint mathematical description problem for the discrete and continuous EMVS structure "a controlled inverter-a synchronous machine actuator" is to use the alignment method (Glebov, 1960; Williamson and Volshenk, 1995). In this case, the whole process is divided into the intervals of constant circuit structure of the whole EMVS determined by a set of conductive valves in an exciter power rectifier. The end of the current interval and thus the beginning of a new interval are determined by either by a switched valve closure (interval switching end) or by another valve opening at a control signal supply (the end of a working interval).

One should keep in mind that the duration of each interval in the transition process changes which conditions the application of the alignment method for numerical calculations exclusively. The analytical methods of bringing the variable structure EC to a permanent structure system based on the introduction of "an undistorted EMF" (Glebov, 1960) are based on serious simplified representation of the interaction process between two components (a discrete and a continuous one) of EMVS and they give only a qualitative assessment of the transition processes. The method of a mathematical model development concerning a permanent structure of considered EMVS through the use of Fourier local transformation which allows you to withdraw from consideration the local transient processes associated with the switching of rectifier valves feeding a synchronous machine actuator due to the transition from continuous to discrete variables (Kuznetsov and Fedotov, 1995a, b; Fedotov and Marfin, 2013; Fedotov *et al*., 2008, 2003; Abdullazyanov *et al*., 2015). It develops the ideas set out by Beregovenko *et al*. (1993) and can be considered as the generalization of the local integral transformation.

FLT theoretical bases: Let's name the following integral by Fourier local transformation (F-conversion):

$$F\{f(t)\} = F(m,k) = \frac{2}{h^{(m)}} \int_{t^{(m)}}^{t^{(m)}+h^{(m)}} f(t) e^{-jk\left(t-t^{(m)}\right)} dt \qquad (1)$$

where; $2\pi n/h^{(m)} = \omega^{(m)} n$; $n = 0\pm1\pm2\pm, ...$; $m = 1, 2, ...$ and $F(m, k)$ is called by the local image (F-image) of function. A reverse transition from the image to the original brings an original continuous function to a discrete form:

$$f\left(t^{(m)}\right) = \frac{1}{2}\sum_{n=-\infty}^{\infty} F(m,k) - \frac{1}{2}\Delta f\left(t^{(m)}\right)$$

If F-image can be represented in the following form:

$$F(m,k) = \sum_{i=1}^{I} D(jk) A_i(m)$$

Then on the basis of subtraction theorem (Ango, 1965), we find that:

Corresponding Author: A.I. Fedotov, Kazan State Power Engineering University, Kazan, Russia

$$\sum_{n=-\infty}^{\infty} F(m,k) = -j\pi \sum_{i=1}^{I} A_i(m) \sum_{s=1}^{S} b_{si} ctg(j\pi a_{si}) \qquad (2)$$

where, S is the number of (simple) function poles of the complex variable D(p) the subtractions of which in the poles $p = a_{si}$ are equal to b_{si}. The function D(p) is derived $D(jk) = D(j\omega^{(m)}n)$ from by the substitution of jn = p. In the case of actual values$_{si}$ it is convenient to use that:

$$\pi ctg(j\pi a_{si}) = \pi cth(\pi a_{si})$$

If d(jk) develops the final sequence according to n, the Eq. 2 is not applied and you should use direct summation formula:

$$f\left(t^{(m)}\right) = \frac{-j\pi}{2} \sum_{i=1}^{I} A_i(m) \sum_{s=1}^{S} b_{si} ctg(j\pi a_{si}) - \frac{1}{2}\Delta f\left(t^{(m)}\right)$$

The use of F-transformation to a series of functions gives the following result.

