

NEWS

OF THE NATIONAL ACADEMY OF SCIENCES OF THE REPUBLIC OF KAZAKHSTAN
PHYSICO-MATHEMATICAL SERIES

ISSN 1991-346X

<https://doi.org/10.32014/2020.2518-1726.18>

Volume 2, Number 330 (2020), 80 – 87

УДК:535.4

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**EXPERIMENTAL RESEARCHES OF JUMP-SHAPED CHANGES
OF CURRENT AND VOLTAGE IN TRANSIENT
SWITCHING CIRCUITS OF AC GENERATION**

Abstract. The article considers the transient process in switching electrical circuits, which are available in electric current generators in the form of a surge of supercurrents and voltage when removing, from isolated plates, brushes and which are lost in unused form. These bursts in collected form account for about-30-35% of the energy generated by the generator. The work is devoted to analysis of the available theoretical works on transients and experimental study of current surges and voltage in switching circuits, similar in electric motors and elk-regenerators. The results are given of the experimental study in the switching circuits of the electric generator in the work.

Keywords: current intensity, voltage, oscilloscope, oscillogram, delay line, switching, transient processes, current and voltage hopping, electro motoring force-EMF.

Introduction Here, it is necessary to recall the evolution of the development of an electromagnetic field based on Faraday 's experiments "on the relationship of a changing magnetic field to the appearance of a changing induction current," and Ersted 's experiments "that, a changing electric field is accompanied by a changing magnetic field." Another consequence of the field theorem should be mentioned. Let there be a turn through which the current arising from the Volt battery flows. Suddenly, the conductor 's connection to the current source breaks. Now, of course, there's no current! But at the moment of this brief break, there is a complex process that can again be predicted by field theory. There was a magnetic field around the conductor before the current broke. It ceased to exist when the current was interrupted. Consequently, due to the current rupture, the magnetic field disappeared. The number of force lines passing through the surface surrounded by the chain changed very rapidly. But such a rapid change, no matter how fast it occurs, should cause an induction current. What really matters are that it is the change in the magnetic field that excites the induction current, the stronger the field change is. This conclusion is another test of theory. The current break must be accompanied by a strong short-term induction current. The experiment again confirms the prediction of the theory. Whoever ever broke the current noticed that there was a good spark. This spark indicates a huge potential difference caused by a rapid change in the magnetic field. The spark has quite considerable energy, so the magnetic field must have no less energy. To consistently apply the concept of field and its language, we must view the magnetic field as a supply of energy. Only by taking this path will we be able to describe magnetic and electrical phenomena in accordance with the law of energy conservation. - (A. Einstein, L. Infeld-Evolution of Physics, M. ed. ACT, 2018, c-151) All this determines the importance of considering switching analysis methods. Switching refers to any change in circuit parameters, its configuration, connection or disconnection of sources, which leads to transient processes. Switching will be considered instantaneous, but the transition process, as noted above, will take some time. In theory, it takes infinitely long to complete the transition,

but in practice it is taken to be finite, depending on the parameters of the chain. Let us assume that switching is performed using the ideal key K (figure 1), whose resistance in the open state is infinitely large, and in the closed state is zero. The direction of closing or opening the key will be indicated by the arrow. We will also consider, unless otherwise stated, that switching takes place at the time of $t = 0$. The first and second switching laws are distinguished. The first switching law is related to the continuity of the change of the magnetic field of the inductor $WL = Li^2/2$ and states that at the initial moment $t = 0$ immediately after switching, the current in the inductance has the same value as at the moment $t = 0-$ before switching and from this moment gradually changes (hereinafter $f(0-)$ means the left-hand limit of the function $f(t)$ if $t \rightarrow 0-$, and under $f(0+) -$ right-hand limit $f(t)$ if $t \rightarrow 0+$)

$$i_L = i_L(0+) \tag{1}$$

The second switching law is related to the continuity of the change of the electric field of the capacity $WC = Cu^2/2$: at the initial moment $t = 0$ immediately after switching, the voltage on the capacity has the same value as at the moment $t = 0-$ before switching and from that moment gradually changes:

$$U_C(0-) = U_C(0+) \tag{2}$$

In contrast to the current in the iL inductance and the voltage at the uC capacitance, the voltage at the inductance uL and the current in the iC capacitance can be varied by a jump since according to (1. 9) and (1. 12) they are derived from iL and uC and are not directly related to magnetic and electric field energy. The values of the currents in the inductance of the $iL(0)$ and the voltages at the capacitances of the $uC(0)$ form the initial conditions of the task. Depending on the initial energy state of the circuit, two types of transient calculation tasks are distinguished: tasks with zero initial conditions, when immediately after switching (at $t = 0$) $iL(0) = 0$; $uC(0) = 0$ (i.e. $WL(0) + WC(0) = 0$) and tasks with non-zero initial conditions when $iL(0+) \neq 0$ and/or $uC(0+) \neq 0$ (i.e. $WL(0) + WC(0) \neq 0$). The zero and non-zero values of the initial conditions for iL and uC are called independent and the initial conditions of the remaining currents and stresses are dependent. Independent initial of conditions is determined by switching laws (1) and (2).

The classical method of calculating transients in electrical circuits is based on the compilation of integral-differential equations for instantaneous values of currents and voltages. These equations are derived from Kirchof laws, contour current methods, nodal stresses, and can contain both independent and dependent variables. For ease of solution, it is generally accepted to draw up differential equations with respect to an independent variable, which may be iL or uC . Solving the obtained differential equations with respect to the selected variable and constitutes the essence of the classical method.

Considering that in some cases the solution of differential equations is simpler than integral-differential equations, the obtained system is reduced to one differential equation of the corresponding order relative to the selected independent variable iL or uC . The order of the differential equation is determined by the number of independent electric and magnetic field energy accumulators. Denote an independent of variable (iL or uC) through $x = x(t)$.

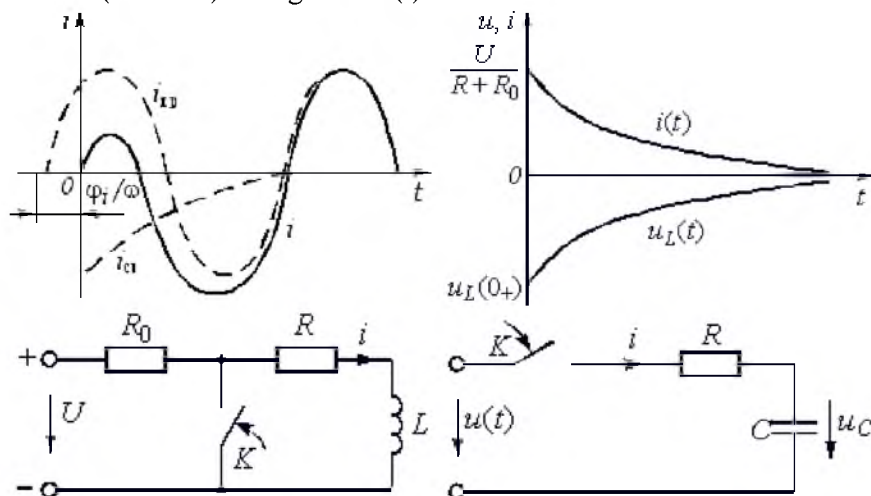


Figure 1

Analysis of the equations shows that in the case $\omega \gg \omega_0$ where the frequency of the applied voltage is substantially higher $\omega \gg \omega_0$ where $\varphi_C \approx 0$ has the resonant frequency of loop 0 at $C \rightarrow 0$, the circuit may be overvoltage, and in the case of $\omega \ll \omega_0$ и $\varphi_C \approx \pi/2$ — overcurrents.

Analysis of equation shows that in the case of a circuit connection to source $u(t)$ at the moment when $\varphi_u = \varphi \pm \pi/2$ Supercurrents may occur in the latter. If the chain time constant τ large enough, then the surge of current in the initial period can reach $i_{\max} \approx 2Im$. In contrast, when the circuit is switched on, when $\varphi_u = \varphi$, In it immediately comes a steady-state regime. Similar picture is observed with voltage of inductance.

