Kombinatsiyalangan energiya majmualarining energiya yetkazib berish ishonchliligini oshirishda DC-DC oʻzgartirgichlarni qoʻllash imkoniyatlari

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Dolzarbligi: Bugungi kunda global energetika tizimida qayta tiklanuvchi energiya manbalarining, xususan, quyosh va shamol energiyasining ulushi tobora ortib bormoqda. Elektr energiyasiga boʻlgan talabning ortishi, ekologik muammolar va yoqilgʻi zahiralarining kamayib borishi ushbu manbalardan samarali foydalanishni taqozo etmoqda. Quyosh va shamol manbalari bir-birini toʻldiruvchi xususiyatga ega boʻlib, ularni kombinatsiyalangan tarzda qoʻllash barqaror energiya ishlab chiqarishni taʼminlaydi. Shu bilan birga, bu ikki manba oʻzgaruvchan tabiati sababli chiqish kuchlanish va tok darajalari barqaror boʻlmaydi. Bu holat isteʼmolchilarga yetkazilayotgan elektr energiyasining sifatiga salbiy taʼsir koʻrsatadi. Kombinatsiyalangan energiya tizimlarida (DC – oʻzgarmas tok) DC-DC oʻzgartirgichlar (quvvat oʻzgartirish qurilmalari) ushbu muammoni hal etishda muhim rol oʻynaydi. Ular turli manbalardan olingan elektr quvvatini muvofiqlashtirib, kerakli kuchlanish va tok darajasiga olib chiqadi hamda energiya oqimini samarali boshqaradi. Shu sababli, DC-DC oʻzgartirgichlarning toʻgʻri tanlanishi va boshqarilishi kombinatsiyalangan quyosh-shamol tizimlarining barqaror va ishonchli ishlashiga bevosita taʼsir koʻrsatadi.
Maqsad: Kombinatsiyalangan energiya tizimlarida DC-DC oʻzgartirgichlar qoʻllash orqali ishlash ishonchliligini oshirish imkoniyatlarini tahlil qilish va asoslash.
Usullari: Matematik tenglamalar va kontur toklar usullaridan foydalaniladi.
Natijalar: "Yashil" iqtisodiyotga oʻtish davrida qayta tiklanuvchi energiya manbalaridan ishonchli, barqaror energiya olish, turli xil energiya manbalaridan kombinatsilashgan usulda energiya olishda yuqo samaradorlikka ega boʻlgan usullardan foydalanish zarur. Tahlil asosida kombinatsiyalangan energiya tizimlarida DC-DC oʻzgartirgichlar qoʻllash orqali ishlash ishonchliligini oshirish boʻyicha tegishli takliflar kiritiladi.
Kalit soʻzlar: DC-DC oʻzgartirgich, qayta tiklanuvchi energiya manbalari, IGBT tranzistor, kombinatsiyalangan tizim, shamol va quyosh fotoelektrik tizim, quyosh fotoelektrik stansiyalari, energiya samaradorlik, toʻldirish koeffisienti

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Возможности использования DC-DC преобразователей для повышения надежности электроснабжения комбинированных электростанций

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Актуальность: Сегодня в мировой энергетической системе увеличивается доля возобновляемых источников энергии, в частности солнечной и ветровой. Растущий спрос на электроэнергию, экологические проблемы и сокращающиеся запасы топлива требуют эффективного использования этих источников. Солнечные и ветровые источники являются взаимодополняющими, а их совместное использование обеспечивает стабильное производство энергии. В то же время, из-за непостоянства этих двух источников, уровни выходного напряжения и тока нестабильны. Это отрицательно влияет на качество электроэнергии, поставляемой потребителям. В комбинированных энергетических системах (DC – постоянный ток) DC-DC-преобразователи (преобразователи мощности) играют важную роль в решении этой проблемы. Они координируют электроэнергию, получаемую от разных источников, доводят ее до требуемых уровней напряжения и тока и эффективно управляют потоками энергии. Поэтому правильный выбор и управление DC-DC-преобразователями напрямую влияют на стабильную и надежную работу комбинированных солнечно-ветровых систем.
Цель: Проанализировать и обосновать возможности повышения надежности работы за счёт применения DC/DC-преобразователей в комбинированных энергосистемах.
Методы: Использованы математические уравнения и методы контурных токов.
Результаты: При переходе к «зелёной» экономике необходимо использовать надёжное, стабильное энергоснабжение от возобновляемых источников энергии, а также высокоэффективные методы комбинирования энергии различных источников. На основе анализа разработаны актуальные предложения

по повышению надёжности работы за счёт применения DC-DC-преобразователей в комбинированных энергосистемах.
Ключевые слова: DC-DC-преобразователь, возобновляемые источники энергии, IGBT-транзистор, комбинированная система, ветро-солнечная фотоэлектрическая система, солнечные фотоэлектрические станции, энергоэффективность, коэффициент заполнения.

Possibilities of using DC-DC converters to improve the reliability of power supply of combined power plants

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Relevance: Today, the share of renewable energy sources, particularly solar and wind, is increasing in the global energy system. Growing demand for electricity, environmental issues and dwindling fuel reserves require efficient use of these sources. Solar and wind sources complement each other, and their combined use ensures stable energy production. At the same time, due to the variability of these two sources, the output voltage and current levels are unstable. This has a negative impact on the quality of electricity supplied to consumers. In combined energy systems, (DC – direct current) DC-DC converters (power converters) play an important role in solving this problem. They coordinate electricity received from different sources, bring it to the required voltage and current levels and effectively manage energy flows. Therefore, the correct selection and control of DC-DC converters directly affect the stable and reliable operation of combined solar-wind systems.
Aim: To analyze and justify the possibilities of increasing the reliability of operation by using DC-DC converters in combined energy systems.
Methods: Mathematical equations and contour current methods are used.
Results: In the transition to a "green" economy, it is necessary to use reliable, stable energy from renewable energy sources, and methods with high efficiency in combining energy from various energy sources. Based on the analysis, relevant proposals are made to increase the reliability of operation by using DC-DC converters in combined energy systems.
Keywords: DC-DC converter, renewable energy sources, IGBT transistor, combined system, wind and solar photovoltaic system, solar photovoltaic power plants, energy efficiency, filling factor

1. Kirish (Introduction)

So‘nggi yillarda qayta tiklanuvchi energiya manbalari (quyosh, shamol, biomassa va boshqalar)dan foydalanish kengayib bormoqda. O‘zbekistonda qayta tiklanuvchi energiya manbalarining rivojlanishi so‘nggi yillarda sezilarli darajada o‘sdi. Bu o‘zgarishlar, birinchi navbatda, mamlakatning energiya resurslarini diversifikatsiya qilish, energetik va ekologik xavfsizlikni ta’minlash maqsadida amalga oshirilmoqda [1]. Ma’lumotlarga [2] ko‘ra O‘zbekistonda jami quvvati 2600 MW dan ortiq quyosh fotoelektrik stansiyalari o‘rnatilgan bo‘lib, 2025-yil davomida qadar qayta tiklanuvchi energiya manbalar hisobidan 12 mlrd kW·h “Yashil eneriya” ishlab chiqarish rejalashtirilgan [3,4], 2030-yilga borib qayta tiklanuvchi energiya manbalarining jami iste’moldagi ulushi 54 foizga yetkazilishini inobatga olib, bu ko‘rsatkichlar keyingi yillarda yanada sezilarli darajada o‘sib boradi.

