An’anaviy noayon qutbli sinxron generatorning Matlab Simulink modeli yordamida o‘z-o‘zini qo‘zg‘atish jarayonini modellashtirish

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Dolzarbligi: O‘z-o‘zini qo‘zg‘atish - bu sistema elementlari va generator chulg‘amlarida kuchlanish va tokning (U va I) o‘z-o‘zidan ortib ketishi bilan xarakterlanuvchi elektromagnit noturg‘unlikdir. O‘z-o‘zini qo‘zg‘atish sodir bo‘lishining zaruriy sharti stator zanjirida mashinaning induktiv karshiligi bilan tebranish konturini vujudga keltiruvchi ulangan sig‘imning mavjud bo‘lishidir. Mashina chulg‘amlarining xususiy va o‘zaro qarshiliklari rotor aylanganda vaqt davomida o‘zgaruvchanligi sababli konturda elektr tebranishlar so‘nmasdan, aksincha ortib boruvchi sharoit yuzaga kelishi mumkin. Bu o‘z-o‘zini qo‘zg‘atishni ifodalaydi. Sinxron generatorning o‘z-o‘zini qo‘zg‘atish jarayoni salbiy holat hisoblanadi, chunki kuchlanish va toklarning qiymatlari juda katta bo‘lishi mumkin va eng asosiysi ularni boshqarib bo‘lmaydi.
Maqsad: An'anaviy noayon qutbli sinxron generatorning Matlab Simulink modeli yordamida o‘z-o‘zini qo‘zg‘atish jarayonini modellashtirish va tahlil qilishdan iborat.
Usullar: tadqiqot jarayonida sinxron generatorlarning elektromagnit o‘tkinchi jarayonlari nazariyasi, matematik aproksimasiya, differensial tenglamalarni echishning Runge-Kutta usuli, o‘z-o‘zini qo‘zg‘atish jarayonlarini MatLab Simulink dasturida modellashtirish, olingan natijalarni taqqoslash va qayta ishlashda matematik statistika usullaridan foydalanilgan.
Natijalar: An'anaviy noayon qutbli sinxron generatorning Matlab Simulink modeli yordamida o‘z-o‘zini qo‘zg‘atish jarayonini modellashtirish natijalari keltirilgan.
Kalit so‘zlar: noayon qutbli sinxron generator, magnit tizim, modellashtirish, sinxron generatorning o‘z-o‘zini qo‘zg‘atish jarayoni, asinxron o‘z-o‘zini qo‘zg‘atish jarayoni.

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Моделирование процесса самовозбуждения обычного неявнополюсного синхронного генератора с использованием модели Matlab Simulink

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Актуальность: Самовозбуждение — электромагнитная неустойчивость, характеризующаяся самопроизвольным увеличением напряжения и тока (U и I) в элементах системы и обмотках генератора. Необходимым условием возникновения самовозбуждения является наличие в цепи статора подключенной емкости, создающей колебательный контур с индуктивным сопротивлением машины. Поскольку удельные и взаимные сопротивления обмоток машины изменяются с течением времени при вращении ротора, могут возникнуть условия, при которых электрические колебания в цепи не затухают, а, наоборот, нарастают. Это называется самовозбуждением. Процесс самовозбуждения синхронного генератора считается негативным явлением, поскольку значения напряжений и токов могут быть очень большими, а главное, ими невозможно управлять.
Цель: Моделирование и анализ процесса самовозбуждения обычного неявнополюсного синхронного генератора с использованием модели MatLab Simulink.
Методы: В процессе исследования использовались теория электромагнитных переходных процессов синхронных генераторов, математическая аппроксимация, метод Рунге-Кутты для решения дифференциальных уравнений, моделирование процессов самовозбуждения в программе MatLab Simulink, математические статистические методы для сравнения и обработки полученных результатов.
Результаты: Представлены результаты моделирования процесса самовозбуждения традиционного синхронного генератора с нестабильными полюсами с использованием модели Matlab Simulink.
Ключевые слова: неявнополюсный синхронный генератор, магнитная система, моделирование, процесс самовозбуждения синхронного генератора, асинхронный процесс самовозбуждения.

Modeling the self-excitation process of a conventional non-salinity pole synchronous generator using the Matlab Simulink model

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Relevance: Self-excitation is an electromagnetic instability characterized by a spontaneous increase in voltage and current (U and I) in system elements and generator windings. A necessary condition for self-excitation is the presence of a connected capacitance in the stator circuit, creating an oscillatory circuit with the machine's inductive reactance. Since the specific and mutual resistances of the machine windings change over time during rotor rotation, conditions may arise in which electrical oscillations in the circuit do not attenuate, but rather increase. This is called self-excitation. The self-excitation process of a synchronous generator is considered a negative phenomenon, since voltages and currents can be very high and, most importantly, impossible to control.
Aim: To model and analyze the self-excitation process of a conventional non-salient-pole synchronous generator using the MatLab Simulink model.
Methods: The study utilized the theory of electromagnetic transient processes in synchronous generators, mathematical approximation, the Runge-Kutta method for solving differential equations, modeling of self-excitation processes in MatLab Simulink, and mathematical statistical methods for comparing and processing the obtained results.
Results: The results of modeling the self-excitation process of a traditional synchronous generator with unstable poles are presented using the Matlab Simulink model.
Keywords: non-salient-pole synchronous generator, magnetic system, modeling, self-excitation process of a synchronous generator, asynchronous self-excitation process.