As a calculation example, consider the case of non-zero initial conditions in the RL chain. Magnetic field energy equal to $WL = Li^2(0-)/2$, where $i(0-) = U/(R_0 + R)$. After switching in the RL circuit, the transient process described by:

$$L \frac{di}{dt} + Ri = 0, \quad (3)$$

where $i(0) = 0$. Solving equation (1), we find, taking into account (2) - (4):

$$i = i_{CB} = Ae^{pt} = Ae^{-t/\tau}.$$

Constant A is found from initial condition $i(0-)$ and switching law (1):

$$i(0-) = i(0+) = \frac{U}{(R + R_0)} = A.$$

Finally, the law of changing the current in the transition mode is described by the equation

$$i = \frac{U}{R + R_0} e^{-t/\tau}. \quad (4)$$

The u_L voltage is defined as

$$u_L = L \frac{di}{dt} = -\frac{U}{R + R_0} R e^{-t/\tau}. \quad (5)$$

Figure 1 shows graphs i and u_L . Note that all energy WL stored in the inductance over time is consumed for heat loss in R . Under non-zero initial conditions, L behaves as a source of current.

Switching on the RLC circuit to harmonic voltage

When RLC circuit is switched to harmonic voltage $u = U_m \sin(\omega t + \varphi_u)$ forced voltage component on capacitance $u_{Cnp} = U_{mC} \sin(\omega t + \varphi_C)$, (5) where $\varphi_C = \varphi_u + \varphi - \pi/2$. Here, the phase shift between the current in the circuit and the applied voltage

$\varphi = \arctg(\omega L - 1/\omega C)/R$, (6) And amplitude of forced voltage at the capacitance

$$U_{mC} = \frac{1}{\omega C} \cdot \frac{U_m}{\sqrt{R^2 + (\omega L - 1/\omega C)^2}} = \frac{1}{\omega C} \cdot I_{mC}. \quad (7)$$

Considering that the oscillatory circuit in radio engineering devices, as a rule, has high quality, that is, the condition is met $R \ll 2\rho$, that the free component of u_s is defined by the equation and the law of voltage change on the capacitance will be

$$u_C = U_{mC} \sin(\omega t + \varphi_C) + Ae^{-\alpha t} \sin(\omega_0 t + \theta). \quad (8)$$

Taking the derivative from the expression (8), and taking into account that for the specified contour $\alpha \ll \omega_0 \approx \omega_C$, let's receive the current equation

$$i = C \frac{du_C}{dt} \approx I_{mC} \cos(\omega t + \varphi_C) + \omega_0 CA e^{-\alpha t} \cos(\omega_0 t + \theta). \quad (9)$$

Permanent integration A and θ We find from initial conditions and switching laws:

$$\left. \begin{aligned} u_C(0_-) = u_C(0_+) = 0 = U_{mC} \sin \varphi_C + A \sin \theta, \\ i(0_-) = i(0_+) = 0 = I_{mC} \cos \varphi_C + \omega_0 C A \cos \theta. \end{aligned} \right\} \quad (10)$$

Where

$$A = U_{mC} \sqrt{\sin^2 \varphi_C + \left(\frac{\omega}{\omega_0}\right)^2 \cos^2 \varphi_C}; \quad (11)$$

$$\theta = \arctg \left\{ \omega_0 \operatorname{tg} \varphi / \omega \right\}. \quad (12)$$

Substituting values A and θ from the equations (11), (12) in (8) and (9), get the final law of change of voltage on capacitance and current in RLC- contour:

$$u_C = U_{mC} \sin(\omega t + \varphi_C) + U_{mC} \sqrt{\sin^2 \varphi_C + (\omega/\omega_0)^2 \cos^2 \varphi_C} \cdot e^{-\alpha t} \sin(\omega_0 t + \theta); \quad (13)$$

$$i = I_{mC} \cos(\omega t + \varphi_C) + I_{mC} \sqrt{(\omega_0/\omega)^2 \sin^2 \varphi_C + \cos^2 \varphi_C} \cdot e^{-\alpha t} \cos(\omega_0 t + \theta). \quad (14)$$

Analysis of the equations (8. 1), (8. 2) shows that in the case ω where the frequency of the applied voltage is substantially higher ω_0 where $\varphi_C \approx 0$ has the resonant frequency of loop 0 at $C=0$, the circuit may be overvoltage, and in the case of $\omega \ll \omega_0$ и $\varphi_C \approx \pi/2$ – overcurrents.