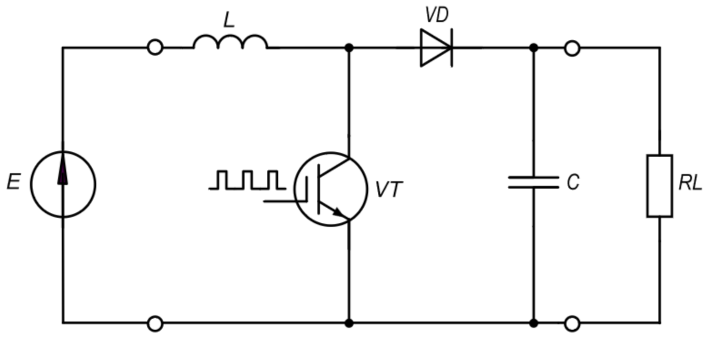
Quyosh fotoelektrik stansiyalar tomonidan ishlab chiqarilayotgan energiya hajmi bir qancha omillarga [5] bog‘liq ekanligini inobatga olib, bugungi kunda qayta tiklanuvchi energiya manbalaridan ishonchli va uzluksiz energiya olish muhim ahamiyat kasb etmoqda. Bunda qayta tiklanadigan energiya manbalari, xususan, shamol va quyosh energiyasidan kombinatsiyalangan holda foydalanish asosiy o‘rinni egallaydi. Kombinatsiyalangan shamol va quyosh energiyasi tizimlari bu ikkita manbaning afzalliklarini birlashtirib, uzluksiz, ishonchli va barqaror elektr energiyasi ishlab chiqarish imkonini beradi [6].

2. Usullar va materiallar (Methods and materials)

So‘nggi yillarda qayta tiklanuvchi energiya manbalariga asoslangan elektr energiyasi ishlab chiqarish tizimlariga talab ortib bormoqda. Xususan, quyosh fotoelektrik panellari va shamol turbinalari orqali energiya ishlab chiqarish texnologiyalari keng joriy etilmoqda [7,8]. Bu manbalarni kombinatsiyalangan holda ishlatish ularning fasliy va vaqtinchalik o‘zgaruvchanligini muvozanatlashtirish imkonini beradi. Biroq, bunday tizimlarda har bir manbaning chiqish kuchlanishi, toki va manbalarning ichki qarshiligi doimiy ravishda bir xil bo‘lmagani sababli, ularni yagona umumiy shina yoki akkumulyator tizimi bilan integratsiyalashda muammolar yuzaga keladi.

Shu nuqtai nazardan, DC-DC o‘zgartirgichlar muhim texnologik element sifatida maydonga chiqadi. Ular nafaqat kuchlanish darajalarini moslashtiradi, balki tizimda energiyani oqimini optimal tarzda taqsimlash, zaxira manbalarini ulash, yuklama talabini qondirish va energiya samaradorligini oshirish vazifalarini bajaradi. DC-DC o‘zgartirgichlar yordamida kombinatsiyalangan tizim ishonchli va yuqori samaradorlikda ishlash imkoniyatiga ega bo‘ladi.

DC-DC o‘zgartirgichning ta’minlash manbasi E hamda yuklama $R_L$birgalikda ishlash sxemasi 1-rasmda keltirilgan.



1-rasm. DC-DC o‘zgartirgichning ta’minlash manbasi hamda yuklama bilan birgalikda ishlash sxemasi
Fig. 1. Scheme of operation of a DC-DC converter with a power source and a load

DC-DC o‘zgartirgich o‘zgarmas T davrli impuls rejimda ishlaydi (2-rasm):

$$T = T_{on} + T_{off},$$

bu yerda: $T_{on} -$ VT tranzistorning darvozasiga uni ochish uchun jo‘natiladigan impulsning davomiyligi;

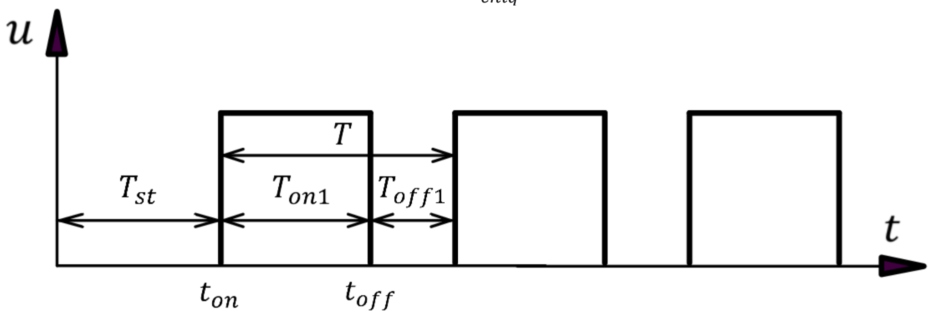
$T_{off} -$ VT tranzistorning berk holatda turish vaqti.

T_{on} to‘ldirish koeffisienti D kattalik orqali aniqlanadi:

$$D = \frac{T_{on}}{T},$$

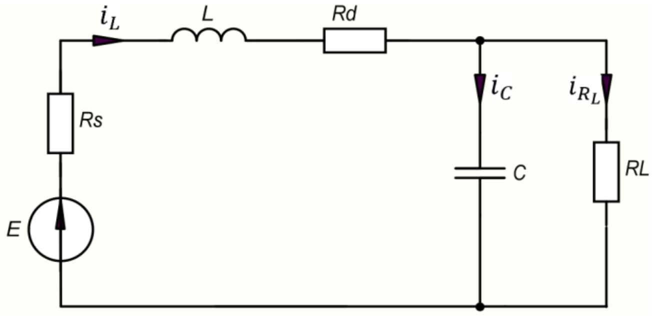
O‘z navbatida to‘ldirish koeffisienti kuchlanishni orttirib beradigan DC-DC o‘zgartirgichlar uchun ularning kirishidagi U_{kir} va chiqishidagi U_{chiq} kuchlanishlar orqali quyidagi ifoda yordamida topiladi:

$$D = \frac{U_{chiq} - U_{kir}}{U_{chiq}}.$$



2-rasm. IGBT (izolyatsiya qilingan eshikli bipolyar tranzistor) tranzistorning boshqariladigan kirishiga beriladigan kenglik bo‘yicha modullangan impulslarning vaqt diagrammasi
Fig. 2. Timing diagram of width-modulated pulses applied to the controlled input of an IGBT (insulated-gate bipolar transistor) transistor

O‘zgartirgich ishni boshlang‘ich vaqt oralig‘i T_{st} g‘altak va kondensatorda energiyani yig‘ib olishdan boshlaydi. Ushbu vaqt oralig‘ida VT tranzistor berk holatda bo‘ladi. 3-rasmda VT tranzistor berk holati uchun DC-DC o‘zgartirgichning ishini tahlil qilishga uning muqobil sxemasi keltirilgan.