Function derivative:

$$F\left\{\frac{df(t)}{dt}\right\} = \frac{2}{h^{(m)}} \int_{t^{(m)}}^{t^{(m)}+h^{(m)}} \frac{df(t)}{dt} e^{-jk(t-t^{(m)})} dt = \frac{2}{h^{(m)}} \Delta f_1^{(m)} + jkF(m,k) \qquad (3)$$

Constant parameter: Let f(t) = c = const:

$$F\{c\} = \frac{2}{h^{(m)}} \int_{t^{(m)}}^{t^{(m)}+h^{(m)}} c\, e^{-jk\left(t-t^{(m)}\right)} d\theta = \begin{cases} 2c, k = 0 \\ 0,\ k \neq 0 \end{cases} \qquad (4)$$

Trigonometric functions: Let f(t) = sin(at-α) and K = ±a at some values n then:

$$F\{\sin(at-\alpha)\} = \begin{cases} -je^{j(at^{(m)}-\alpha)},\ k = a; \\ je^{j(at^{(m)}+\alpha)},\ k = -a; \\ 0,\quad k \neq \pm a \end{cases} \qquad (5)$$

The presented formulas do not exhaust FLT properties of PSL but they are sufficient for the understanding of subsequent material.

MATERIALS AND METHODS

Actuator mathematical model development with control valves: Let's assume that the actuator of the synchronous machine is fed via a controllable converter from the mains, Fig. 1. Actuator valves are located along a bridge circuit, the valves are ideal, the inverter output is connected to the excitation winding of the synchronous machine with the active resistance rf and inductive resistance xf. The influence of the stator winding is not considered for the clarity of the proposed method while the bringing of its mathematical model to a discrete form is not difficult. On the part of the supply network we take into account the phase resistances r_c, x_c. The inductive resistances are specified for the industrial frequency ω. Network EMF form a direct sequence:

$$e_a = E\sin\theta,\ e_b = E\sin(\theta - 2\pi/3),$$
$$e_c = E\sin(\theta - 4\pi/3),\ \theta = \omega t$$

The estimated equivalernt circuit is shown on Fig. 2. Let's choose a sampling interval h equal to the angular measure of the transducer repeatability interval: h = π/3. To be specific, let's assume that the valve converter operates in the first mode the mode of alternate conduction for two and three valves and rectified current a continuous one.

We use a step coordinate system in which the initial reference point of a time coordinate is shifted discretely by π/3 during each turning on of a new valve. The control angle α at each interval is calculated from the zero value of phase EMF.

The numbering of the mains phases is purely arbitrary and makes no effect on the course of electromagnetic processes. Therefore, we assume without the loss of generality that the anode group valve of the phase "a" comes into operation.

The estimated equivalent circuit at switching intervals γ is shown on Fig. 2a. The corresponding balance equation of voltages for the circuit that includes the load:

$$(2r_c + r_f)i_f + (2x_c + x_f)\frac{di_f}{d\theta} - \left(r_c i_\gamma + x_c \frac{di_\gamma}{d\theta}\right) = e_a - e_b,\quad \theta \in [\alpha; \alpha+\gamma] \qquad (6)$$

On the non-switching interval we have the following, Fig. 2:

$$(2r_c + r_f)i_f + (2x_c + x_f)\frac{di_f}{d\theta} = e_a - e_b,\quad \theta \in [\alpha+\gamma; \alpha+\pi/3] \qquad (7)$$

