Asinxron generatorga aktiv yuklama ulangandagi o‘tkinchi jarayonlarda chiqish kuchlanishini barqarorlashtirilishiga doir tadqiqot natijalari

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Dolzarbligi: So‘nggi yillarda dunyoning ko‘plab mamlakatlarida energiya resurslarini tejash, yangidan yangi muqobil energiya manbalarini yaratish va mavjud qayta tiklanuvchi energiya (QTE) manbalaridan oqilona foydalanish masalalariga alohida ahamiyat berilmoqda. Rivojlangan mamlakatlar bo‘yicha, «2020-yil uchun samaradorlikning muhim ko‘rsatkichlari sharhida QTE manbalarining eng katta ulushlari Shvetsiyaga - 60,1%, Finlyandiyaga - 43,8% va Latviyaga - 42,1% to‘g‘ri kelishi ma’lum qilingan. Ushbu mamlakatlardagi asosiy energiya ishlab chiqarish manbalari GES va SHES lar, shuningdek, biomassani qayta ishlash manbalari hisoblanadi» [1]. Bu borada, avtonom tizimlar quvvat manbalari tuzilishining soddaligi, texnik xizmat ko‘rsatishning qulayligi, nisbatan kichik massa (kVA/kg) va hajmga ega bo‘lishi, hamda holat parametrlarining barqarorligi kabi talablarga alohida e’tibor qaratilmoqda. O‘zgaruvchan tok generatorlarining tuzilishida asosan sinxron mashinalar, fazali rotorli hamda qisqa tutashgan rotorli asinxron mashinalar qo‘llaniladi. Faza rotorli asinxron mashinalarda stator va rotor zanjirlariga integratsiyalangan chastota o‘zgartkichlari generatorning qo‘zg‘atish jarayonlarini faol boshqarish imkonini beradi, biroq bunday tizimlarda generator rejimlarini optimal nazorat qilish uchun qo‘shimcha tashqi quvvat manbalari zarur bo‘ladi. Qisqa tutashgan rotorli asinxron mashinalarda esa magnit o‘zagidagi qoldiq magnitlanishdan foydalanish orqali stator chulg‘amlariga kondensator batareyalarini ulash generatorning o‘z-o‘zini qo‘zg‘atish mexanizmini ishga tushirish va chiqish kuchlanishining barqarorligini ta’minlash imkonini beradi. Ushbu kondensatorli qo‘zg‘atish sxemasi markazlashmagan xarakterga ega bo‘lib, avtonom energiya ta’minoti sharoitida generator qurilmasining ish rejimlariga moslashuvchanlik va mustaqil boshqaruv imkoniyatini yaratadi, bu esa shamol energetikasi tizimlarida yuqori samaradorlik va ishonchlilikni kafolatlaydi. Mazkur maqolada, o‘tkazilgan tajriba natijalari asosida quvvati 4 kW bo‘lgan qisqa tutashgan rotorli asinxron generator (AG) ga turli qiymatlarga ega aktiv yuklamalar ulangan holatlari uchun o‘tkinchi jarayonlaridagi chiqish kuchlanish qiymatini aks ettirgan ossillogrammalar olindi va tahlil qilindi.
Maqsad: avtonom holatda ishlayotgan AG ning aktiv yuklamasini o‘zgartirish jarayoniga mos o‘tkinchi jarayonlarda chiqish kuchlanishini barqarorlashtirish va natijalarini tahlil qilish.
Usullari: tajriba asosida elektr energetikasi tizimlarining barqarorlashgan va o‘tkinchi jarayonlarini tahlil qilish usullardan foydalanildi.
Natijalar: avtonom tizimlarning quvvat manbalari konstruksiyasining soddaligi, texnik xizmat ko‘rsatishning qulayligi, nisbatan kichik massa (kVA/kg) va hajmga ega bo‘lishi, chiqish holat parametrlarining barqarorligi kabi talablarga javob berishi lozim. Tahlil asosida AG ni qayta tiklanuvchi energiya manbalarida foydalanish bo‘yicha tegishli takliflar kiritiladi.
Kalit so‘zlar: qisqa tutashgan rotorli o‘z-o‘zidan qo‘zg‘atishli AG, reaktiv quvvatni avtomatik rostlash qurilmasi.