3-rasm. T_{off} vaqt oralig'idagi jarayonlarni tahlil qilish uchun DC-DC o'zgartirgichning muqobil sxemasi
Fig. 3. Alternative DC-DC converter circuit for analyzing processes in the T_{off} time interval

Kontur toklar usulidan foydalanib, tenglamalar tizimini tuzamiz:

$$i_L(R_S + R_D + R_L) + L\frac{di_L}{dt} - i_C R_L = E \qquad (1)$$

$$-i_L R_L + i_C R_L + \frac{1}{C}\int i_C dt = 0 \qquad (2)$$

(1) tenglamani i_C tokka nisbatan yechamiz, (2) tenglamadan esa hosila olamiz:

$$i_C = \frac{1}{R_L}\left[-E + i_L(R_S + R_D + R_L) + L\frac{di_A}{dt}\right] \qquad (3)$$

$$-R_L\frac{di_L}{dt} + R_L\frac{di_C}{dt} + \frac{i_C}{C} = 0 \qquad (4)$$

(3) tenglamani (4) tenglamaga qo'yamiz:

$$-R_L\frac{di_L}{dt} + R_L\frac{1}{R_L}\frac{d\left[-E + i_L(R_S + R_D + R_L) + L\frac{di_L}{dt}\right]}{dt} + \frac{1}{CR_L}\left[-E + i_L(R_S + R_D + R_L) + L\frac{di_L}{dt}\right] = 0.$$

Natijaviy tenglamadan hosila olib, uni ixchamlaymiz:

$$L\frac{d^2 i_L}{dt^2} + \left(R_S + R_D + \frac{L}{CR_L}\right)\frac{di_L}{dt} + \frac{R_S + R_D + R_L}{CR_L}i_L = \frac{1}{CR_L}E.$$

Olingan ikkinchi darajali differensial tenglamani yechish uchun uning xarakteristik tenglamasini tuzamiz:

$$Ls^2 + \left(R_S + R_D + \frac{L}{CR_L}\right)s + \frac{R_S + R_D + R_L}{CR_L} = 0$$

va uni kanonik shaklga keltiramiz:

$$s^2 + \left(\frac{R_S+R_D}{L} + \frac{1}{CR_L}\right)s + \frac{R_S+R_D+R_L}{LCR_L} = 0.$$

Belgilanishlar kiritamiz:

$$M = \frac{R_S+R_D}{L} + \frac{1}{CR_L},$$

$$N = \frac{R_S+R_D+R_L}{LCR_L}.$$

U holda xarakteristik tenglamaning ildizlari quyidagi ifodalar orqali topiladi:

$$s_1 = -\frac{M}{2} + \sqrt{\frac{M^2}{4} - N}\,,$$

$$s_2 = -\frac{M}{2} - \sqrt{\frac{M^2}{4} - N}\,.$$

G'altakdan oqib o'tayotgan tok i_L ikkita tashkil qiluvchidan: majburiy va erkin hadlardan iborat bo'ladi:

$$i_L = i_{L_{maj}} + i_{L_{erk}} = \frac{E}{R_S + R_D + R_L} + A_1 e^{s_1 t} + A_2 e^{s_2 t}.$$

Integrallash doimiylari A_1 va A_2 larning qiymatlarini topish yo'lida induktivlik g'altagidan oqib o'tayotgan tokning hamda kondensatordagi kuchlanishning yangi rejim boshlanishidagi qiymatlari $i_L(+0)$ $u_L(+0)$ uchun tenglamalar tizimini tuzamiz:

$$A_1 + A_2 = i_L(-0) - i_{L_{maj}},$$

$$s_1 A_1 + s_2 A_2 = \frac{u_L(+0)}{L}.$$

Ushbu tizim quyidagi yechimga ega bo'ladi:

$$A_1 = \frac{\begin{vmatrix} i_L(-0) - i_{L_{maj}} & 1 \\ \frac{u_L(+0)}{L} & s_2 \end{vmatrix}}{\begin{vmatrix} 1 & 1 \\ s_1 & s_2 \end{vmatrix}} = \frac{\left[i_L(-0) - i_{L_{maj}}\right] s_2 - \frac{u_L(+0)}{L}}{s_2 - s_1},$$

$$A_2 = \frac{\begin{vmatrix} 1 & i_L(-0) - i_{L_{maj}} \\ s_1 & \frac{u_L(+0)}{L} \end{vmatrix}}{\begin{vmatrix} 1 & 1 \\ s_1 & s_2 \end{vmatrix}} = \frac{\frac{u_L(+0)}{L} - \left[i_L(-0) - i_{L_{maj}}\right] s_1}{s_2 - s_1}.$$

Endi DC-DC o‘zgartirgichning ishini to‘liq tahlil qilishga imkon beradigan boshqa kattaliklar: g`altakdagi kuchlanish u_L, kondensatordagi kuchlanish u_C va undan hamda yuklamadan oqib o‘tayotgan toklar i_C va i_{R_L} uchun ifodalar olamiz:

$$u_L = Ls_1A_1e^{s_1t} + Ls_2A_2e^{s_2t}, \quad (5)$$

$$u_C = E - u_L - i_L(R_S + R_D), \quad (6)$$

$$i_{R_L} = \frac{u_C}{R_L}, \quad (7)$$

$$i_C = i_L - i_{R_L}. \quad (8)$$

Agar xarakteristik tenglamaning ildizlari haqiqiy sonlar bo‘lmasdan kompleks sonlar bo‘lsa, ya’ni:

$$s_1 = -\frac{M}{2} + j\sqrt{N - \frac{M^2}{4}} = -\delta + j\omega,$$

$$s_1 = -\frac{M}{2} - j\sqrt{N - \frac{M^2}{4}} = -\delta - j\omega,$$

bu yerda: $\delta = \frac{M}{2}$ – tebranishlarning so‘nish koeffisienti;

$\omega = \sqrt{N - \frac{M^2}{4}}$ – tebranishlar takrorligi, u holda quyidagi belgilanishlarni kiritib:

$$F = i_L(-0) - i_{L_{maj}};$$

$$H = \frac{u_L(+0)}{L},$$

g‘altakdagi tokning erkin tashkil etuvchisi uchun ifoda olamiz:

$$A_1 + A_2 = i_L(-0) - i_{L_{maj}} = F,$$

$$s_1A_1 + s_2A_2 = \frac{u_L(+0)}{L} = H.$$

$$A_1 = \frac{\begin{vmatrix} F & 1 \\ H & s_2 \end{vmatrix}}{\begin{vmatrix} 1 & 1 \\ s_1 & s_2 \end{vmatrix}} = \frac{Fs_2 - H}{s_2 - s_1},$$

$$A_2 = \frac{\begin{vmatrix} 1 & F \\ s_1 & H \end{vmatrix}}{\begin{vmatrix} 1 & 1 \\ s_1 & s_2 \end{vmatrix}} = \frac{H - Fs_1}{s_2 - s_1} =.$$

$$i_{L_{erk}} = A_1e^{s_1t} + A_2e^{s_2t} = \frac{1}{-j2\omega}\left[(-F\delta - H - jF\omega)e^{(-\delta+j\omega)t} + (H + F\delta - jF\omega)e^{(-\delta-j\omega)t}\right]$$

$$= \frac{e^{-\delta t}}{-j2\omega}\left[(-F\delta - H - jF\omega)e^{j\omega t} + (H + F\delta - jF\omega)e^{-j\omega t}\right]$$

$$= \frac{e^{-\delta t}}{-j2\omega}\left[(-F\delta - H)(e^{j\omega t} - e^{-j\omega t}) - jF\omega(e^{-j\omega t} + e^{-j\omega t})\right]$$

$$= \frac{e^{-\delta t}}{\omega}\left[(-F\delta - H)\frac{e^{j\omega t} - e^{-j\omega t}}{-j2} - jF\omega\frac{e^{j\omega t} + e^{-j\omega t}}{-j2}\right]$$

$$= \frac{e^{-\delta t}}{\omega}\left[(F\delta + H)\sin\omega t + F\omega\cos\omega t\right] = \frac{\sqrt{(F\delta + H)^2 + F^2\omega^2}}{\omega}e^{-\delta t}\sin(\omega t + \varphi),$$

bu yerda agar $F\delta + H$ ning ishorasi musbat bo‘lsa $\varphi = \arctan\left(\frac{F\omega}{F\delta+H}\right)$, aks holda, ya’ni uning ishorasi manfiy bo‘lsa, u holda $\varphi = \pi - \arctan\left(\frac{F\omega}{F\delta+H}\right)$.