1. Kirish (Introduction)

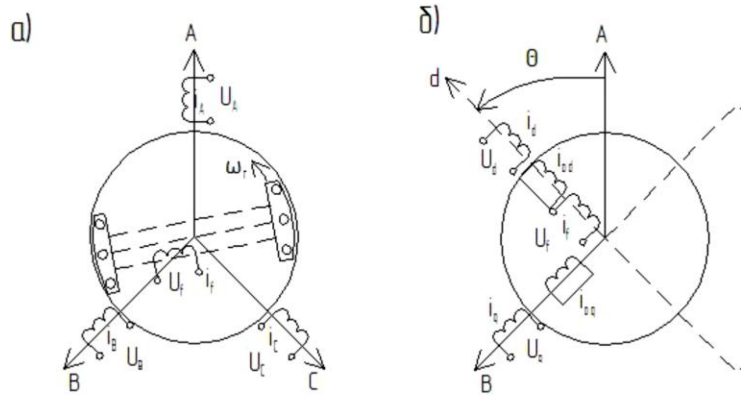
O‘z-o‘zini qo‘zg‘atish - bu sistema elementlari va generator chulg‘amlarida kuchlanish va tokning (U va I) o‘z-o‘zidan ortib ketishi bilan xarakterlanuvchi elektromagnit noturg‘unlikdir. O‘z-o‘zini qo‘zg‘atish sodir bo‘lishining zaruriy sharti stator zanjirida mashinaning induktiv karshiligi bilan tebranish konturini vujudga keltiruvchi ulangan sig‘imning mavjud bo‘lishidir. Mashina chulg‘amlarining xususiy va o‘zaro qarshiliklari rotor aylanganda vaqt davomida o‘zgaruvchanligi sababli konturda elektr tebranishlar so‘nmasdan, aksincha ortib boruvchi sharoit yuzaga kelishi mumkin. Bu o‘z-o‘zini qo‘zg‘atishni ifodalaydi. Sinxron generatorning o‘z-o‘zini qo‘zg‘atish jarayoni salbiy holat hisoblanadi, chunki kuchlanish va toklarning qiymatlari juda katta bo‘lishi mumkin va eng asosiysi ularni boshqarib bo‘lmaydi.

2. Materiallar va usullar (Methods and materials)

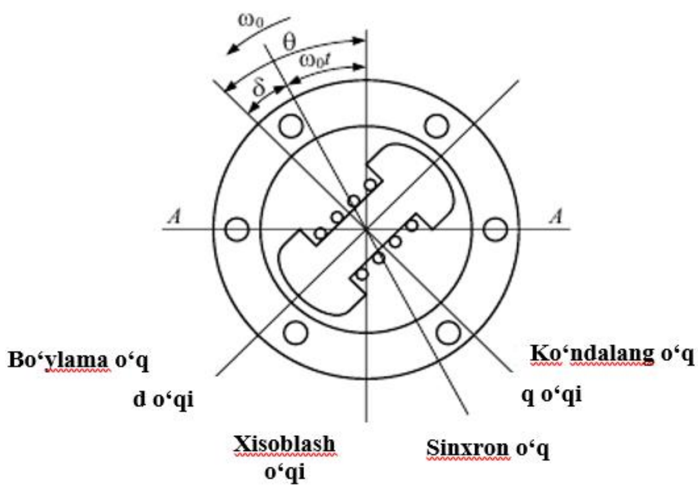
Sinxron mashinalarning differensial tenglamalarini tuzishda va ularni echishda quyidagi chekinishlarni hisobga olinadi [1-5]:
1) sinxron mashinaning po‘lat o‘zagining magnit singdiruv-chanligi cheksizlikga teng va to‘yinmagan;
2) stator va rotorning magnit maydoni havo orlig‘i bo‘ylab sinusoidal tarqaladi;
3) faza chulg‘amlari simmetrik;
4) tinchlantiruvchi (dempfer) chulg‘am sterjenlari rotor o‘qiga nisbatan simmetrik joylashgan.
Mashinaning stator kuchlanishlari tenglamasi 3.2-a. rasmga ko‘ra quyidagicha bo‘ladi:

$$\left.\begin{aligned} U_A &= i_A r_s + \frac{d\psi_A}{dt} \\ U_B &= i_B r_s + \frac{d\psi_B}{dt} \\ U_C &= i_C r_s + \frac{d\psi_C}{dt} \end{aligned}\right\} \tag{1}$$

bu yerda i_A, i_B, i_C – stator faza toklarining oniy qiymati; r_s – stator faza chulg‘amining aktiv qarshiligi; Ψ_A, Ψ_B, Ψ_C – stator faza chulg‘amlarining oqim ilashimligi [6].