If the frequency of the reference voltage $\omega = \omega_0$, that is, isochronism phenomena occur in the circuit when the voltage on the capacitance and the current in the circuit change smoothly according to equations:

$$u_C = U_{mC} (1 - e^{-\alpha t}) \sin(\omega_0 t + \varphi_C); \quad (15)$$

$$i = I_{mC} (1 - e^{-\alpha t}) \cos(\omega_0 t + \varphi_C). \quad (16)$$

At the same time the transient process proceeds without overvoltage and overcurrents (figure 2, a).

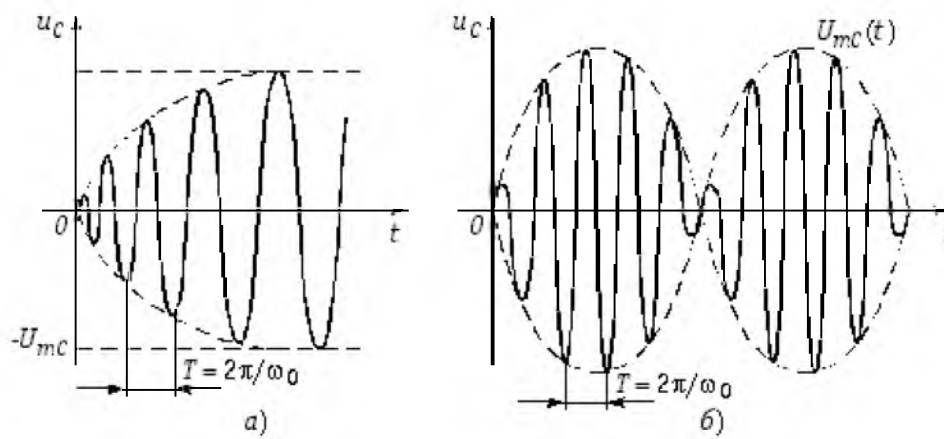


Figure 2

When the frequency of a given voltage ω and resonant frequency of the circuit ω_0 close to each other, then beat phenomena occur in the circuit. Let's put that

$$\begin{aligned} u_C &= U_{mC} [\sin(\omega t + \varphi_C) + \sin(\omega_0 t + \varphi_C)] = \\ &= U_{mC}(f) \sin(\omega_0 t + \varphi_C), \end{aligned} \quad (17)$$

where $U_m C(t) = 2U_m C \cos \Omega t$ - amplitude of beats with angular frequency $\Omega = (\omega - \omega_0)/2$. In figure 2, b, is a graph of the change in beat voltages (17).

Experimental study of surge voltages and currents in transient processes during generation of electric energy

For experimental investigation of surge-like pulsation of voltages and currents in generators during generation of electric energy, which are as a result of transient processes taking place in current-collecting contacts (brushes), specifically for this purpose, we have assembled an electric installation based on a DC motor. At the same time, standard stator windings, DC motors, were rewound in the number of 9 windings simulcast along stator walls. (figure 3). Electric motor is supplied from accumulator with voltage of 24B, which through contactors is alternately supplied to stator windings symmetrically wound by us 9 (figure 4).



Figure 3 Photo – Symmetrically wound 9 stator windings



Figure 4 – Oscillogram of impulses

When voltage is transferred from one winding to another, transient processes occur in contactor where voltage surge is generated and which is supplied to base of transistor "JR-260," which operates as electronic switch, in collector circuit of which stator winding is connected. Such electronic keys are only 9-pieces, one for each stator winding (figure 4).

Thus, 9-pulses of voltage surges are generated in one revolution of motor in collector circuit of winding as a result of phenomenon of transient processes due to switching of 24B supply voltage from one winding to another. The number of stator windings, we specially increased from 3 to 9 by hand winding 9 new windings located symmetrically on the inner surface of the stator. (figure 1). Such changes allow us to obtain in one revolution the collector of 9-pulses of voltage jump as a result of transient processes when switching the supply voltage from one winding to another. During the study, the parameters of voltage hopping pulses were carefully studied by their oscillograms. With (figure 3, $U = 250V$, $t = 0,6 ms$).

According to the electronic diagram assembled by us (figure 6), used as an electronic switch, the 24B supply voltage is switched from one winding to another. At each switching (break and connection of inducting circuit) $U =$ surge voltage pulse appears as a result of transient processes (figure 5).