Majburiy tashkil qiluvchini qo‘shib, g‘altakdan oqib o‘tayotgan tok uchun natijaviy ifodaga ega bo`lamiz:

$$i_L = \frac{E}{R_S+R_D+R_L} + \frac{\sqrt{(F\delta+H)^2+F^2\omega^2}}{\omega} e^{-\delta t}\sin(\omega t+\varphi). \quad (9)$$

G‘altakdagi kuchlanishni topish uchun (9) ifodadan vaqt bo‘yicha hosila olamiz va natijani L induktivlikka ko‘paytiramiz:

$$u_L = L\frac{\sqrt{(F\delta+H)^2+F^2\omega^2}}{\omega}\left[-\delta e^{-\delta t}\sin(\omega t+\varphi)+\omega e^{-\delta t}\cos(\omega t+\varphi)\right]$$
$$= -L\frac{\sqrt{(F\delta+H)^2+F^2\omega^2}}{\omega}e^{-\delta t}[\delta\sin(\omega t+\varphi)-\omega\cos(\omega t+\varphi)]$$
$$= -L\frac{\sqrt{(F\delta+H)^2+F^2\omega^2}}{\omega}e^{-\delta t}\sqrt{\delta^2+\omega^2}\sin(\omega t+\varphi-\beta)$$
$$= L\frac{\sqrt{[(F\delta+H)^2+F^2\omega^2]\cdot(\delta^2+\omega^2)}}{\omega}e^{-\delta t}\sin(\omega t+\varphi-\beta-\pi),$$

bu yerda: $\beta = \arctan\left(\frac{\omega}{\delta}\right)$.

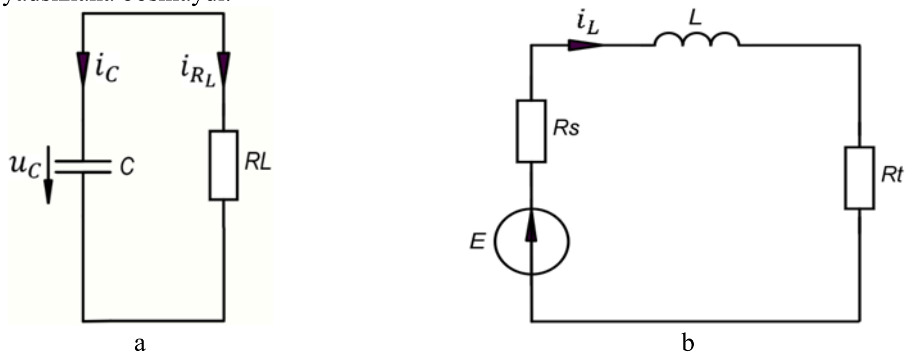
Bu hol uchun ham kondensatordagi kuchlanish u_C , undan va yuklamadan oqib o‘tayotgan toklar i_C va i_{R_L} uchun ifodalar (6), (7) va (8) ifodalar bilan bir xil bo‘ladi.

Endi IGBT-tranzistor darvozasida uni ochuvchi impuls mavjudligidagi, ya’ni T_{on} vaqt oralig‘idagi DC-DC o‘zgartirgichdagi jarayonlarni tahlil qilamiz.

Impuls tranzistorga kelib tushishi bilan u darhol ochiadi, tranzistorning kollektori va emitteri orasidagi kuchlanish nulga teng bo‘ladi, natijada diod D ning anodidagi potensial katoddagiga nisbatan pasayib ketadi. Bu esa diodning berkilishiga va zanjirning ikkita mustaqil qismga bo‘linib qolishiga olib keladi (4-rasm).

Zanjirning bir qismida (4-rasm, a) ochiq holida juda ham oz qarshilikka ega tranzistor orqali ta’minlash manbasi E ga ulanadi va tokning qiymati keskin osha boshlaydi.

Zanjirning ikkinchi qismida (4-rasm, b) esa ta’minlash manbasi E dan uzilib qolgan, lekin oldingi vaqt oralig‘ida kondensatorda elektr maydonining energiyasi to‘planib olinganligi sababli u yuklama R_L orqali zaryadsizlana boshlaydi.



4-rasm. T_{on} vaqt oralig‘idagi jarayonlarni tahlil qilish uchun DC-DC o‘zgartirgichning muqobil sxemalari

Fig. 4. Alternative DC-DC converter circuits for analyzing processes in the time interval T_{on}

Zanjirning birinchi qismi uchun Kirxgofning ikkinchi qonuni asosida differensial tenglama tuzamiz:

$$L\frac{di_L}{dt} + i_L(R_S+R_T) = E.$$

Uning xarakteristik tenglamasi quyidagicha bo‘ladi:

$$Ls_L + R_S + R_T = 0.$$

Jarayonning so‘nish koeffisientini topamiz:

$$s_L = -\frac{R_S+R_T}{L}.$$

Differensial tenglamaning yechimi quyidagicha bo‘ladi:

$$i_L = i_{L_{maj}} + i_{erk} = \frac{E}{R_S+R_T} + Ae^{s_L t}. \quad (10)$$

Integrallash doimiysi A ni rejim boshidagi g‘altakdan oqib o‘tayotgan tokning qiymati uchun tuzilgan tenglamadan topamiz:

$$A = i_L(-0) - \frac{E}{R_S+R_T}.$$

Olingan natijani (10) ifodaga qo‘yib, tok uchun yakuniy ifodani olamiz:

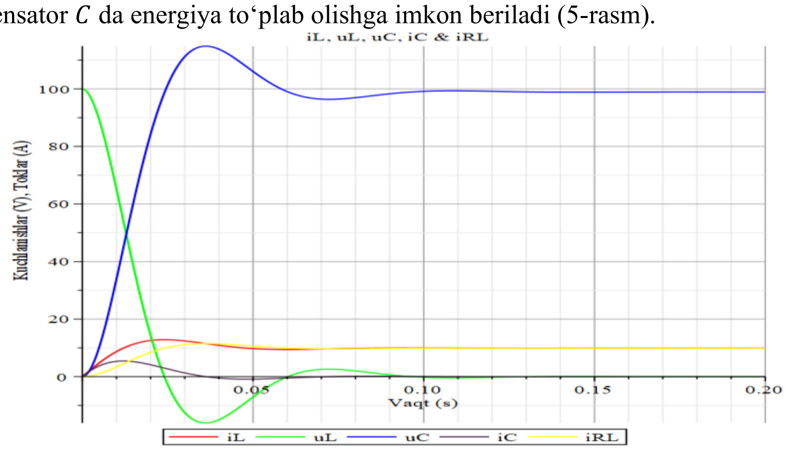
$$i_L = \frac{E}{R_S+R_T} + \left[i_L(-0) - \frac{E}{R_S+R_T}\right]e^{-\frac{R_S+R_T}{L}t} = \frac{E}{R_S+R_T}\left(1-e^{-\frac{R_S+R_T}{L}t}\right) + i_L(-0)e^{-\frac{R_S+R_T}{L}t}.$$

