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MUQOBIL GIBRID ENERGIYA MANBALARINING MATEMATIK TENGLAMALARI ULARNING ISH REJIMLARINI MATLAB DA MODELLASHTIRISH

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Annotatsiya: Ushbu maqolada gibrid energiya tizimini tashkil qiluvchi asosiy komponentlar - fotoelektrik (PV) panellar, shamol turbinalari, mikroGES, energiya saqlash elementlari (batareya) va yuk/quvvat boshqaruv tizimlari uchun matematik modellar taqdim etiladi. Bundan tashqari maqolada gibrid energiya tizimining ish rejimi va yuqori darajadagi matematik modellari berilgan. PV (single-diode), shamol (Cp surface), mikroGES va batareya (Thevenin) modellari tizim dinamikasini va energiya balansini to‘liq qamrab olingan. MATLAB muhitida ushbu modellarni, MPPT va EMS ni implementatsiya qilish, va tajribaviy hisoblashlar bilan modelning xaqiqiy ekvivalentligini tekshirish tavsiya qilingan.

Kalit so‘zxlar: PV (single-diode), shamol (Cp surface), mikroGES, shamol turbinalari, energiya saqlash elementlari.

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Аннотация: В данной статье представлены математические модели основных компонентов гибридной энергетической системы: фотоэлектрических (ФЭ) панелей, ветровых турбин, микрогидроэлектростанций, накопителей энергии (аккумуляторов) и систем управления нагрузкой/мощностью. Кроме того, в статье представлены режим работы и высокоуровневые математические модели гибридной энергетической системы. Модели фотоэлектрических PV (single-diode), ветровых (Cp surface), микрогидроэлектростанций и аккумуляторных (Thevenin) систем полностью охватывают динамику системы и энергетический баланс. Рекомендуется реализовать эти модели, MPPT и EMS в среде MATLAB и проверить их реальную эквивалентность экспериментальными расчетами.

Ключевые слова: фотоэлектрические PV (single-diode), ветровые (Cp surface), микрогидроэлектростанции, ветровые турбины, накопители энергии.

Abstract: This paper presents mathematical models of the main components of a hybrid energy system: photovoltaic (PV) panels, wind turbines, micro hydro power plants, energy storage (battery) and load/power management systems. In addition, the paper presents the operating mode and high-level mathematical models of the hybrid energy system. The models of PV (single-diode), wind (Cp surface), micro hydro power plants and battery (Thevenin) systems fully cover the system dynamics and energy balance. It is recommended to implement these models, MPPT and EMS in the MATLAB environment and verify their real equivalence by experimental calculations.

Keywords: photovoltaic PV (single-diode), wind (Cp surface), microhydroelectric power plants, wind turbines, energy storage.

Kirish.

Hozirgi kunda energetika sohasida qayta tiklanadigan energiya manbalaridan samarali foydalanish masalasi jahon miqyosida strategik ahamiyat kasb etmoqda. Neft, gaz va ko‘mir kabi an’anaviy yoqilg‘ilarning zaxiralari cheklanganligi, ulardan foydalanish jarayonida ekologik muammolarning ortishi, atmosferaga chiqariladigan SO_2 miqdorining ko‘payishi va global iqlim o‘zgarishi alternativ energiya manbalarini joriy etishni taqozo etmoqda.

Shu bilan birga, alohida qo‘yosh yoki shamol stansiyalari tabiatdagi o‘zgaruvchan omillarga bog‘liq bo‘lgani sababli, ularning ishonchliligi va uzluksiz quvvat ta’minlash imkoniyati cheklangan. Mazkur muammoni hal qilishning eng samarali yo‘li — bu turli energiya manbalarini uyg‘unlashtirgan holda gibrid energiya ta’minoti tizimlarini qo‘llashdir. Bunday tizimda qo‘yosh panellari, shamol

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turbinalari, mikro-GES va akkumulyator batareyalari birgalikda ishlab, bir-birini to‘ldirib beradi va umumiy barqarorlikni ta’minlaydi.