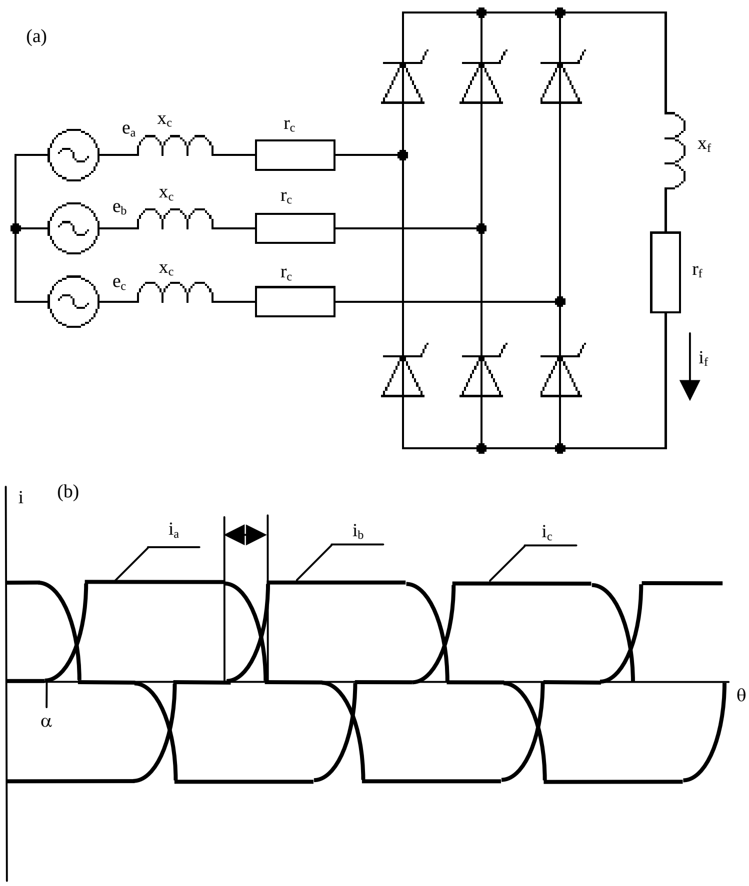

Fig. 1: Valve actuator of the synchronous machine-principal diagram of the valve converter; diagram of the inverter phase currents

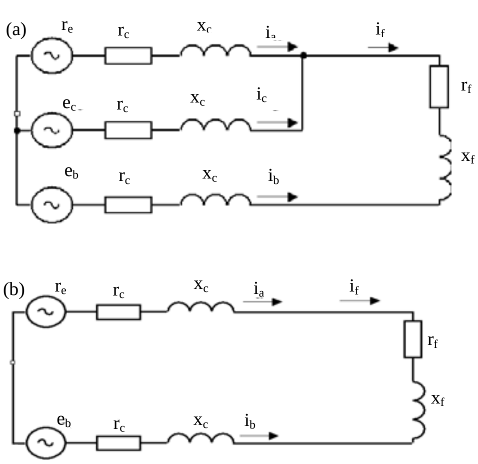

Fig. 2: Actuator substitution diagrams substitution diagram for switching interval; substitution diagram for non-switching interval

The following boundary conditions are fair for the switching current i_γ:

$$i_\gamma(\alpha) = i_f(\alpha); \quad i_\gamma(\alpha+\gamma) = 0$$

The Eq. 6 and 7 can be combined by the introduction of a switching multiplierk (θ-γ):

$$\begin{aligned}&(2r_c + r_f)i_f + (2x_c + x_f)\frac{di_f}{d\theta} - K(\theta-\gamma)\left(r_c i_\gamma + x_c\frac{di_\gamma}{d\theta}\right) = e_a - e_b\\&K(\theta-\gamma) = 1(\theta-\alpha) - 1(\theta-\alpha-\gamma); \quad \theta \in [\alpha; \alpha+\pi/3]\end{aligned} \tag{8}$$

where, 1(θ-α), 1(θ-α-γ) are the single functions in fact. Let's apply EMF Eq.1-8. Taking into account the boundary conditions for the switching of current and an assumed value h = π/3 we obtain the following:

$$\left(r_s + jkx_s\right)\dot{I}_f(m,k) + \frac{6x_s}{\pi}\Delta i_f^{(m)} + \frac{6x_c}{\pi} i_{1f}^{(m)} - \frac{6\left(r_c + jkx_c\right)}{\pi} \times \int_{\alpha}^{\alpha+\gamma^{(m)}} i_\gamma e^{-jk(\theta-\alpha)} d\theta = -\frac{6\sqrt{3}}{\pi} E \frac{\cos\left(\alpha - \pi/6\right) + jk\sin\left(\alpha - \pi/6\right)}{(k^2 - 1)} \quad (9)$$

where, $r_s = 2r_c+rf$, $x_s = 2x_c+xf$. From the Eq. 9 we find the expression for the rectifying load current in the field of F-images:

$$\dot{I}_f(m,k) = -\frac{6\sqrt{3}}{\pi} E \frac{\cos\left(\alpha - \pi/6\right) + jk\sin\left(\alpha - \pi/6\right)}{\left(r_s + jkx_s\right)(k^2 - 1)} - \frac{6}{\pi}\frac{x_s\Delta i_f^{(m)} + x_c i_{1f}^{(m)}}{\left(r_s + jkx_s\right)} + \dot{A}(m,k)\frac{r_c + jkx_c}{r_s + jkx_s} i_{1f}^{(m)},$$
$$k = 6n, \quad n = 0, \pm 1, \pm 2, \cdots \quad (10)$$