G‘altakdagi kuchlanishni topish uchun tokning ifodasidan hosila olamiz va induktivlikka ko‘paytiramiz:

$$u_L = L\frac{di_L}{dt} = L\frac{d}{dt}\left[\frac{E}{R_S+R_T}\left(1-e^{-\frac{R_S+R_T}{L}t}\right)+i_L(-0)e^{-\frac{R_S+R_T}{L}t}\right]$$
$$= L\cdot\left[\frac{E}{R_S+R_T}\cdot\frac{R_S+R_T}{L}\cdot e^{-\frac{R_S+R_T}{L}t}+i_L(-0)\cdot\left(-\frac{R_S+R_T}{L}\right)\cdot e^{-\frac{R_S+R_T}{L}t}\right]$$
$$= [E - i_L(-0)\cdot(R_S+R_T)]\cdot e^{-\frac{R_S+R_T}{L}t}.$$

Zanjirning ikkinchi qismi uchun Kirxgofning ikkinchi qonuni asosida tenglama tuzamiz:
$$u_C - i_{R_L}R_L = 0.$$
Yuklamadan oqib o‘tayotgan tok i_{R_L} teskari yo‘nalishdagi tok i_C ga teng, u esa o‘z navbatida kondensatordagi kuchlanish bilan funksional bog‘langan:
$$i_{R_L} = -i_C = -C\frac{du_C}{dt}.$$
Olingan ifodani undan oldingisiga qo‘yamiz:
$$u_C + R_L C\frac{du_C}{dt} = 0.$$
Ushbu differensial tenglamaning xarakteristik tenglamasi quyidagicha bo‘ladi:
$$CR_L s_C + 1 = 0,$$
undan s_C koeffisientni topamiz:
$$s_C = -\frac{1}{CR_L}.$$
Differensial tenglamaning yechimi quyidagi shaklda topiladi:
$$u_C = Be^{s_L t}.$$
Integrallash doimiysi kommutasiya qonuni asosida tuzilgan tenglamadan topiladi:
$$B = u_C(-0).$$
Kondensatordan oqib o‘tayotgan tokning ifodasi kuchlanishning ifodasi orqali olinadi:
$$i_C = C\frac{du_C}{dt} = CB\left(-\frac{1}{CR_L}\right)e^{s_C t} = -\frac{u_C(-0)}{R_L}e^{s_C t}.$$
Yuklamadan oqayotgan tok esa:
$$i_{R_L} = -i_C = \frac{u_C(-0)}{R_L}e^{s_C t}.$$
Endi olingan ifodalardan foydalanib, quyidagi berilganlarga:
$$E = 100\,V;\ R_S = 0.01\,\Omega;\ L = 0.1\,H;\ C = 1000\cdot10^{-6}\,F;\ R_D = 0.1\,\Omega;$$
$$R_L = 10\,\Omega;\ R_T = 0.1\,\Omega;\ T = 0.05\,s;\ T_{on} = 0.03\,s;\ T_{off} = T - T_{on} = 0.02\,s$$
ega bo‘lgan konkret kuchlanishni oshiruvchi DC-DC o‘zgartirgich ishining hisob-kitobini MATLAB hamda MAPLE hisoblash dasturlaridan foydalanib o‘tkazamiz.

Dastlabki 200 ms, ya’ni $t = 0$ dan IGBT-tranzistorning darvozasiga birinchi impuls kelib tushish oni $t = t_{on1} = 200\ ms$ ga qadar o‘zgartirgichga o‘zining energiya to‘plovchilari: induktivlik g‘altagi L da va kondensator C da energiya to‘plab olishga imkon beriladi (5-rasm).



5-rasm. Ish jarayoni boshlanishida va IGBT-tranzistor berkligidagi induktivlik g‘altagi, kondensator hamda yuklamadan oqib o‘tayotgan toklar i_L, i_C, i_{R_L} va kuchlanishlar u_L, u_C ning vaqt diagrammalari
Fig. 5. Time diagrams of currents i_L, i_C, i_{R_L} and voltages u_L, u_C flowing through the inductor, capacitor and load at the beginning of the operation process and when the IGBT transistor is closed

5-rasmdan ko‘rinib turibdiki, kondensatordagi kuchlanish u_C va induktivlik g‘altagidan oqib o‘tayotgan tok i_L ularda yig‘iladigan energiyalarni xarakterlagani uchun nuldan boshlandi va so‘ngra o‘sib 98.91 V hamda 9.89 A qiymatlarga erishadi.

Xarakteristik tenglamaning ildizlari kompleks sonlar bo‘lgani sababli, zanjirdagi o‘tish jarayoni so‘nuvchi tebranma jarayon bo‘lgani uchun reaktiv elementlar o‘zlarida energiya jamlashdan tashqari ma’lum bir vaqt oraliqlarida zanjirga energiya qaytarishlari ham kuzatilmoqda.

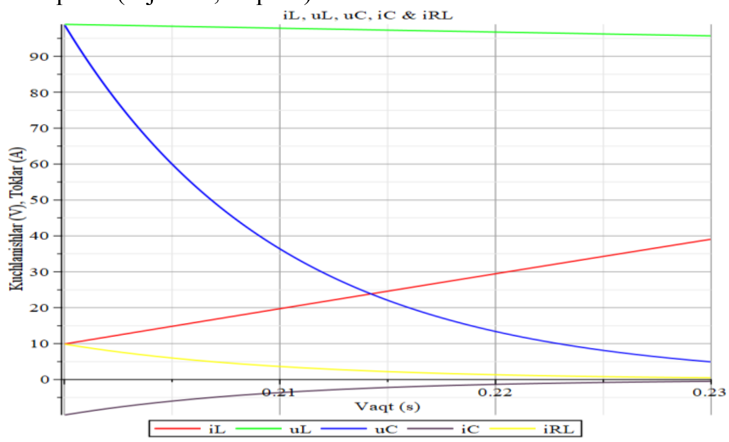
3. Natijalar va muhokamalar (Results and discussion)

IGBT tranzistorning boshqariluvchi kirishiga birinchi impuls tushishiga qadar, ya’ni $t_{on1} = 0.2\ s$ oniga manbadan o‘zgartirgichga 197.82 J energiya kelib tushdi, shundan 4.892 J va 4.8915 J kondensatorda va induktivlik g‘altagida elektr va maydoni energiyalari sifatida jamlandi hamda keyingi bosqichga zahira sifatida olib qo‘yildi, 185.84 J energiya yuklamaga uzatildi va foydali ishga sarflandi, 2.2056 J energiya esa IGBT tranzistorda va manba ichida behuda yo‘qotildi. Yuklamaning 0 dan 0.20 s vaqt oralig‘idagi o‘rtacha quvvati 929.18 W ni tashkil etdi (1-jadval, 2-qator).