1-rasm. Ayon qutbli sinxron mashinaning a) faza (A, B, C) koordinata tizimida va b) rotorning (d, q) koordinata tizimidagi ko'rinishi.
Fig.1. View of a salient-pole synchronous machine in (a) the phase (A, B, C) coordinate system and (b) the rotor (d, q) coordinate system.



2-rasm. dempfer va qo'zg'atish chulg'ami uchun (d, q) o'qlari bo'yicha kuchlanishlar tenglamasi quyidagicha bo'ladi:
Fig. 2. For the damper and field windings shown in the figure, the voltage equations along the (d, q) axes are as follows:

$$\left.\begin{aligned} U_f &= i_f r_f + \frac{d\psi_f}{dt} \\ 0 &= i_{Dd} r_{Dd} + \frac{d\psi_{Dd}}{dt} \\ 0 &= i_{Dq} r_{Dq} + \frac{d\psi_{Dq}}{dt} \end{aligned}\right\} \tag{2}$$

bu yerda U_f – qo'zg'atish chulg'amidagi kuchlanish; i_f, i_{Dd}, i_{Dq} – qo'zg'atish va dempfer chulg'amining *d* va *q* o'qlari bo'yicha toklari; r_f, r_{Dd}, r_{Dq} – qo'zg'atish va dempfer chulg'amining d va q o'qlari bo'yicha aktiv qarshiklari; Ψ_f, Ψ_{Dd}, Ψ_{Dq} – qo'zg'atish va dempfer chulg'amining d va q o'qlari bo'yicha oqim ilashimligi [6].
Sinxron mashinaning oqim ilashimligi tenglamalari:

$$\left.\begin{aligned}
\psi_A &= L_A i_A + M_{AB} i_B + M_{AC} i_C + M_{Af} i_f + M_{ADd} i_{Dd} + M_{ADq} i_{Dq} \\
\psi_B &= L_B i_B + M_{AB} i_A + M_{BC} i_C + M_{Bf} i_f + M_{BDd} i_{Dd} + M_{BDq} i_{Dq} \\
\psi_C &= L_C i_C + M_{CB} i_B + M_{CA} i_A + M_{Cf} i_f + M_{CDd} i_{Dd} + M_{CDq} i_{Dq} \\
\psi_f &= L_f i_f + M_{fA} i_A + M_{fB} i_B + M_{fC} i_C + M_{fDd} i_{Dd} \\
\psi_{Dd} &= L_{Dd} i_{Dd} + M_{DdA} i_A + M_{DdB} i_B + M_{DdC} i_C + M_{Ddf} i_f \\
\psi_{Dq} &= L_{Dq} i_{Dq} + M_{DqA} i_A + M_{DqB} i_B + M_{DqC} i_C + M_{Dqf} i_f
\end{aligned}\right\} \quad (3)$$

bu yerda L ва M – har xil chulg‘amning induktivligi va o‘zaro induktivligi hamda $M_{AB}=M_{BA}$; $M_{fA}=M_{Af}$; $M_{DdA}=M_{Add}$ ва L_f – Stator faza chulg‘amlarining induktivligi va o‘zaro induktivligi, mashinaning d o‘qi va A fazasi o‘qlari orasidagi θ burchakning davriy funksiyasidir [6, 2-5]: [20, 2-5].

Stator faza chulg‘amlarining induktivligi va o‘zaro induktivligi, mashinaning d o‘qi va A fazasi o‘qlari orasidagi θ burchakning davriy funksiyasidir [6, 2-5]:

$$\left.\begin{aligned}
L_A &= L_0 + L_2 \cos 2\theta \\
L_B &= L_0 + L_2 \cos\left(2\theta + \frac{2\pi}{3}\right) \\
L_C &= L_0 + L_2 \cos\left(2\theta + \frac{4\pi}{3}\right) \\
M_{AB} &= M_0 + M_2 \cos\left(2\theta - \frac{2\pi}{3}\right) \\
M_{AC} &= M_0 + M_2 \cos\left(2\theta + \frac{2\pi}{3}\right) \\
M_{BC} &= M_0 + M_2 \cos 2\theta
\end{aligned}\right\} \quad (4)$$

bu yerda $L_0=2M_0$ ва $L_2=M_2$, stator chulg‘amlari simmetrik joylashtirilgan.