Gibrid energiya tizimlarining ish rejimlarini to‘g‘ri tashkil etish va ularni matematik modellashtirish masalasi - energiya samaradorligini oshirish, ishonchli ta’minot va iqtisodiy maqbullikni ta’minlashda hal qiluvchi ahamiyatga ega. Shuning uchun mazkur tadqiqot dolzarb hisoblanadi.

Tadqiqotning asosiy maqsadi - muqobil gibrid energiya manbalari ish rejimlarini matematik modellashtirish orqali ularning energetik parametrlarini tahlil qilish, optimal taqsimotini aniqlash va samaradorligini oshirish. Maqsad - tizimning dinamik va statik qavvat muvozanatini aniqlay oluvchi modellar yaratish va ularni MATLAB/Simulink muhitida simulyasiya qilish uchun zarur bo‘lgan tenglamalarni berish.

Uslub va materiallar.

Quvvat balansi tenglamalari va umumiy quvvat balansi. Gibrid tizimning soddalashtirilgan quvvat balansi turli manbalarning chiqish quvvati va yuk talablari bilan shakllanadi. Bir vaqt momentda quyidagicha ifodalanadi:

$$P_{umumiy}(t) = P_{quyosh}(t) + P_{shamol}(t) + P_{gidro}(t) + P_{zaxira}(t) + P_{tarmoq}(t) - P_{yuklama}(t) - P_{isrof}(t)$$

bu yerda: $P_{umumiy}(t)$ - tizimning umumiy tarkibiy quvvati (ishlab chiqarilgan — sarflangan) (W); $P_{quyosh}(t), P_{shamol}(t), P_{gidro}(t)$ - alohida manbalarning vaqt bo‘yicha ishlab chiqargan quvvatlari (W); $P_{zaxira}(t)$ - dizel yoki boshqa zaxira manbalari (W); $P_{tarmoq}(t)$ - tarmoq bilan aloqa quvvati (tashqi yoki ichki), manfiy bo‘lishi mumkin (W); $P_{yuklama}(t)$ - yuklama talablari (W); $P_{isrof}(t)$ -tizim ichki isroflari (o‘zgarkichlar, quvvat elektronikalari, o‘tkazgichlardagi, transformatorlardagi va h.k.) (W). $P_{quyosh}(t)$ – fotoelektrik paneldan chiquvchi quvvat; $P_{shamo}(t)$ - shamol turbinasi quvvati; $P_{gidro}(t)$ - mikroGES chiqish quvvati; $P_{zaxira}(t)$ - akkumulyator batareyasi bergan/olgan quvvat.

Fotoelektrik panel (PV) — bir diodli model

Single-diode model - PV modulining keng tarqalgan modeli. Asosiy tenglamasi:

$$I = I_{ph} - I_0\left(e^{\frac{V+IR_s}{nV_t}} - 1\right) - \frac{V + IR_s}{R_{sh}}$$

bu yerda: I- chiqish to‘lami (A), V - voltaj (V); I_{ph} - foto-tok (A), I_0- diodning to‘yinish toki (saturation current) (A); R_s- seriya rezistor (Ω), R_{sh} - parallel (shunt) rezistor (Ω); n - ideallik faktori (din), $V_t = \frac{kT}{q}$ - termik voltaj (k - Boltsman, q - elektron zaryadi, T - absolyut harorat K).

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Odatdagi amaliyotda PVning qulay ishlanishi uchun STC (Standard Test Conditions) - irradiance G_{STC}=1000 W/m^2, temperatura T_{STC}=25°C=298.15 K.

Quvvat: $P_{pv}=V\times I$. Maksimal nuqta uchun MPPT algoritmi orqali V_{mp} va I_{mp} topiladi: $P_{max}=V_{mp}I_{mp}$.