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Результаты исследования стабилизации выходного напряжения в переходных процессах при подключении активной нагрузки к асинхронному генератору

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Актуальность: В последние годы во многих странах мира особое внимание уделяется экономии энергоресурсов, созданию новых альтернативных источников энергии и рациональному использованию существующих возобновляемых источников энергии (ВИЭ). На сегодняшний день в развитых странах

«Обзору ключевых показателей эффективности за 2020 год по развитым странам, наибольшие доли ВИЭ приходятся на Швецию — 60,1% от общего энергопотребления, Финляндию — 43,8% и Латвию — 42,1%. Основными источниками производства энергии в этих странах являются ГЭС и ВЭС, а также переработка биомассы» [1]. В этом направлении, в частности, уделяется особое внимание повышению требований к источникам мощности автономных систем, таким как простота конструкции, удобство технического обслуживания, относительно малая масса (кВА/кг) и объем, а также стабильность выходных параметров. В конструкции генераторов переменного тока в основном используются синхронные машины, асинхронные машины с фазным ротором и с короткозамкнутым ротором. В асинхронных машинах с фазным ротором интегрированные частотные преобразователи в цепях статора и ротора позволяют эффективно управлять процессом возбуждения генератора, однако для оптимального контроля режимов работы таких систем требуется дополнительный внешний источник питания. В асинхронных машинах с короткозамкнутым ротором остаточная намагниченность магнитного сердечника позволяет через подключение конденсаторных батарей к обмоткам статора обеспечить самовозбуждение генератора и стабильность выходного напряжения. Данная схема конденсаторного возбуждения носит децентрализованный характер и обеспечивает гибкость режимов работы генераторной установки в условиях автономного энергоснабжения, что гарантирует высокую эффективность и надежность ветряных энергетических систем. В данной статье, на основе результатов проведенных экспериментов, получены и проанализированы осциллограммы, отражающие значение выходного напряжения в переходных процессах для случаев подключения активных нагрузок различных значений к АГ с короткозамкнутым ротором мощностью 4 кВт.

Цель: стабилизация выходного напряжения в переходных процессах, соответствующих процессу изменения активной нагрузки автономно работающей АГ, и анализ результатов.

Методы: использовались методы анализа установившихся и переходных процессов в системах электроэнергетики на основе экспериментов.

Результаты: автономные системы должны отвечать таким требованиям, как простота конструкции источника питания, удобство технического обслуживания, относительно малая масса (кВА/кг) и объем, а также стабильность выходных параметров. На основе анализа внесены соответствующие предложения по использованию АГ в возобновляемых источниках энергии.

Ключевые слова: самовозбуждающийся АГ с короткозамкнутым ротором, устройство автоматической регулировки реактивной мощности.

Results of the study of the stabilization of the output voltage in transient processes when connecting the active load to the asynchronous generator

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Relevance: In recent years, many countries around the world have been paying special attention to energy resource conservation, the creation of new alternative energy sources, and the rational use of existing renewable energy sources (RES). Currently, according to the «2020 Key Performance Indicators Review for developed countries, the highest shares of renewable energy usage are observed in Sweden (60,1% of energy consumption), Finland (43,8%), and Latvia (42,1%). The primary sources of energy production in these countries include hydropower plants, wind power plants, and biomass processing» [1]. In this field, particular attention is paid to increasing the requirements for the structural simplicity of power sources for autonomous systems, ease of maintenance, relatively low weight (kVA/kg) and volume, as well as the stability of output parameters under operating conditions. The construction of alternating current generators primarily involves synchronous machines, phase-wound rotor asynchronous machines, and squirrel-cage asynchronous machines. In phase-wound rotor asynchronous machines, integrated frequency converters in the stator and rotor circuits enable effective control of the generator's excitation process; however, additional external power sources are required for optimal operation control. In squirrel-cage asynchronous machines, the residual magnetization of the magnetic core allows the connection of capacitor banks to the stator windings, providing self-excitation of the generator and stabilization of the output voltage. This capacitor excitation scheme is decentralized, ensuring flexible operation modes of the generator unit under autonomous power supply conditions, which guarantees high efficiency and reliability in wind energy systems. In this article, based on the results of the conducted experiments, oscillograms reflecting the value of the output voltage in transient processes were obtained and analyzed for cases of connecting active loads of various values to an AG with a 4 kW short-circuited rotor.