where, A(m,k) the coefficient which depends on the accepted approximation of the switching current i_γ. Let us turn now from the images to the finite differences. The first two terms in the Eq. 10 are converted in an analytical form. The third term is convenient to converted into numerical form, performing the summation in accordance with the Eq. 10. Let's put down the first two terms of the Eq. 10 right side in the following form after the substitution 6jn = 6p:

$$I_{1f}(p) = -\frac{6\sqrt{3}}{\pi} E \frac{\cos\left(\alpha - \pi/6\right) + 6p\sin\left(\alpha - \pi/6\right)}{\left(r_s + 6px_s\right)(-36p^2 - 1)} - \frac{6}{\pi}\frac{x_s\Delta i_f^{(m)} + x_c i_{1f}^{(m)}}{\left(r_s + 6px_s\right)}$$

The corresponding poles:

$$a_1 = -\frac{r_s}{6x_s}, \; a_2 = j\frac{1}{6}, \; a_3 = -j\frac{1}{6}$$

Then:

$$I_{11f} = -j\pi\frac{1}{2}\frac{6\sqrt{3}}{\pi} E \frac{\cos\left(\alpha - \pi/6\right) - 6\frac{r_s}{6x_s}\sin\left(\alpha - \pi/6\right)}{6x_s\left(36\frac{r_s^2}{36x_s^2} + 1\right)} \mathrm{ctg}\left(-j\pi\frac{r_s}{6x_s}\right) -$$
$$j\pi\frac{1}{2}\frac{6\sqrt{3}}{\pi} E \frac{\cos\left(\alpha - \pi/6\right) + 6j\frac{1}{6}\sin\left(\alpha - \pi/6\right)}{\left(r_s + 6j\frac{1}{6}x_s\right) * 2 * 36j\frac{1}{6}} \mathrm{ctg}\left(-j\pi j\frac{1}{6}\right) -$$
$$j\pi\frac{1}{2}\frac{6\sqrt{3}}{\pi} E \frac{\cos\left(\alpha - \pi/6\right) - 6j\frac{1}{6}\sin\left(\alpha - \pi/6\right)}{\left(r_s - 6j\frac{1}{6}x_s\right) * 2 * 36\left(-j\frac{1}{6}\right)} \mathrm{ctg}\left(j\pi j\frac{1}{6}\right) -$$
$$j\pi\frac{1}{2}\left[-\frac{6}{\pi}\frac{x_s\Delta i_f^{(m)} + x_c i_{1f}^{(m)}}{6x_s} \mathrm{ctg}\left(-j\pi\frac{r_s}{6x_s}\right)\right]$$

After the performance of intermediate transformations taking into account that:

$$-j\mathrm{ctg}\left(-j\pi\frac{r_s}{6x_s}\right) = \mathrm{cth}\left(\pi\frac{r_s}{6x_s}\right) = \frac{\dfrac{e^{\pi r_s/6x_s} + e^{-\pi r_s/6x_s}}{2}}{\dfrac{e^{\pi r_s/6x_s} - e^{-\pi r_s/6x_s}}{2}} = \frac{1 + e^{-\pi r_s/3x_s}}{1 - e^{-\pi r_s/3x_s}}, \; \cos\phi_s = \frac{r_s}{z_s}, \quad \sin\phi_s = \frac{x_s}{z_s},$$
$$z_s = \sqrt{r_s^2 + x_s^2}, \quad \mathrm{ctg}\left(\frac{\pi}{6}\right) = \sqrt{3},$$

We obtain the following:

$$i_{1f}^{(m)} = \frac{\sqrt{3}E}{z_s}\frac{\cos\left(\alpha - \phi_s\right) - \cos\left(\alpha - \phi_s - \pi/3\right)e^{-\pi r_s/3x_s}}{1 - e^{-\pi r_s/3x_s}} - \left(\frac{1}{e^{-\pi r_s/3x_s}} - \frac{1}{2}\right)\Delta i_f^{(m)} - \frac{x_c}{2x_s}\frac{i_{1f}^{(m)}}{e^{-\pi r_s/3x_s}}. \quad (11)$$

While:

$$i_f^{(m)}(\alpha) = i_{1f}^{(m)} = i_{1f}^{(m)} - \frac{1}{2}\Delta i_f^{(m)} + a_\gamma i_{1f}^{(m)} \quad (12)$$