Sinxron generator chulg‘amlari orasidagi o‘zaro induktivlik quyidagi ko‘rinishga ega [6, 8-11]:

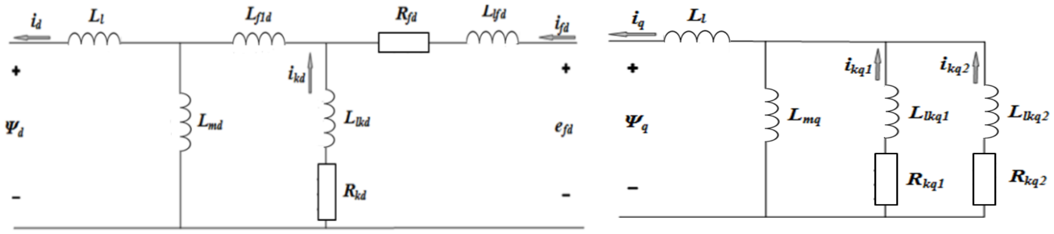
$$\left.\begin{aligned}
M_{Af} &= M_{Afd} \cos\theta \\
M_{Bf} &= M_{Afd} \cos\left(\theta - \frac{2\pi}{3}\right) \\
M_{Cf} &= M_{Afd} \cos\left(\theta + \frac{2\pi}{3}\right) \\
M_{ADd} &= m_{ADd} \cos\theta \\
M_{BDd} &= m_{ADd} \cos\left(\theta - \frac{2\pi}{3}\right) \\
M_{CDd} &= m_{ADd} \cos\left(\theta + \frac{2\pi}{3}\right) \\
M_{ADq} &= m_{ADq} \cos\theta \\
M_{BDq} &= m_{ADq} \cos\left(\theta - \frac{2\pi}{3}\right) \\
M_{CDq} &= m_{ADq} \cos\left(\theta + \frac{2\pi}{3}\right)
\end{aligned}\right\} \quad (5)$$

bu yerda M_{Afd}, m_{Add}, m_{ADq} – A fazasi chulg‘ami va qo‘zg‘atish chulg‘ami d va q o‘qlari hamda dempfer konturlarining mos kelish paytidagi o‘zaro induktivlik.
(4) va (5) tenglamlar tizimini echish qiyinligining sababi shundaki, induktivlik va o‘zaro induktivliklar rotor holatining davriy funksiyasi hisoblanadi [6, 2-5].
Stator va rotor konturlarining oqim ilashimligi tenglamalari quyidagicha:

$$\left.\begin{aligned}
\psi_d &= L_{sd} i_{sd} + M_{Ad}\left(i_f + i_{Dd}\right) \\
\psi_q &= L_{sq} i_{sq} + M_{Aq} i_{Dq} \\
\psi_f &= L_f i_f + M_{Ad} i_d + \frac{3}{2} M_{Ad} i_{sd} \\
\psi_{Dd} &= L_{Dd} i_{Dd} + M_{Ad} i_f + \frac{3}{2} M_{Ad} i_{sd} \\
\psi_{Dq} &= L_{Dq} i_{Dq} + \frac{3}{2} M_{Aq} i_{sq}
\end{aligned}\right\} \qquad (6)$$

bu yerda L_{sd}, L_{sq} – sinxron generator stator chulg‘amining d va q o‘qlari bo‘yicha induktivligi;
M_{Ad}, M_{Aq} – sinxron mashinaning d va q o‘qlari bo‘yicha har qanday juft konturning o‘zaro induktivligi.

Quyidagi dinamik ekvivalent sxemasi yordamida an'anaviy sinxron generatorning tenglamalari tuziladi:



d – bo‘ylama o‘q bo‘yicha *q* – ko‘ndalang o‘q bo‘yicha

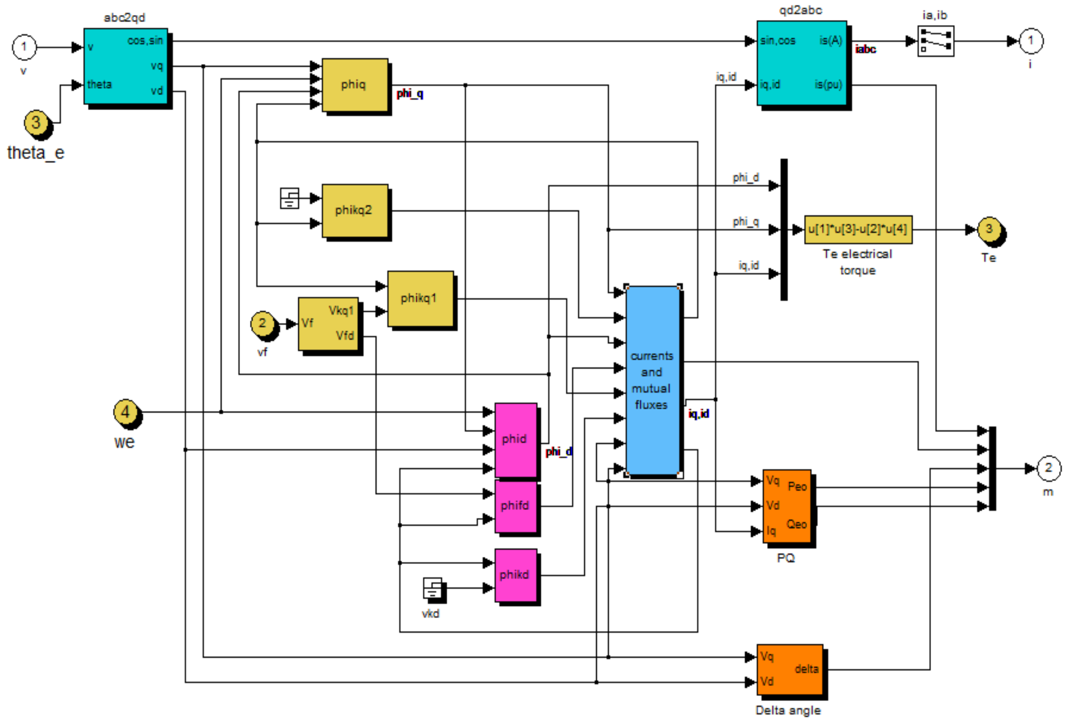
3-rasm. An'anaviy sinxron generatorning dinamik ekvivalent sxemasi.
Fig. 3. Dynamic equivalent circuit of a conventional synchronous generator.

Davriy koeffisientlarni yo‘qotish uchun, tenglamani rotorga nisba-tan qo‘zg‘almas (d, q) koordinata tizimida yoziladi:

$$\left.\begin{aligned}
U_{sd} &= i_{sd} r_s + \frac{d\psi_d}{dt} - \omega_s \psi_q \\
U_{sq} &= i_{sq} r_s + \frac{d\psi_q}{dt} + \omega_s \psi_d \\
U_f &= \frac{d\psi_f}{dt} + r_f i_f \\
0 &= \frac{d\psi_{Dd}}{dt} + r_{Dd} i_{Dd} \\
0 &= \frac{d\psi_{Dq}}{dt} + r_{Dq} i_{Dq} \\
M_Э &= \frac{3}{2}\left(\psi_d i_{sq} - \psi_q i_{sd}\right) \\
J\omega_s \frac{ds_M}{dt} &= M_{МЭХ} - M_Э
\end{aligned}\right\} \qquad (7)$$

Bu yerda $s_M=(\omega_r-\omega_s)/\omega_s$ – sinxron generatorning sirpanishi; J – sinxron generator rotorining inersiya momenti; M_{MEX} – sinxron generator validagi mexanik moment; Me – sinxron generatorning elektromagnit momenti [9, 11-13].
Yuqoridagi tenglamalar tizimini echish uchun Matlab Simulink modeli quyidagicha tuziladi [14, 15]:

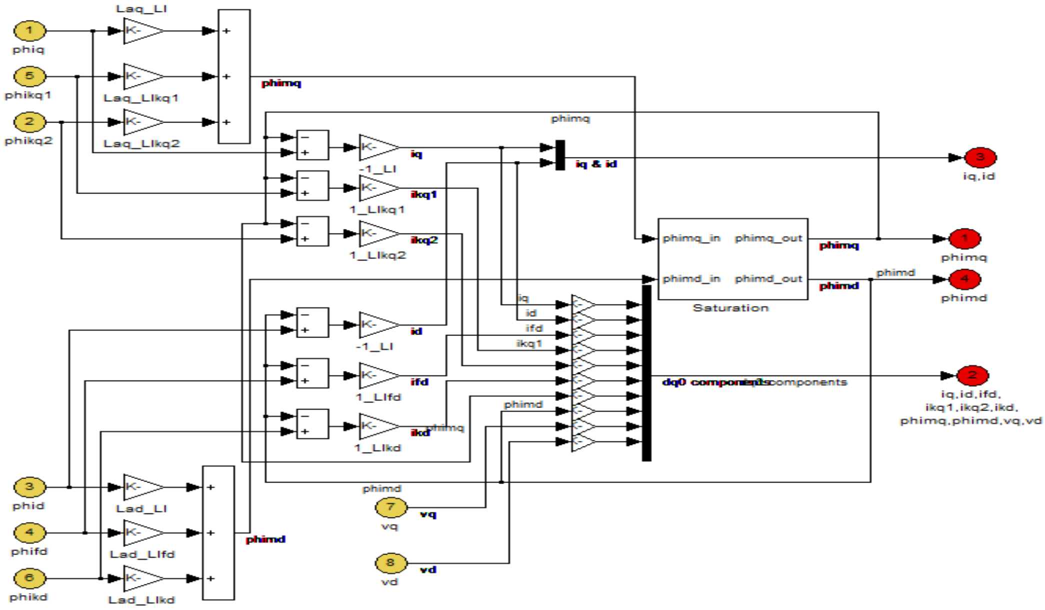
Yuqoridagi sinxron generator differensial tenglamalar tizimiga etibor berilsa, tenglamalar tizimi asosiy ikki qismdan iborat bo‘lib, u elektr kattaliklar qismi va mexanik kattaliklar qismdan tashkil topgan. (3.58) differensial tenglamalar tizimining avvalgi 6 ta tashkil etuvchisi elektromagnit jarayonlarni ifodalovchi differensial tenglama-lardir va tenglamalar tizimining oxirgi 7-tashkil etuvchisi sinxron generator rotorining mexanik harakat tenglamasi hisoblanadi [7, 16-19]. Shuning uchun Matlab Simulink modelini yaratishda ikkita asosiy qism ko‘rib chiqiladi. Buning uchun elektr va mexanik qismdan iborat quyidagi Matlab Simulink modeli yaratiladi [16-19].