Aim: stabilization of the output voltage in transient processes corresponding to the process of changing the active load of autonomously operating AG and analysis of the results.

Methods: methods for analyzing established and transient processes in electric power systems based on experiments were used.

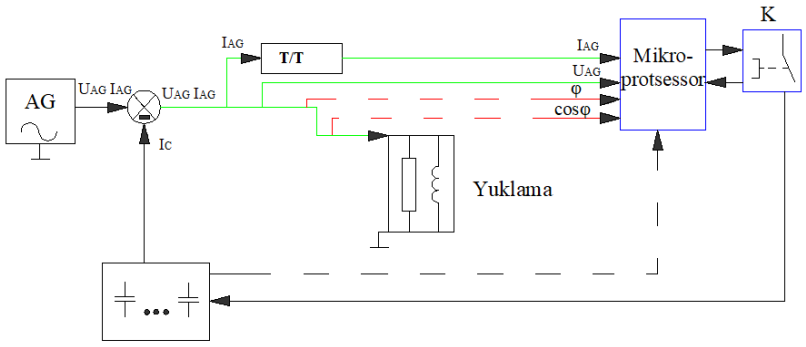
Results: autonomous systems must meet requirements such as the simplicity of power supply design, ease of maintenance, relatively small mass (kVA/kg), and volume, as well as the stability of output parameters. Based on the analysis, appropriate proposals will be submitted for the use of AG in renewable energy sources.
Keywords: self-exciting short-circuited rotor AG, a device for automatic regulation of reactive power.

1. Kirish (Introduction)

Jahon miqyosida elektr energiyasiga bo‘lgan talabning sezilarli darajada ortishi fonida, qayta tiklanuvchi energiya manbalaridan foydalanish doimiy ravishda kengayib bormoqda. 2024-yil holatiga ko‘ra, dunyoda ishlab chiqarilgan elektr energiyasining 33,5 % qayta tiklanuvchi manbalar hisobiga ta’minlangan bo‘lib, shundan 8,6 % shamol energetikasi loyihalariga to‘g‘ri keladi. Ushbu tendensiya shamol energiyasini rivojlantirish va uning global energetika tizimlaridagi ulushini oshirishning iqtisodiy va ekologik ahamiyatini yaqqol ko‘rsatadi [2]. Markazlashgan elektr ta’minotidan uzoqda joylashgan kichik quvvatli avtonom iste’molchilarni ta’minlash birinchi navbatda shamol energiyasi manbalaridan foydalanishga bog‘liq. International Renewable Energy Agency agentlik ma’lumotlariga ko‘ra, 2023-yilda qayta tiklanuvchi energiya manbalarining o‘rnatilgan umumiy quvvati 3870 GW ni tashkil etib, yangi rekordga erishdi [3,4]. 2024-yilda ishga tushirilgan yangi energetika quvvatlarining 86 foizi qayta tiklanuvchi energiya manbalariga to‘g‘ri keladi. So‘nggi yillarda respublikamiz hududlarida shamol energetikasi qayta tiklanuvchi energiya manbalarining eng istiqbolli turlaridan biri sifatida keng joriy etilmoqda [5]. Hozirgi kunga kelib, mamlakatda jami 148 ta elektr stansiya faoliyat yuritmoqda, ularning umumiy quvvati 25 797 MW ni tashkil etadi, shundan shamol energetikasi stansiyalarining quvvati 1 652 MW ga teng. 2025-yil davomida quvvati 752 MW bo‘lgan yangi shamol elektr stansiyalari ishga tushirilgan bo‘lib, bu sohadagi investitsiya va ishlab chiqarish salohiyatining sezilarli o‘sishini ko‘rsatadi [6,7]. Shamol elektr stansiyalari (SHES) va gidro elektr stansiyalar (GES) dan foydalanishni kengaytirilishi maqsadga muvofiq hisoblanadi. O‘tkazilgan nazariy va amaliy tadqiqotlardan, mazkur stansiyalarda o‘z–o‘zidan qo‘zg‘atishli, qisqa tutashgan rotorli asinxron generatorlardan foydalanish boshqa turdagi generatorlarga qaraganda texnik va iqtisodiy, hamda xizmat ko‘rsatilishi bo‘yicha qator afzalliklarga ega ekanligi ma’lum bo‘ldi.