1-jadval. Zanjirdagi energiya oqimi
Table 1. Energy flow in the chain

Y_{nomi}	Y_{zahira}	Y_{tushum}	Y_{LE}	Y_{CE}	Y_{RLE}	$Y_{RsRdRtE}$	$Y_{istemol}$	$Y_{yangizahira}$	$Y_{quvvatRL}$
"1-bosqich"	0	197.82	4.8915	4.892	185.84	2.2056	188.04	9.7835	929.18
"2-bosqich"	9.7835	73.698	71.472	-4.8799	4.8799	2.2258	7.1056	76.375	243.99
"Jami"	9.7835	271.52	76.363	0.012126	190.72	4.4314	195.15	86.159	866.89

IGBT tranzistorning boshqariluvchi kirishiga birinchi impuls tushishi bilan zanjir go‘yo ikkita avtonom qismga bo‘linadi: manba, induktivlik g‘altagi va IGBT tranzistordan iborat qismida g‘altakda kuchaytirilgan energiya jamlash jarayoni boshlab yuboriladi (5, 6-rasm), natijada manbadan shu qismga kelib tushgan 73.698 J energiyadan 71.472 J g‘altakka jamlanadi va undagi energiya miqdori oldingi bosqichdan qolgan zahira (4.8915 J) hisobiga 76.3635 J gacha oshadi. Manba va tranzistordagi behuda yo‘qotish 2.2258 J ni tashkil qiladi (1-jadval, 3-qator).



6-rasm. IGBT-tranzistor ochiqligidagi, ya’ni birinchi impuls tranzistorning kirishiga berilgandagi induktivlik g‘altagi, kondensator hamda yuklamadan oqib o‘tayotgan toklar i_L, i_C, i_{R_L} va kuchlanishlar u_L, u_C ning vaqt diagrammalari
Fig. 6. Time diagrams of the currents i_L, i_C, i_{R_L} and voltages u_L, u_C flowing through the inductor, capacitor and load when the IGBT transistor is open, that is, when the first pulse is applied to the input of the transistor

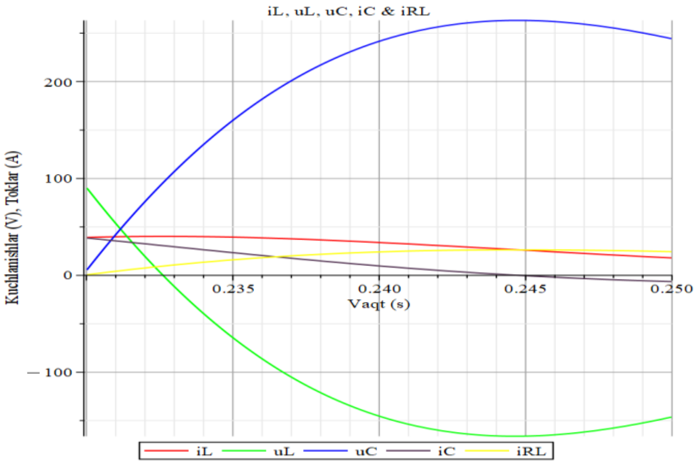
Kondensator va yuklamadan iborat ikkinchi qismda birinchisi ikkinchisiga energiyasini bera boshlaydi. Natijada kondensatorda oldingi bosqichdan qolgan 4.892 J energiyadan 4 8799 J foydali ishga sarflanadi, bunda yuklama olayotgan quvvat 243.99 W ni tashkil etadi.

Kondensatorda qolayotgan 0.0121 J energiya g‘altakdagi bilan jamlanganda 76.375 J ga yetadi va u keyingi bosqich uchun zahira hisoblanadi. Yuklamaning bu bosqichdagi o‘rtacha quvvati 243.99 W dir.

Ikkita bosqich uchun yuklamaning o‘rtacha quvvati 866.89 W (1-jadval, 4-qator).

Birinchi impuls tugashi bilan zanjirning butunligi qayta tiklanadi va jarayonning boshlanishida g‘altak manbadan energiya olayotgan bo‘lsa ham keyin u zanjirga energiya berish rejimiga o‘tib oladi va natijada kondensator hamda yuklamaning zanjirdan energiya olish imkoniyati keskin ko‘payadi (7-rasm).

Natijada manbadan berilgan 64.351 J va g‘altakda zahira holatda turgan 76.3633 energiyadan 92.375 J i yuklamaga beriladi, 2.3919 J i manbada va diodda behuda sarflanadi, 29.824 J i kondensatorga uzatiladi va undagi energiya miqdori oldingi bosqichdan qolgan 0.0121 J energiya bilan 29.836 J ga yetkaziladi. G‘altakdagi energiya miqdori 60.24 J ga ozayib, oldingi 76.363 J dan 16.123 J ga tushib qoladi. Keyingi bosqichga zahira sifatida qoldirilayotgan energiya miqdori 45.959 J ni ni tashkil qiladi. Ushbu bosqichda yuklama olayotgan quvvat 4618.8 W ga teng bo'ldi (2-jadval).



7-rasm. Birinchi impuls tugagandan keyindagi induktivlik g'altagi, kondensator hamda yuklamadan oqib o'tayotgan toklar i_L, i_C, i_{R_L} va kuchlanishlar u_L, u_C ning vaqt diagrammalari
Fig. 7. Time diagrams of the currents i_L, i_C, i_{R_L} and voltages u_L, u_C flowing through the inductor, capacitor and load after the end of the first pulse

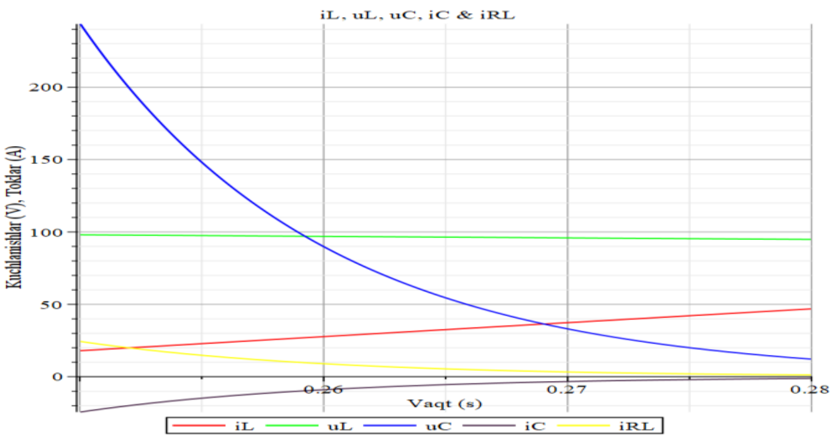
2-jadval. Birinchi impuls tugashi bilan zanjirdagi energiya oqimi
Table 2. Energy flow in the circuit at the end of the first pulse

Y_{nomi}	Y_{zahira}	Y_{tushum}	Y_{LE}	Y_{CE}	Y_{RLE}	$Y_{RsRdRtE}$	$Y_{istemol}$	$Y_{yangizahira}$	$Y_{quvvatRL}$
"1-bosqich"	76.375	64.351	-60.24	29.824	92.375	2.3919	94.767	45.959	4618.8
"2-bosqich"	45.959	97.501	93.785	-29.762	29.762	3.7158	33.478	109.98	1488.1
"Jami"	122.33	161.85	33.545	0.06183	122.14	6.1077	128.25	155.94	2442.8

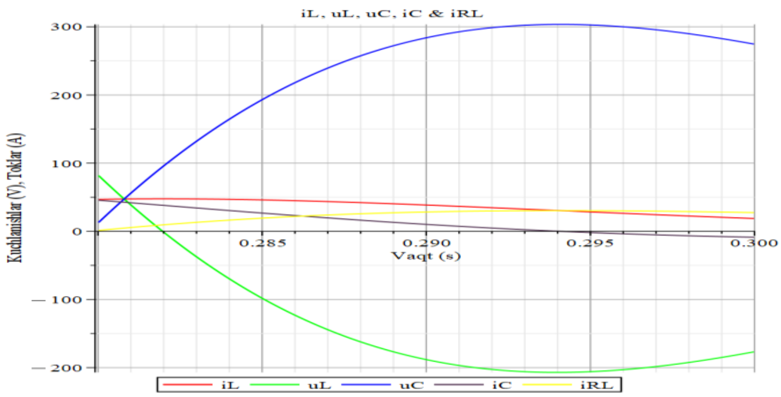
Keyingi bosqichda (8-rasm) tranzistorga ikkinchi impuls qo'yilgan. Shu sababli zanjir yana ikki qismga bo'linadi, unung birinchi qismida tezlatilgan sur'atda g'altakda energiya jamlana boshlanadi. Manbadan berilayotgan 97.501 J ning 93.785 J I g'altakka berilib, undagi energiyaning miqdori 109.91 J ga yetkaziladi, qolgan 3.7158 J i manbadan va tranzistorda behuda sarf bo'ladi.