4-rasm. Sinxron generatorning elektr qismi uchun
Matlab Simulink nimtizimi.
Fig. 4. Matlab/Simulink subsystem for the electrical part of the synchronous generator.

Sinxron generatorning elektr qismi Matlab Simulink modelini yaratishda (3), (4), (5) va (6) tenglamalar tizimi uchun toklar va oqim ilashimliklari uchun quyidagi nimtizim tuziladi [20-22]:
(A, B, C) faza koordinata tizimini (d, q) koordinata tizimiga o‘tkazuvchi nimtizim; (d, q) koordinata tizimini (A, B, C) faza koordinata tizimiga o‘tkazuvchi nimtizim; (d, q) o‘qlari bo‘yicha oqim ilashimliklari, dempfer kattaliklar hamda toklarni hisoblovchi nimtizimlar; Aktiv va reaktiv quvvatlarni hisoblovchi nimtizimdan iborat [23-27].

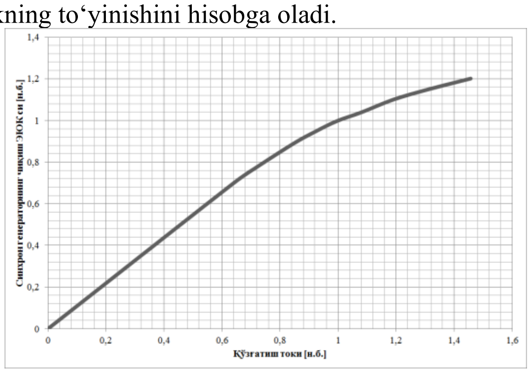
Sinxron generatorning yuqoridagi (3) - (5) tenglamalar tizimi uchun d va q o‘qlari bo‘yicha toklari va oqim ilashimliklarini hisoblovchi quyidagi nimtizim tuziladi. Ushbu nimtizimda sinxron generator magnit o‘zagining to‘yinishini hisobga oluvchi nimtizim mavjud. Ushbu nimtizim yordamida sinxron generatorning yuksiz ishlash xaraketristikasini polinom aproksimasiyalash yordamida barcha o‘tkinchi jarayonlarni hisoblashda magnit o‘zak to‘yinishini hisobga olishning imkoniyati mavjud [20].



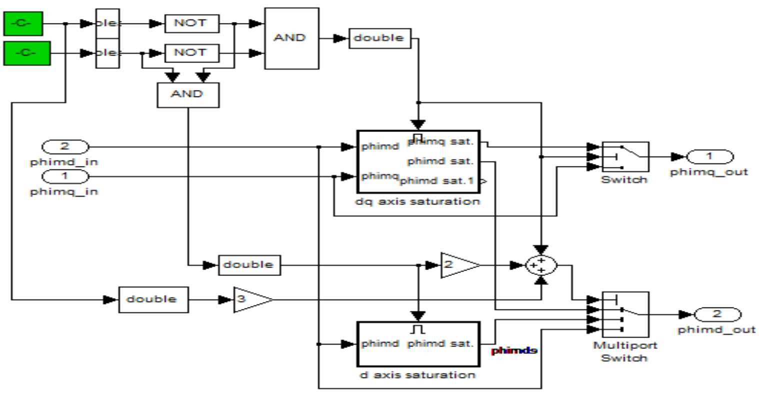
5-rasm. Sinxron generatorning d va q o‘qlari bo‘yicha, toklari va oqim ilashimliklarini hisoblovchi nimtizim.
Fig.5. Subsystem for calculating the currents and flux linkages of a synchronous generator along the d and q axes.