Then this pulse is supplied to the base of transistor of JR-260 type, as a result of which emitter-collector transition of transistor and supply voltage is opened 24B supplied to the next winding of stator. Such transistor-based electronic switches JR-260 only 9, one for each winding.

The obtained pulse voltages and currents on transistor collectors we can smooth and accumulate on capacitances via RC-chain diodes for further use of accumulated electric energy. For example: -to charge the power battery or for the direct underside of the stator rim. A similar use of energy obtained from the hopping pulses generated in the respective transients of each coil will increase the efficiency of motors and electric current generators by about 30%.

Typically, these pulses occurring in transients accompanying the operation of motors and generators based on the principle of electromagnetic induction are not used and wasted.



Figure 5 – Photo of manifold with contactors

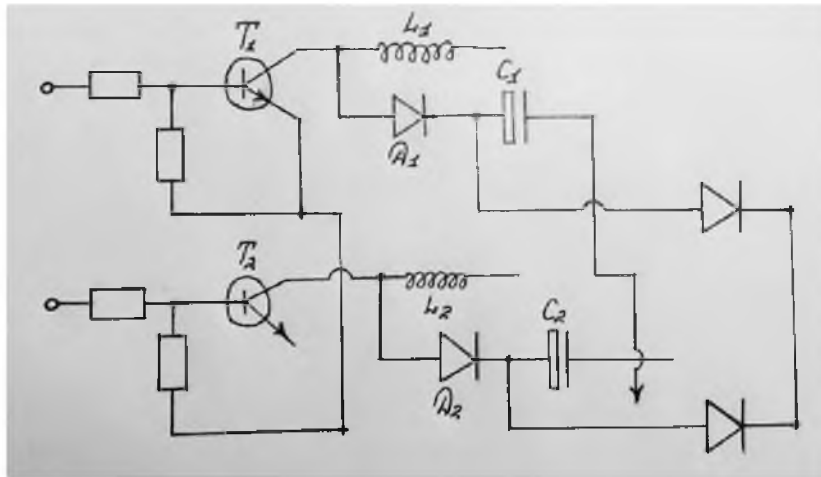


Figure 6 – Diagram of electronic switch for obtaining transient process in stator windings

Analysis of results of experimental studies of jump pulses in transient processes

1. Each time the 24B power supply switches from one winding to another, as a result of the power circuit break of the next winding, a surge voltage pulse appears as in standard transients.

2. Voltage pulse as a result of switching of power supply sources from one winding to another, by oscillograms obtained on the collector of the corresponding electronic key is estimated to be about 250B at pulse signal duration of about 0, 6 m/s. (figure 5).

At the same time duration of signal-pulse depends on rotation speed of rotor, windings of which are powered from the same power supply source of 24B, which powers simultaneously windings of stator and circuit of electronic switch.

3. Increase of battery supply voltage increases frequency of rotor turn and amplitude of pulse-signal on oscilloscope.

4. Pulse currents generated on the collectors of electronic key transistors can be smoothed and accumulated at capacitances through diodes and RC-chains (figure 6) followed by using it to charge batteries or use it to directly feed stator and rotor windings.

5. Similar use of surge voltage pulses appearing in transient processes in all electrical systems applying electromagnetic induction phenomenon makes it possible to use pulses and increase their efficiency up to 30% and more.

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**АЙНЫМАЛЫ ТОКТЫ ГЕНЕРАЦИЯЛАУ КЕЗІНДЕ,
ӨТПЕЛІ ПРОЦЕСТІ ТУГЫЗАТЫН, КОММУТАЦИЯ ТІЗБЕГІНДЕГІ ТОК КҮШІНІҢ
ЖӘНЕ КЕРНЕУДІҢ СЕКІРМЕЛІ ТҮРДЕ ТЕЗ ӨСУІН ЭКСПЕРИМЕНТ ЖҮЗІНДЕ ЗЕРТТЕУ**

Аннотация: Мақалада электр тогының генераторларындағы асқын токтардың қалқуы және бір-бірімен оқшауланған, щеткалардан тұратын пластиналардан алу кезіндегі кернеу түріндегі электр тогы бар коммутациялық электр тізбектеріндегі ауыспалы процесті және олар пайдаланылмаған күйінде жоғалуы қарастырылады. Жиналған түрдегі бұл қалқалар генератор өндіретін энергияның шамамен – 30-35% құрайды. Жұмыс өтпелі кезеңдегі теориялық жұмыстарды талдауға және электр қозғалтқыштары мен электр генераторларына ұқсас коммутациялық тізбектердегі ток пен кернеу қалқандарын тәжірибелік зерттеуге арналған. Мақалада электрлік генератордың коммутациялық тізбектеріндегі тәжірибелік зерттеу нәтижелері келтірілген.