Kondensator o'zida oldingi bosqichdan zahira sifatida qolgan 29.836 J energiyadan 29.762 J ini yuklamaga berib, uning olayotgan quvvatini 1488.1 W ga yetkazadi.

Ikkala bosqich bo'yicha yuklama olayotgan o'rtacha quvvat 2442.8 W ga yetdi. Bundan tashqari keyingi bosqichga qolayotgan zahira energiya miqdori 109.98 J ni tashkil qilmoqda.



8-rasm. IGBT-tranzistorning kirishida ikkinchi impuls berilgandagi induktivlik g'altagi, kondensator hamda yuklamadan oqib o'tayotgan toklar i_L, i_C, i_{R_L} va kuchlanishlar u_L, u_C ning vaqt diagrammalari
Fig. 8. Timing diagrams of the currents i_L, i_C, i_{R_L} and voltages u_L, u_C flowing through the inductor, capacitor and load when the second pulse is applied to the input of the IGBT transistor



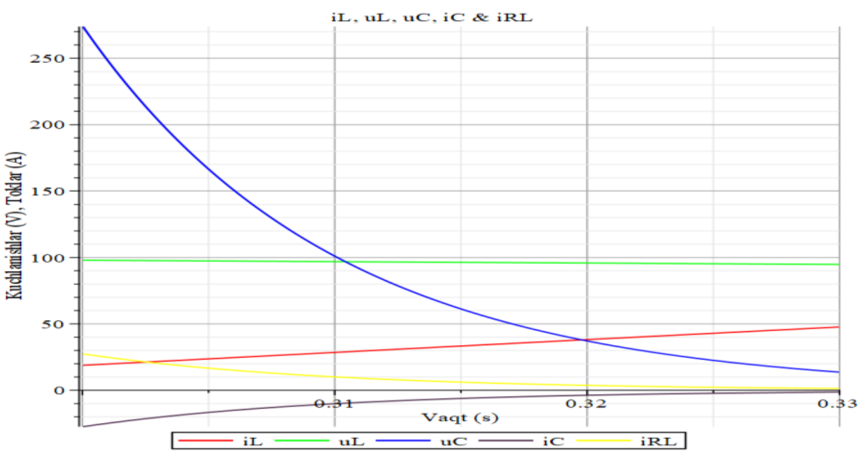
9-rasm. Ikkinchi impuls tugagandan keyindagi induktivlik g‘altagi, kondensator hamda yuklamadan oqib o‘tayotgan toklar i_L, i_C, i_{R_L} va kuchlanishlar u_L, u_C ning vaqt diagrammalari
Fig. 9. Time diagrams of the currents i_L, i_C, i_{R_L} and voltages u_L, u_C flowing through the inductor, capacitor and load after the end of the second pulse

3-jadval. Ikkinchi impuls tugashi bilan zanjirdagi energiya oqimi
Table 3. Energy flow in the circuit at the end of the second pulse

Y_{nomi}	Y_{zahira}	Y_{tushum}	Y_{LE}	Y_{CE}	Y_{RLE}	$Y_{RsRdRtE}$	$Y_{istemol}$	$Y_{yangizahira}$	$Y_{quvvatRL}$
"1-bosqich"	109.98	73.539	-92.278	37.622	125.03	3.1683	128.2	55.326	6251.4
"2-bosqich"	55.326	99.923	96.032	-37.602	37.602	3.8907	41.493	113.76	1880.1
"Jami"	165.31	173.46	3.754	0.019482	162.63	7.059	169.69	169.08	3252.6

Ikkinchi impuls tugashi bilan zanjir yana tiklanadi va zahiradagi 109.98 J hamda manbadan berilayotgan 73.539 J energiya kondensatorga va yuklamaga yo‘naltiriladi. Natijada kondensator qo‘shimcha 37.622 J energiya olib, o‘zidagini 37.696 J ga, yuklama esa 125.03 J energiya olib, o‘rtacha quvvatini 6251.4 W ga yetkazib oladi. G‘altakdagi energiya 17.63 J ga qadar kamayadi va keyingi bosqich uchun olib qo‘yiladigan zahira energiya 55.326 J ni tashkil etadi (3-jadval).

Vaqtning t=0.30\ s onida tranzistorning kirishiga uchunchi impuls beriladi va zanjir yana ikkita alohidagi qism sifatida ishlab, manbadan berilayotgan 99.923 J energiyaning 96.032 J ini g‘altak o‘ziga oladi. Qolgan 3.8907.J i manbadan va tranzistorda yo‘qotiladi. Kondensator 37.602 J energiyasini yuklamaga beradi va buning natijasida yuklama olayotgan quvvatning o‘rtachasi 1880.1 W ni tashkil qiladi. Bosqich yakunida kondensatorda qolgan 0.0934 J va g‘altakda jamlangan 113.66 J energiya keyingi bosqich uchun zahira sifatida qoladi (4-jadval).



10-rasm. IGBT-tranzistorning kirishida uchinchi impuls berilgandagi induktivlik g‘altagi, kondensator hamda yuklamadan oqib o‘tayotgan toklar i_L, i_C, i_{R_L} va kuchlanishlar u_L, u_C ning vaqt diagrammalari.
Fig. 10. Timing diagrams of the currents i_L, i_C, i_{R_L} and voltages u_L, u_C flowing through the inductor, capacitor, and load when the third pulse is applied to the input of the IGBT transistor.

Yuklamaning o‘tgan ikkala bosqich uchun o‘rtacha quvvati 3252.6 W tashkil qiladi. Agar e’tibor beradigan bo‘lsak, yuklamaga qo‘yilyotgan quvvat muntazam oshib bormoqda. Keyingi bosqichlarda ham bu jarayon davom etib, o‘rtacha quvvat avval 3341.9 J ga (4-jadval), keyin 3347.5 J ga (5-jadval) va nihoyat 3347.7 J ga (6-jadval) teng bo‘ladi.