Where:

$$a_\gamma = \frac{1}{2i_{1f}^{(m)}}\sum_{n=-\infty}^{n=\infty}\frac{6}{\pi}\frac{r_c + j6nx_c}{r_s + j6nx_s}\int_{\alpha}^{\alpha+\gamma^{(m)}} i_\gamma e^{-j6n(\theta-\alpha)} d\theta$$

Substituting the Eq. 11 into the Eq. 12 we obtain the following at last:

$$i_{1f}^{(m)} = \frac{\sqrt{3}E}{z_s}\frac{\cos\left(\alpha - \phi_s\right) - \cos\left(\alpha - \phi_s - \pi/3\right)e^{-\pi r_s/3x_s}}{1 - e^{-\pi r_s/3x_s}} - \frac{1}{1 - e^{-\pi r_s/3x_s}}\Delta i_f^{(m)} - \frac{x_c}{2x_s}\frac{1 + e^{-\pi r_s/3x_s}}{1 - e^{-\pi r_s/3x_s}} i_{1f}^{(m)} + a_\gamma i_{1f}^{(m)} \quad (13)$$

The equation in finite differences Eq. 13 must be brought to the canonical form:

$$\Delta i_f^{(m)} = \sqrt{3}E\frac{\cos(\alpha-\phi_s)-\cos(\alpha-\phi_s-\pi/3)e^{-\pi r_s/3x_s}}{z_s} - \left[(1-a_\gamma)(1-e^{-\pi r_s/3x_s}) + \frac{x_c}{2x_s}(1+e^{-\pi r_s/3x_s})\right]i_{1f}^{(m)} \quad (14)$$

Strictly speaking Eq. 14 is not a linear one, since the coefficient αγ depends on the duration of the switching interval which depends on the rectified current value by a complicated way. However, as studies showed αγ makes the impact on the accuracy of transient processes within a few percent and this rate is sufficient to determine from the conditions of a set mode at a rectilinear approximation of the switching current form. In this case the switching angle can be determined by the converter operation at a fully smoothed rectified current:

$$\cos(\alpha+\gamma-\pi/6) = \left[1-\frac{6x_c/\pi}{(2-3\gamma/2\pi)r_c + r_f + 3x_c/\pi}\right]\cos(\alpha-\pi/6) \quad (15)$$

For this case, when you can assume that $x_s >> r_s$, x_c one may consider that$\varphi s \approx \pi/2$, $e^{-}\pi r_s/\approx 1\text{-}\pi rs/3x_s \approx\ \alpha_r \approx (3\gamma/2\ \pi)$ rc/rs and the equation (14) attains a simpler form:

$$\left(r_s - \frac{3\gamma}{2\pi}r_c + \frac{3}{\pi}x_c\right)i_{1f}^{(m)} + \frac{3}{\pi}x_s\Delta i_f^{(m)} = \frac{3\sqrt{3}}{\pi}E\cos\left(\alpha-\frac{\pi}{6}\right) \quad (16)$$

The obtained expression (Eq. 16) reduces the initial system of a variable structure to a permanent structure system and describes an electromagnetic transient process by a discrete form in the valve exciter with an idle operation of a synchronous machine.

If the synchronous machine is loaded, the algorithm of equation development for electric machine valve system is the following one. The transformation (1) is applied to the classical Park-Gorev equations (Vazhnov, 1960) and the Eq. 8 of the actuator is transformed to the following form:

$$u_f + 2r_c i_f + 2x_c\frac{di_f}{d\theta} - K(\theta-\gamma)\left(r_c i_\gamma + x_c\frac{di_\gamma}{d\theta}\right) = e_a - e_b \quad (17)$$

Applying the transformation (Eq. 1) to the Eq. 17 we have the following:

$$\dot{U}_f(m,k) + (r_c + jkx_c)\dot{I}_f(m,k) + \frac{6}{\pi}\left(x_s\Delta i_f^{(m)} + x_c i_{1f}^{(m)}\right) - \dot{A}(m,k)i_{1f}^{(m)} = -\frac{6\sqrt{3}}{\pi}E\frac{\cos(\alpha-\pi/6)+jk\sin(\alpha-\pi/6)}{k^2-1} \quad (18)$$

Collectively with the F-images of Park-Gorev equations, Eq. 18 forms a closed system of equations that can be solved analytically using the Eq. 2 or numerically for a limited number of considered series members. Thus, the system of finite-difference EMVS equations of the permanent structure will be developed.