PV Model - amaliyotdagi parametrlar va MPPT

Fotopanel modelida diod toki

Foto-tok I_{ph} radiatsiya va haroratga bog‘liq:

$$I_{ph} = \left(\frac{G}{G_{STC}}\right)\left[I_{ph,STC} + \alpha_{Isc}(T - T_{STC})\right]$$

Bu yerda:

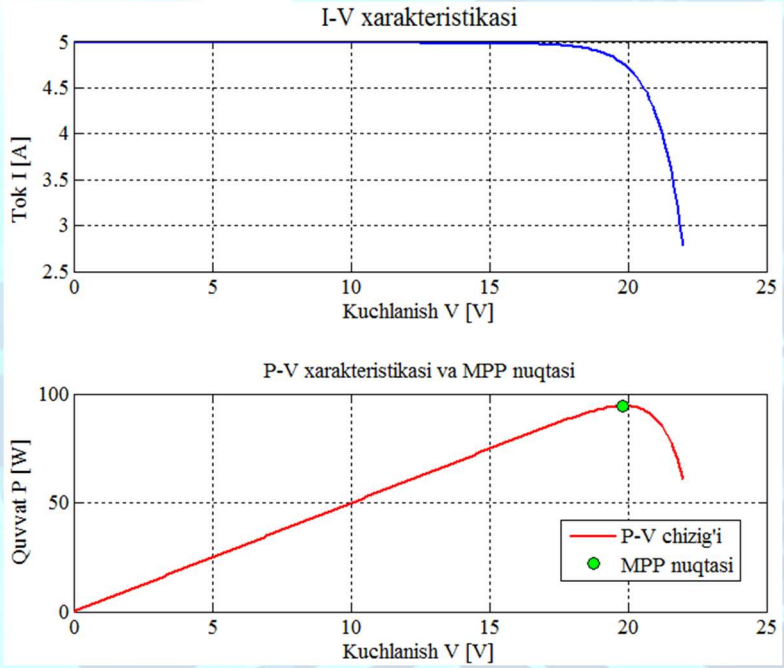
T - ishchi harorat (Kelvinda),

T_{STC} - standart harorat (298 K),

k - Bolsman konstantasi (1.38×10^{-23}J/K,

G -joriy radiatsiya (W/m²), α_{Isc} - tokning harorat koeffisiyenti.

Fotopanelning umumiy ekvivalent modelida asosiy elementlar: tok manbai, diod, seriyali va parallel qarshiliklardir. Diodning qiymatini hisoblashda quyidagi ifoda qo‘llaniladi:



1-rasm. Maksimal quvvat nuqtasini hisoblash algoritmining Perturb & Observe - “Ta’sir qilish va kuzatish” usuli urdamida modellashtirilgan quyosh panelining xarakteristikalari

Shamol turbinasi — aerodinamik va generator modeli. Aerodinamik quvvat:

$$P_{shamo} = \frac{1}{2}\rho A C_p(\lambda, \beta)\vartheta^3$$

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bu yerda: ρ- havo zichligi (kg/m³), odatda ≈ 1.225 kg/m³ (stand. sharoitlarda); $A=\pi R^2$ - rotor maydoni (m²), R – parrak radiusi (m); Cp(λ,β) - quvvat koeffisiyenti (Betz limiti bilan cheklangan, maksimal ≈ 0.59), u turbinaning tip speed ratio (λ) va pitch angle (β) ga bog‘liq; v - shamol tezligi (m/s).

Tip speed ratio: $$\lambda = \frac{\omega_r R}{\vartheta}$$

bu yerda ω_r - rotor burchaq tezligi (rad/s).

Mexanik moment:

$$M_{mex} = \frac{P_{shamol}}{\omega_r}$$

Generator bilan o‘zaro ta’sir dinamikasini hisoblash uchun rotor inersiyasi J va isroflar hisobga olinadi:

$$J\dot{\omega}_r = M_{mex} - M_{gen} - B\omega_r$$

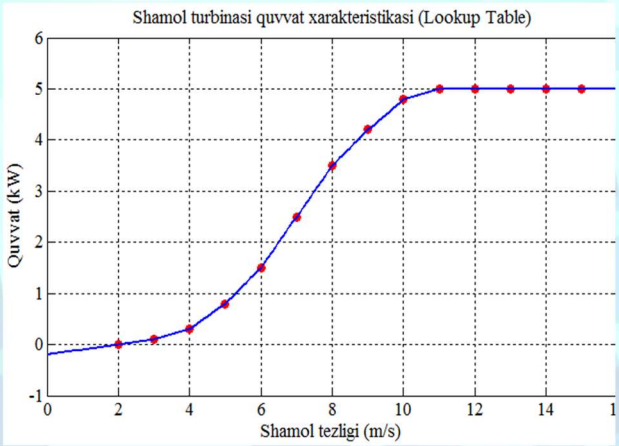
bu yerda M_{gen} - generator tomonidan olingan moment, B - aerodinamik isrof koeffisiyenti.