2. Usullar va natijalar (Methods and materials)

AG ning chiqish kuchlanishini rostlovchi mikroprotsessorli reaktiv quvvatni avtomatik rostlash qurilmasi (RQARQ) ning strukturaviy sxemasi 1-rasmda ko‘rsatilgan bo‘lib, u generatorning barqaror ishlashini va elektr energiyasi sifati parametrlarini ta’minlashga mo‘ljallangan.



1-rasm. Mikroprotsessorli RQARQ strukturaviy sxemasi.
Fig.1. Structural diagram of the microprocessor ARPRD.

1-rasmdagi struktural sxema asosida AG, yuklamani 380 V sinusoidal kuchlanish bilan ta’minlaydi. Bunday holda, taqqoslash elementi yuklama tokini generator salt ishlash toki bilan solishtiradi, ya’ni joriy toklar vektorlari yig‘indisini yaratadi. Natijada, generatorga ulangan yuklamaga mos U_{AG} va I_{AG} signallari uzatiladi [8].

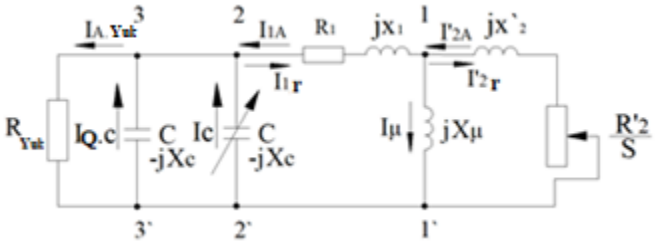
Shuningdek, mikroprotsessorga faza siljish burchagi (φ) va kuchlanish–tok orasidagi burchak kabi qo‘shimcha parametrlar ham uzatilishi mumkin, bu esa mikroprotsessorli RQARQ ga kuchlanish barqarorligini optimallashtirish imkoniyatini yaratadi.

AG ning turli yuklanish sharoitlarida chiqish kuchlanishini RQARQ orqali barqaror holatga keltirish ta’minlandi, ya’ni kuchlanish regulyatsiyasi kanali faoliyatga jalb qilindi. Har qanday ortib boruvchi yoki pasayuvchi yuklama sharoitida kondensator batareyalarini avtomatik ketma-ket ishga tushirish orqali tizimning statik barqarorligi ta’minlanadi [9].

AG ni qo‘zg‘atishda, miqdor va xarakter jihatidan turli yuklamalarni qo‘shish vaqtidagi o‘tkinchi kuchlanish qiymatining o‘zgarishini qayd etish jarayonlari “UTD1000L” rusumidagi ossillografdan

foydalanildi.