Since, the greatest interest is the verification of the display adequacy of the valve part of the system with respect to transit macro-processes, the calibration calculations according to the proposed mathematical model are presented for a controlled rectifier connected to the active-inductive load which corresponds to idling operation of the synchronous machine. Benchmark calculations were performed by the integration of differential equations in the instant variable values ??at the intervals of converter constancy structure. The alignment method was used to set the initial values of load current on each new interval.

RESULTS AND DISCUSSION

Numerical example: The initial constant data for the following calculations: r_c = 0.5 Ohms; r_f = 5 Ohms; x_c = 4 Ω E = 100 V. The mode 1 and 2 accepted the following: x_f = 30 Ω and α = 60°; the modes 3 and 4 accepted the following: x_f = f = 6 Ω and α = 60°; the modes 3 and 4 accepted the following: x_f = 6 Ω and α = 110°.

Figure 3 shows the values of the rectified current in the reference points of each new interval in which discrete variables were defined according to Eq. 14. The shape of the rectified current during all stage of the transition process was presented for mode 2 and only in the steady process for other modes. For clarity, the discrete values ofcurrents are interconnected by line segments. The forms of instantaneous current for each mode are presented in the set mode.

The set switching angles were determined from the calculations according to the instantaneous values of variables r_p and according to Eq. 15 r_u. The coefficients r_p were calculated according to the values of αγ. Calculation results are presented in Table 1. The calculations of rectifier load current $i^{(m)}{}_{if}$ coincided almost completely with the instantaneous values of this current in the corresponding points-the error does not exceed 2%, at that the values of were used, presented in Table 1.

The calculations according to Eq. 16 were also carried out which in the conditions of the accepted assumption determine not only current $i^{(m)}{}_{if}$ but the average value of the rectified current at each interval, i.e., $i^{(m)}{}_{if}$. The comparison with the calculations according to the instantaneous valuesof the variables showed that the difference does not exceed 5%. Thus, if the calculations

Table 1: Calculation parameters in various modes of a converter

Mode number	Control angle $\alpha_0 = \alpha$-30 (g)	Switching angle γ_p (g)	Switching angle γ_u (g)	α_γ r.u.
1	30	0.86	0.87	0.0496
2	30	0.13	0.14	0.0488
3	80	0.85	0.87	0.0650
4	80	0.12	0.14	0.1207

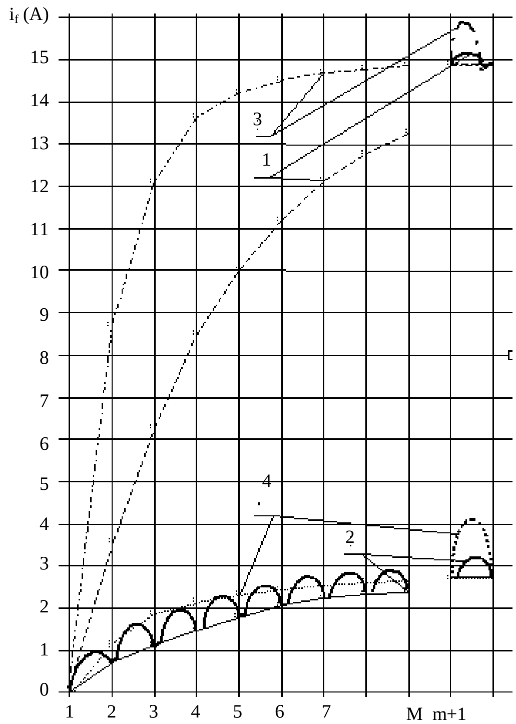

Fig. 3: The current in rectifying load during a transient process. 1, 2, 3, 4 calculation modes

are performed according to the "useful" part of the rectified current, then it is permissible to use a simpler Eq. 16, where the calculations of α_γ coefficient included in the Eq. 13 is not required.