Тізбектің ауыспалы жұмыс режимі онда магнит және электр өрістерінің энергиясы жинақталатын реактивті элементтердің (индуктивтілік, сыйымдылық) болуымен байланысты. Әр түрлі әсер ету кезінде (тізбекке қосу немесе электр энергиясы көздерін ажырату, тізбек параметрлерін өзгерту) тізбектің энергетикалық жұмыс режимі өзгереді, бұл өзгерістер электр және магнит өрістері энергиясының үздіксіздігіне байланысты (үздіксіздік принципі) бірден жүзеге асырыла алмайды, бұл өтпелі процестердің туындауына алып келеді. Көптеген Байланыс құрылғылары мен жүйелеріндегі өтпелі процестер олардың жұмыс режимінің құрамдас "қалыпты" бөлігі болып табылатынын атап өткен жөн. Сонымен қатар, бірқатар жағдайларда өтпелі процестер аса ағындар мен асқын кернеулердің пайда болуы сияқты жағымсыз құбылыстарға әкелуі мүмкін.

Оның барлығы коммутацияны талдау әдістерін қарастырудың маңыздылығын анықтайды. Коммутация тізбек параметрлерінің, оның конфигурациясының кез келген өзгеруін, өтпелі процестердің туындауына әкелетін көздердің қосылуын немесе өшірілуін атауға болады. Коммутация бір сәттік деп есептейміз, бірақ өтпелі процесс, жоғарыда айтылғандай, белгілі бір уақытта өтеді. Өтпелі процесті аяқтау үшін теориялық тұрғыдан шексіз үлкен уақыт талап етіледі, бірақ іс жүзінде оны тізбек параметрлеріне байланысты шекті түрінде қабылдайды. Коммутация К идеалды кілтіннің көмегімен жүзеге асырылады деп есептейміз. Тұйықталған күйде кедергісі шексіз үлкен, ал тұйықталмаған жағдайда нөлге тең. Кілттің тұйықталуы немесе ажыратылу бағытын көрсеткімен көрсетеміз. Сонымен қатар, егер басқа айтылмаса, коммутация $t = 0$ сәтінде жүзеге асырылады деп есептейміз. Коммутацияның бірінші және екінші заңдары бар. Коммутацияның бірінші заңы $W_L = Li^2/2$ индуктивтілік катушкасының магнит өрісінің өзгеруінің үздіксіздігімен байланысты және бастапқы сәтте $T=0_+$ тікелей коммутациядан кейін индуктивтілік тогы бірдей мәнге ие, бұл $T=0_-$ коммутацияға дейін және осы сәттен бастап бірқалыпты өзгереді (мұнда және одан әрі $F(0_-)$ деп $T=0$ кезіндегі $F(t)$ функциясының сол жақты шегі, ал $F(0_+)$ деп $t=0_+$ кезіндегі $f(t)$ оң жақты шегі түсініледі)

$$i_L(0_-) = i_L(0_+). \quad (1)$$

Коммутацияның екінші заңы сыйымдылығы $W_C = Cu^2/2$ электр өрісінің үздіксіз өзгеруімен байланысты: бастапқы сәтте $T=0_+$ коммутациядан кейін сыйымдылықтағы кернеу $t=0_-$ коммутацияға дейін және осы сәттен бастап бірқалыпты өзгереді:

$$u_C(0_-) = u_C(0_+). \quad (2)$$

i_L индуктивтілік тогынан және u_C сыйымдылығындағы кернеуден айырмашылығы u_L индуктивтілік кернеуі және i_C сыйымдылығындағы ток секіру түрінде өзгереді.