Sinxron generator magnit o‘zagining to‘yinishini hisobga oluvchi nimtizimga sinxron generatorning quyidagi salt ishlash xarakteristikasi parametrlari kiritilgan bo‘lib, o‘tkinchi jarayonlarni modellashtirishda magnit o‘zakning to‘yinishini hisobga oladi.

i_{f*}	U_*
0	0
0,6404	0,7
0,7127	0,7698
0,8441	0,8872
0,9214	0,9466
0,9956	0,9969
1,082	1,0495
1,19	1,1
1,316	1,151
1,457	1,201

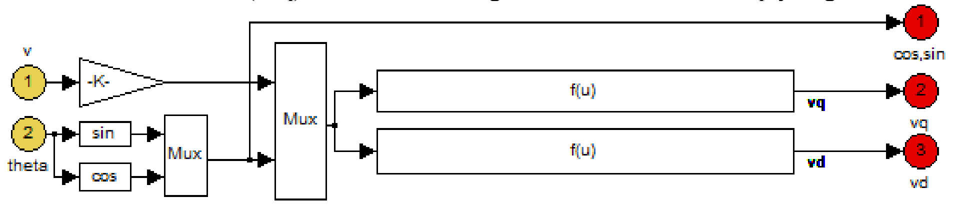


6-rasm. Sinxron generatorning salt ishlash xarakteristikasi.
Fig.6. No-load characteristic of the synchronous generator.



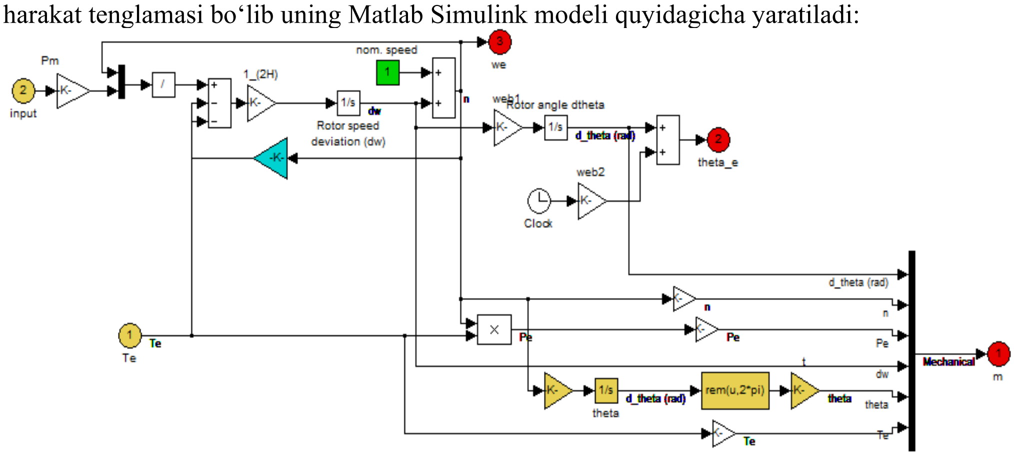
7-rasm. Sinxron generator magnit o‘zagining magnit maydoniga to‘yinishini hisobga oluvchi nimtizim.
Fig.7. Model considering the magnetic saturation of the magnetic core of the synchronous generator.

(*A, B, C*) faza koordinata tizimini (d, q) koordinata tizimiga o‘tkazuvchi nimtizim quyidagicha bo‘ladi:



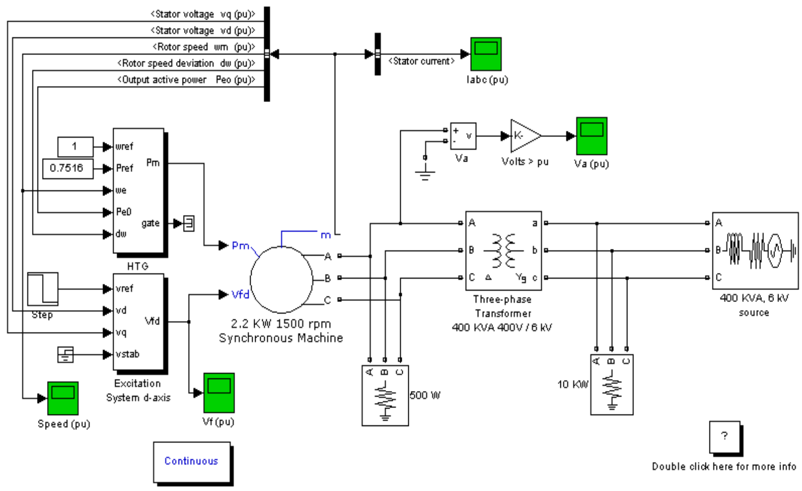
8-расм. (A, B, C) faza koordinata tizimini (*d, q*) koordinata tizimiga o‘tkazuvchi nimtizim
Fig.8. Model converting the (A, B, C) phase coordinate system to the (d, q) coordinate system.