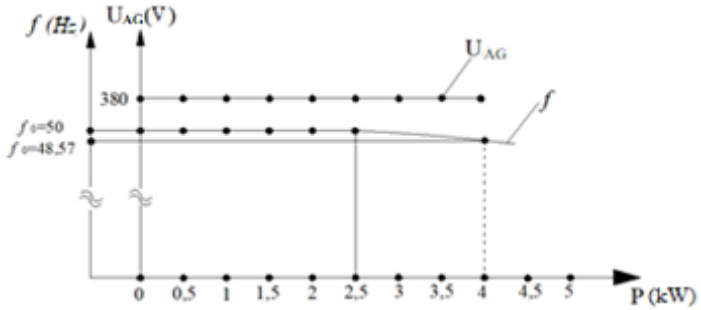
Nominal kuchlanishda qo‘zg‘atilgan AG chiqishiga avtomatik rostlovchi qurilma ulanganda, aktiv yuklamaning ortishi AG ning chiqish kuchlanishi va chastotasining o‘zgarishsiz qolishini ta’minlanishiga doir tajriba, quyidagi almashtirish sxema asosida o‘tkazildi, 2 - rasm [10].



2-rasm. Kuchlanishni avtomatik rostlash qurilmasiga ega AG ning almashtirish sxemasi.
Fig.2. Replacement circuit of an AG with an automatic voltage control device.

Bunda: Ic – avtomatik o‘zgaruvchan sig‘imli kondensator toki.

So‘ngra AG chiqishiga kontaktorlar va mikroprotsessordan iborat avtomatik rostlovchi qurilmani ulanib, chiqish kuchlanishi va chastotasini aktiv yuklamaga bog‘lanishiga doir tajriba o‘tkazildi. Ushbu tajribaga doir bog‘lanish grafigi 3 - rasmda keltirilgan.



3-rasm. RQARQ ga ega AG kuchlanish va chastotasining aktiv yuklamaga bog‘liq grafigi.
Fig.3. Graph of voltage and frequency depending on the active load of an AG with ARPRD.

3-rasmda, AG chiqishiga ulangan 4 kW gacha ortib boruvchi aktiv yuklamada, kontaktorlar va mikroprotsessordan iborat avtomatik rostlovchi qurilma hisobiga chiqish kuchlanishining nominal qiymati darajasida o‘zgarishsiz qolishi, shuningdek, chiqish chastotasi esa 2,5 kW yuklamagacha f = 50 Hz miqdorida saqlanishi ma’lum bo‘ldi. Bundan, kontaktorlar va mikroprotsessordan iborat avtomatik rostlovchi qurilmaning chastotani o‘zgarmasligiga ham (oldingidan 1,3 kW ga ortiqcha) ijobiy ta’sirini ko‘rsatadi, xususan, AG yuklamasi nominal yuklamaning 70 foizigacha (2,5 kW /3,44 kW) uning chastotasi f = 50 Hz miqdorida, o‘zgarishsiz qolishini, 4 kW ga teng yuklamada esa f = 48,57 Hz ni tashkil etishi ma’lum bo‘ldi [11].

4-rasm. RQARQ dan iborat avtomatik rostlovchi qurilmaga ega bo‘lgan AG ga 0,45 kW 0,9 kW va 3 kW aktiv quvvatli yuklamalar ketma-ket ulanganida chiqish kuchlanishining o‘zgarishi ossillogrammasi.
Fig.4. oscillogram of the change in output voltage when loads with an active power of 0,45 kW, 0.9

kW, and 3 kW are connected in series to an AG with an automatic regulation device consisting of an ARPRD.

4- rasmda, AG chiqishiga 4 kW gacha ortib boruvchi uch fazali aktiv yuklama ulanganda, chiqish kuchlanishi kontaktorlar va mikroprotsessordan iborat avtomatik rostlovchi qurilma hisobiga, o‘zining nominal qiymati darajasida barqaror qolishi ma’lum bo‘ldi. Ossillogrammadan, AG chiqishiga 3 kW yuklama ulanganda o‘sha faza kuchlanishining 3 sek davomida 200 V gacha tushib, kontaktorlar va mikroprotsessordan iborat avtomatik rostlovchi qurilma hisobiga qayta tiklanganligini ko‘rish mumkin [12].