Түйін сөздер: Ток күші, кернеу, осциллограф, осциллограмма, кешігу сызығы, линия задержки, коммутация, ауысу процестері, ток пен кернеудің секірмелі өзгеруі, электр қозғаушы күш – ЭҚК.

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**ЭКСПЕРИМЕНТАЛЬНЫЕ ИССЛЕДОВАНИЯ СКАЧКООБРАЗНЫХ ИЗМЕНЕНИЙ
СИЛЫ ТОКА И НАПРЯЖЕНИЙ В ПЕРЕХОДНЫХ КОММУТАЦИОННЫХ ЦЕПЯХ
ГЕНЕРАЦИИ ПЕРЕМЕННОГО ТОКА**

Аннотация. В статье рассматривают переходный процесс в коммутационных электрических цепях, которые имеются в генераторах электрического тока в виде всплеска сверхтоков и напряжения при снятии, с

изолированных между собой, пластин щетками и которые теряются в неиспользованном виде. Эти всплески в собранном виде составляют около 30-35% энергии, вырабатываемого генератором. Работа посвящена анализу имеющихся теоретических работ по переходным процессам и экспериментальному исследованию всплесков тока и напряжений в коммутационных цепях, аналогичного в электродвигателях и электрогенераторах. В работе приведены результаты экспериментального исследования в коммутационных цепях электрогенератора.

Переходной режим работы цепи обусловлен наличием в ней реактивных элементов (индуктивности, емкости), в которых накапливается энергия магнитного и электрического полей. При различного рода воздействиях (подключении к цепи или отключения источников электрической энергии, изменении параметров цепи) изменяется энергетический режим работы цепи, причем эти изменения не могут осуществляться мгновенно в силу непрерывности изменения энергии электрического и магнитного полей (принцип непрерывности), что и приводит к возникновению переходных процессов. Следует подчеркнуть, что переходные процессы во многих устройствах и системах связи являются составной "нормальной" частью режима их работы. В то же время в ряде случаев переходные процессы могут приводить к таким нежелательным явлениям, как возникновение сверхтоков и перенапряжений.

Все это определяет важность рассмотрения методов анализа коммутации. Коммутацией принято называть любое изменение параметров цепи, ее конфигурации, подключение или отключение источников, приводящее к возникновению переходных процессов. Коммутацию будем считать мгновенной, однако переходный процесс, как было отмечено выше, будет протекать определенное время. Теоретически для завершения переходного процесса требуется бесконечно большое время, но на практике его принимают конечным, зависящим от параметров цепи. Будем считать, что коммутация осуществляется с помощью идеального ключа K (рисунок 6. 1), сопротивление которого в разомкнутом состоянии бесконечно велико, а в замкнутом равно нулю. Направление замыкания или размыкания ключа будем показывать стрелкой. Будем также считать, если не оговорено иное, что коммутация осуществляется в момент $t = 0$. Различают первый и второй законы коммутации. Первый закон коммутации связан с непрерывностью изменения магнитного поля катушки индуктивности $WL = Li^2/2$ и гласит: в начальный момент $t = 0+$ непосредственно после коммутации ток в индуктивности имеет то же значение, что и в момент $t = 0-$ до коммутации и с этого момента плавно изменяется (здесь и далее под $f(0-)$ понимается левосторонний предел функции $f(t)$ при $t \rightarrow 0-$, а под $f(0+)$ - правосторонний предел $f(t)$ при $t \rightarrow 0+$)

$$i_L(0_-) = i_L(0_+). \quad (1)$$

Второй закон коммутации связан с непрерывностью изменения электрического поля емкости $WC = Cu^2/2$: в начальный момент $t = 0+$ непосредственно после коммутации напряжение на емкости имеет то же значение, что и в момент $t = 0-$ до коммутации и с этого момента плавно изменяется:

$$u_C(0_-) = u_C(0_+). \quad (2)$$

В отличие от тока в индуктивности i_L и напряжения на емкости u_C напряжение на индуктивности u_L и ток в емкости i_C могут изменяться скачком.

Ключевые слова: сила тока, напряжение, осциллограф, осциллограмма, линия задержки, коммутация, переходные процессы, скачкообразные изменения тока и напряжения, электродвижущая сила-ЭДС.

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