4-jadval. Uchinchi impuls tugashi bilan zanjirdagi energiya oqimi
Table 4. Energy flow in the circuit at the end of the third pulse

Y_{nomi}	Y_{zahira}	Y_{tushum}	Y_{LE}	Y_{CE}	Y_{RLE}	$Y_{RsRdRtE}$	$Y_{istemol}$	$Y_{yangizahira}$	$Y_{quvvatRL}$
"1-bosqich"	113.76	74.409	-95.935	38.397	128.7	3.2486	131.95	56.217	6434.9
"2-bosqich"	56.217	100.08	96.173	-38.395	38.395	3.9018	42.297	114	1919.7
"Jami"	169.97	174.48	0.23824	0.0019689	167.09	7.1504	174.24	170.21	3341.9

5-jadval. To‘rtinchi impuls tugashi bilan zanjirdagi energiya oqimi
Table 5. Energy flow in the circuit at the end of the fourth pulse

Y_{nomi}	Y_{zahira}	Y_{tushum}	Y_{LE}	Y_{CE}	Y_{RLE}	$Y_{RsRdRtE}$	$Y_{istemol}$	$Y_{yangizahira}$	$Y_{quvvatRL}$
"1-bosqich"	114	74.46	-96.171	38.441	128.94	3.2534	132.19	56.266	6446.8
"2-bosqich"	56.266	100.08	96.177	-38.441	38.441	3.9021	42.343	114	1922.1
"Jami"	170.26	174.54	0.0057687	0.00011571	167.38	7.1555	174.53	170.27	3347.5

6-jadval. Beshinchi impuls tugashi bilan zanjirdagi energiya oqimi
Table 6. Energy flow in the circuit at the end of the fifth pulse

Y_{nomi}	Y_{zahira}	Y_{tushum}	Y_{LE}	Y_{CE}	Y_{RLE}	$Y_{RsRdRtE}$	$Y_{istemol}$	$Y_{yangizahira}$	$Y_{quvvatRL}$
"1-bosqich"	114	74.46	-96.177	38.442	128.94	3.2534	132.2	56.267	6447.1
"2-bosqich"	56.267	100.08	96.176	-38.442	38.442	3.9021	42.344	114	1922.1
"Jami"	170.27	174.54	-0.00079571	1.9071e-06	167.38	7.1555	174.54	170.27	3347.7

7-jadval. Oltinchi va keyingi impulslar tugashi bilan zanjirdagi energiya oqimi
Table 7. Energy flow in the circuit at the end of the sixth and subsequent pulses

Y_{nomi}	Y_{zahira}	Y_{tushum}	Y_{LE}	Y_{CE}	Y_{RLE}	$Y_{RsRdRtE}$	$Y_{istemol}$	$Y_{yangizahira}$	$Y_{quvvatRL}$
"1-bosqich"	114	74.46	-96.176	38.442	128.94	3.2534	132.19	56.266	6447.1
"2-bosqich"	56.266	100.08	96.176	-38.442	38.442	3.9021	42.344	114	1922.1
"Jami"	170.27	174.54	-0.00013672	-4.9867e-07	167.38	7.1555	174.54	170.27	3347.7

Keyingi bosqichlarda o‘zgarish bo‘lmayapti, o‘rtacha quvvati 3347.7 W da saqlanib qolayapti (7-jadval). Bu esa zanjirda o‘tish jarayonlarining tugaganligidan va unda stasionar rejimning o‘rnatilganidan darak bermoqda.

4. Xulosa (Conclusion)

Kombinatsiyalangan quyosh va shamol energiyasi tizimlarida DC-DC o‘zgartirgichlarning roli juda muhimdir. Ular turli energiya manbalarini yagona tizimga birlashtirish, kuchlanish darajalarini barqarorlashtirish, yuklamalarga moslashtirish va energiya oqimini samarali boshqarish imkonini beradi. Bu orqali tizimning umumiy samaradorligi oshiriladi, ishonchliligi ta’minlanadi va energiya yo‘qotishlari kamaytiriladi.

Shuningdek, DC-DC o‘zgartirgichlarning turli arxitekturalari (buck, boost, buck-boost va boshqalar)ni to‘g‘ri tanlash va ularni intellektual boshqaruv algoritmlari bilan birlashtirish – zamonaviy energiya tizimlari uchun strategik texnologik yechim hisoblanadi. Shunday qilib, DC-DC o‘zgartirgichlarni chuqur o‘rganish va ular asosida samarali energiya boshqaruv tizimlarini ishlab chiqish, qayta tiklanuvchi energiya manbalaridan to‘liq va ishonchli foydalanishni ta’minlashda asosiy omil bo‘lib xizmat qiladi.

ADABIYOTLAR

1. Р.А. Захидов, У.А. Таджиев, Ф.М. Махаммадиев, Э.Т. Юсупов, “Об энергетической безопасности Узбекистана и возможности ее обеспечения используя
возобновляемые источники энергии. Часть 1.” Журнал “Гелиотехника”, №2.

2. С.Д. Исакулов, “Перспективы развития энергетики Республики Узбекистан с учетом экологических рисков”, журнал “Проблемы энерго- и ресурсосбережения”, специальный выпуск (№86) – 2024 г., 200 с.

3. https://minenergy.uz/uz/news/view/4295 O‘zbekiston Respublikasi Energetika vazirligi rasmiy veb sayti.

4. https://president.uz/uz/lists/view/7055 O‘zbekiston Respublikasi Prezidentining rasmiy veb sayti.

5. Захидов Р.А., Таджиев У.А., Махаммадиев Ф.М., Юсупов. О возможностях возобновляемой энергетики в обеспечении энергетической безопасности Узбекистана. Часть 2., журнал Гелиотехника, 2025 г.

6. Zaxidov R.A., Yusupov E.T., Muminov A.B. Kombinatsiyalangan shamol va quyosh energiyasidan elektr energiyasini ishlab chiqarish tizimlari turlari. “Energetika va energiya tejash muammolari” Respublika ilmiy-amaliy anjumani, 2025-yil 13-14 may. Toshkent, 161-163-betlar.

7. O‘z DSt 3661:2023 «Kombinatsiyalangan shamol va fotoelektrik tizimlar. Texnik talablar» milliy standarti

8. Zakhidov, R.A., Tajiyev, U.A., Kiseleva, E.I. et al. On the Possibility of Sustainable Energy and Water Supply of Low-Rise Residential Buildings Located in Areas with an Arid Climate using Combined Wind and Solar Photovoltaic Power Complexes of Low Power. Appl. Sol. Energy 58, 159–164 (2022). https://doi.org/10.3103/S0003701X22010200

REFERENCES

1. R.A. Zakhidov, U.A. Tadjiev, F.M. Makhammadiev, E.T. Yusupov, “On the energy security of Uzbekistan and the possibility of ensuring it using renewable energy sources. Part 1.” Journal “Geliotekhnika”, No. 2.

2. S.D. Isakulov, “Prospects for the development of the energy sector of the Republic of Uzbekistan taking into account environmental risks”, journal “Problems of energy and resource saving”, special issue (No. 86) – 2024, 200 p.

3. https://minenergy.uz/uz/news/view/4295 Official website of the Ministry of Energy of the Republic of Uzbekistan.

4. https://president.uz/uz/lists/view/7055 Official website of the President of the Republic of Uzbekistan.

5. Zakhidov R.A., Tadzhiev U.A., Makhammadiev F.M., Yusupov. On the possibilities of renewable energy in ensuring the energy security of Uzbekistan. Part 2., Solar Engineering magazine, 2025.

6. Zakhidov R.A., Yusupov E.T., Muminov A.B. Types of combined wind and solar power generation systems. “Problems of energy and energy conservation” Republican scientific and practical conference, May 13-14, 2025. Tashkent, pp. 161-163.

7. National standard O‘z DSt 3661:2023 “Combined wind and photovoltaic systems. Technical requirements”

8. Zakhidov, R.A., Tajiyev, U.A., Kiseleva, E.I. et al. On the Possibility of Sustainable Energy and Water Supply of Low-Rise Residential Buildings Located in Areas with an Arid Climate using Combined Wind and Solar Photovoltaic Power Complexes of Low Power. Appl. Sol. Energy 58, 159–164 (2022). https://doi.org/10.3103/S0003701X22010200