The transition from the system of variable structure, conditioned by the presence of valves to the system of a permanent structure is possible due to the exclusion of local transient processes from consideration associated with the switching of valves. The mechanism of this transition implementation is the use the local Fourier transformation on the interval of a circuit structure repetition. The cost of this is the loss of information about the process within the sampling intervals. During the formulation of an adequate representation task in respect of electromagnetic transient processes in an electric power system, the part of which are the synchronous generators. Macro processes are of interest, in respect to which mathematical models are developed using LVF. If, however, the task of valve converter parameter selection is set,an adequate representation of local electromagnetic processes is absolutely necessary, possible only on a variable structure model.

Numerical calculations show that at high angles of valve control the rectified current pulsation becomes visible which can lead to an inaccurate assessment of active power losses in an excitation winding at the use of a synchronous machine discrete mathematical model. Thus, as can be seen from the calculations the values of discrete currents coincide with the instantaneous values of continuous currents. Hence, knowing the original values of current at the beginning of each interval, determined on a discrete model, it is possible to calculate an exact shape of a rectified current at each interval of a converter repetition if it is necessary to evaluate a coil heating during a transient process at big pulsations of the rectified current.

CONCLUSION

The discrete Fourier transformation allows to bring the differential equations of an electric machine valve system of a variable structure to the permanent structure equations in F-image area. Further, they can be reduced to the equations of a finite-difference type either analytically or numerically. Local transient processes caused by the switching of valves are accounted by indirect nonlinear coefficient which can be replaced by a constant factor, calculated for a steady state.

The use of finite-difference equations with a sampling interval equal to the period of valve converter repeatability in the automatic control systems by power system modes. By the virtue of numerical calculation multiple acceleration on discrete models it is possible to "predict" the development of an emergency mode and a proactive development of control actions by emergency equipment.

ACKNOWLEDGEMENTS

The results presented in the study are obtained within the framework of R&D "Power supply reliability and power quality improvement methods in distribution networks" (the task No. 2014/448 for public work performance in the field of scientific activity as the basic part of the Russian Education and Science Ministry).

REFERENCES

Abdullazyanov, E.Y., A.I. Fedotov, S.N. Zaripova, E.A. Fedotov and N.V. Chernova *et al*., 2015. Theoretical basis of the mathematical modeling of thyristor converters for calculation current and voltage harmonics in power system. Mod. Appl. Sci., 9: 320-343.

Ango, A., 1965. Mathematics for Electrical and Radio Engineers. Fizmatgiz Publisher, Moscow, Russia, Pages: 779.

Beregovenko, G.Y., G.E. Pukhov and S.E. Sauh, 1993. Numerical Operator Methods for Differential Equation Solution and the Analysis of Dynamic Systems. Naukova Dumka Publishers, Kiev, Ukraine, Pages: 264.

Fedotov, A.I. and V.V. Marfin, 2013. Mathematical model of synchronous motor exciter on the basis of equivalent equations. Proc. Univ. Energe. Prob., 1: 142-146.

Fedotov, A.I., A.N. Krivov and S.V. Bezugly, 2008. Mathematical model of valve actuator permanent structure in continuous variables. Energe. Prob., 3: 83-87.

Fedotov, A.I., R.R. Karimov, E.A. Fedotov and E.Y. Abdullazyanov, 2003. Theoretical basics of discrete simulation for electric machine valve systems. Scientific Publication, Kazan, Russia, Pages: 120.

Glebov, I.A., 1960. Excitation Systems of Synchronous Generators with Controlled Converters. Publishing House of the USSR Academy of Sciences, Russia, Pages: 335.

Kuznetsov, V.A. and A.I. Fedotov, 1995a. Mathematical model of synchronous generator with rectifier load. Electr. Technol., 2: 19-27.

Kuznetsov, V.A. and A.I. Fedotov, 1995b. Analysis of a synchronous machine with a harmonic excitation system by means of a discrete current method. Electr. Technol., 4: 109-121.

Vazhnov, A.I., 1960. Theory Basics of Transient Synchronous Machine Processes. Gosenergoizdat Publisher, Moscow, Russia, Pages: 312.

Williamson, S. and A.F. Volschenk, 1995. Time-stepping finite element analysis for a synchronous generator feeding a rectifier load. IEEE. Proc. Electr. Power Appl., 142: 50-56.