5-rasm. RQARQ dan iborat avtomatik rostlovchi qurilmaga ega bo‘lmagan AG ga 0,45 kW, 0,9 kW va 3 kW quvvatli aktiv yuklamalar ketma-ket ulanganida chiqish tokining ortib borish ossillogrammasi.
Fig. 5. oscillogram of the change in output current when loads with an active power of 0.45 kW, 0.9 kW, and 3 kW are connected in series to an AG with an automatic regulation device consisting of an ARPRD.

Ossillogrammadan, nominal kuchlanishda qo‘zg‘atilgan, biroq kontaktorlar va mikroprotsessordan iborat avtomatik rostlovchi qurilma ega bo‘lmagan AG ning chiqishiga oshib boruvchi yuklamalar ulanganida generator tokining ortishi tasvirlangan. Tajriba davomida tok o‘zgarishining ossillogrammasini qayd etishda aktiv qarshiligi R = 1 Ω bo‘lgan shuntdan foydalanildi.

Yuqorida keltirilgan natijalar shuni ko‘rsatadiki, AG chiqishiga aktiv yuklama yoki turli xarakterdagi yuklamalar ulanayotgan holatlarda ham chiqish kuchlanishining barqarorligini saqlash sababi, talab etilayotgan reaktiv quvvatning to‘g‘ridan-to‘g‘ri generatordan emas, balki ishchi kondensator batareyalari orqali uzatilishidadir. Shu bilan birga, kondensatorlar reaktiv quvvatni ta’minlash orqali AG ning chiqish kuchlanishini nominal qiymatlarda barqaror saqlashga imkon beradi va tizimning statik barqarorligini kafolatlaydi [13].

3. Natijalar va muhokama (Results and discussion)

Sanoatda ishlab chiqarilishi keng yo‘lga qo‘yilgan, kichik o‘lchamlardagi turli sig‘imli, arzon kondensatorlar batareyalaridan foydalanilgan holda, Qoraqalpoq davlat universiteti “Energetika muhandisligi” kafedrasida, ishlab chiqilgan reaktiv quvvatni avtomatik rostlash qurilmasi (RQARQ) dan AG chiqish kuchlanish rostlagichi sifatida tatbiq qilinishi, kontaktorlar va mikroprotsessordan iborat avtomatik rostlovchi qurilma yordamida qisqa tutashgan an’anaviy rotorli AG ning har qanday yuklamasida ham chiqish kuchlanishini nominal kuchlanish miqdorida o‘zgarishsiz qolishi ta’minlandi [14,15].

4. Xulosa (Conclusion)

Xulosa qilish mumkinki, sig‘imi avtomatik rostlanuvchi kondensatorlar majmuasidan tashkil topgan RQARQ orqali, AG yuklamasining har qanday o‘zgarishlari natijasida ham generator chiqish kuchlanishi nominal qiymatlarda barqaror saqlanishi ta’minlanadi. Ushbu yechim generator tizimining elektr parametrlarini dinamik ravishda boshqarish imkonini berib, chiqish kuchlanishining barqarorligi va energiya sifatining uzluksizligini kafolatlaydi.

Dunyo mamlakatlari qayta tiklanadigan energiya manbalariga o‘tishda davom etar ekan, qisqa tutashgan rotorli AG larni shamol elektr stansiyalariga tatbiq etishga doir o‘tkazilgan nazariy va amaliy tadqiqotlar natijalari, elektr energiya ishlab chiqarishga qisqa tutashgan rotorli AG larni joriy etish, kelajakda iste’molchilarni barqaror va ishonchli elektr energiya bilan ta’minlashdagi istiqbolli yo‘nalishlardan biri ekanligini namoyon etadi.

Mamlakatimiz miqyosidagi mavjud shamol energiyasi miqdorlari hisob-kitobi, kelajakda SHES

larni keng tatbiq qilish orqali elektr energiya ishlab chiqarilishini joriy etish maqsadida ushbu sohaga salmoqli investitsiyalar kiritilishi - kelajakda samarali va ekologik jihatdan toza energiya manbai yaratilishiga imkoniyat yaratadi.

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