(7) differensial tenglamalar tizimining oxirgi 7 chi tashkil etuvchisi sinxron generator rotorining mexanik harakat tenglamasi bo‘lib uning Matlab Simulink modeli quyidagicha yaratiladi:



9-rasm. Rotorining mexanik harakati modeli.
Fig.9. Model of the rotor’s mechanical motion.

Юқоридаги моделларни бириктириб, қуйидаги блоклар тузилади:

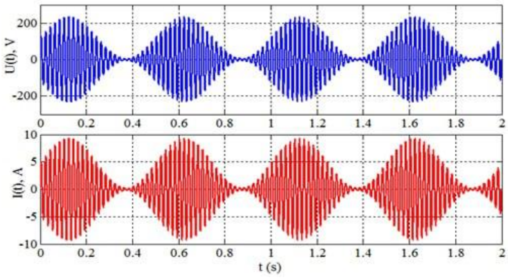


10-rasm. Quvvati 3 kVA bo‘lgan an'anaviy sinxron generatorning Matlab Simulink modeli.
Fig.10. Matlab Simulink model of a conventional synchronous generator with a power of 3 kVA.

3. Natijalar (Results)

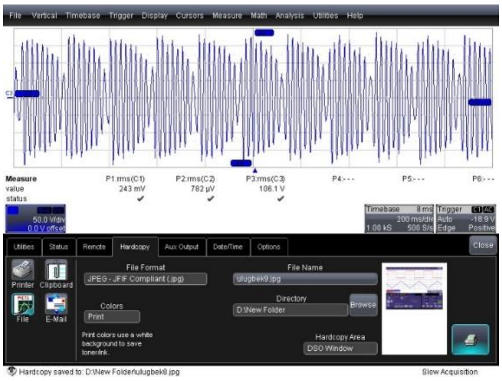
Ushbu Matlab Simulink modeldan foydalanib va yuqoridagi sinxron generatorning parametrlarini kiritib, sinxron generatorning o‘z-o‘zini qo‘zg‘atish jarayoni modellashtiriladi. Sinxron generator o‘z-o‘zini qo‘zg‘atish jarayonida tok va kuchlanish qiymatlarining amplitudasi ortib borib, sinxron generator sinxronizmdan chiqib ketishi ham mumkin [2].

11-rasmda quvvati 3 kVA, kuchlanishi 230 V va aylanish chastotasi 1500 ayl/min bo‘lgan qo‘zg‘atish toklari boshqarilmagan holatdagi noayon qutbli sinxron generatorning o‘z-o‘zini qo‘zg‘atish jarayonidagi tok va kuchlanishning Matlab Simulink modeli yordamida olingan o‘zgarishi ko‘rsatilgan.



11- rasm. Qo‘zg‘atish toklari boshqarilmagan holatdagi noayon qutbli sinxron generatorning o‘z-o‘zini qo‘zg‘atish jarayonidagi tok va kuchlanishning o‘zgarishi.
Fig.11. Variation of current and voltage during the self-excitation process of a salient-pole synchronous generator with uncontrolled excitation currents.

12-rasmda esa quvvati 3 kVA, kuchlanishi 230 V va aylanish chastotasi 1500 ayl/min bo‘lgan qo‘zg‘atish toklari boshqarilmagan holatdagi noayon qutbli sinxron generatorning o‘z-o‘zini qo‘zg‘atish jarayonidagi tok va kuchlanishning tajribada olingan ossillogrammasi ko‘rsatilgan.



12-rasm. Qo‘zg‘atish toklari boshqarilmagan holatdagi noayon qutbli sinxron generatorning o‘z-o‘zini qo‘zg‘atish jarayonidagi tajriba yo‘li bilan olingan tok va kuchlanishning ossillogrammasi.
Fig.12. Experimental oscillogram of current and voltage during the self-excitation process of a salient-pole synchronous generator with uncontrolled excitation currents.

4. Xulosa (Conclusion)

1. Shunday qilib, noayon qutbli sinxron generatorning o‘z-o‘zini qo‘zg‘atish jarayonida generator chulg‘amlarida kuchlanish va tokning (U va I) o‘z-o‘zidan ortib ketishi bilan xarakterlanuvchi elektromagnit noturg‘unlik hisoblanar ekan. Noayon qutbli sinxron generatorlarda faqat asinxron o‘z-o‘zini qo‘zg‘atish sodir bo‘ladi.
2. O‘z-o‘zini qo‘zg‘atish sodir bo‘lishining zaruriy sharti stator zanjirida mashinaning induktiv karshiligi bilan tebranish konturini vujudga keltiruvchi ulangan sig‘imning mavjud bo‘lishi hisoblanadi.
3. Sinxron generatorning o‘z-o‘zini qo‘zg‘atish jarayoni salbiy holat hisoblanadi, chunki kuchlanish va toklarning qiymatlari juda katta bo‘lishi mumkin va eng asosiysi ularni boshqarib bo‘lmaydi.

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