Shamol turbinasi - Cp surface va maksimum quvvat koeffisiyenti

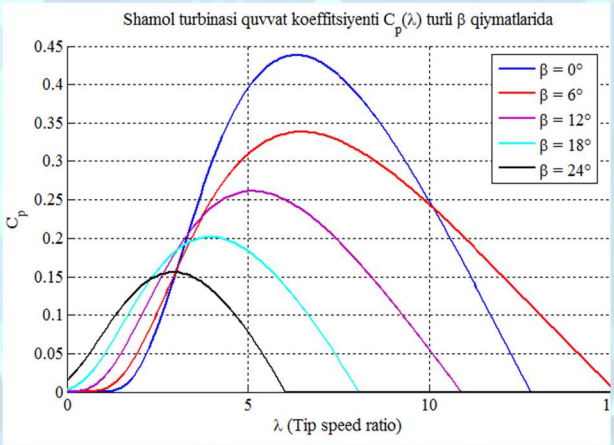
Koeffisiyent Cp(λ,β) uchun empirik model:

$$C_p(\lambda,\beta) = c_1\left(\frac{c_2}{\lambda_i} - c_3\beta - c_4\right)\cdot e^{-\frac{c_5}{\lambda_i}} + c_6\lambda$$

yoki turli turbinalar uchun berilgan lookup tablisa/polinomlar.



2-rasm. Quvvati 5kW bo‘lgan shamol turbinasi pasport jadvalini interpolyasiya qilish orqali modellashtirish.



3-rasm. Shamol turbinasi samaradrligining parrak burilish burchagi bog‘liqligi.

MikroGES (turbogenerator)

MikroGES uchun tasnif:

Suv resursdan keladigan energiya: $P_{gidro} = \eta_t \rho g Q H$

bu yerda: η_t – gidroturbina samaradorligi, ρ - suv zichligi (≈ 1000 kg/m³), g - erkin tushish tezlashuvi (9.81 m/s²), Q - suv oqimi (m³/s), H - bosim/Pa da (m).

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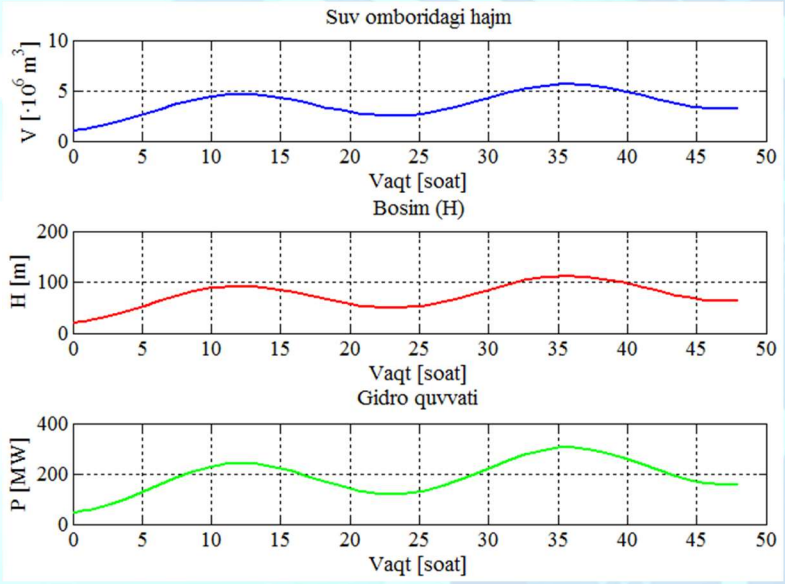
Dinamik model sifatida turbina boshqaruvi (gaday klapanlar, wicket gates) va generator dinamikasi (inersiya, vozbujdeniye) qo‘shiladi.

Turbina quvvati

Gidroturbinaning vaqt bo‘yicha chiqish quvvati quyidagicha yoziladi:

Suv resurslari uchun: $P_{gidro}(t) = \eta_{turb}(Q(t), H)\rho g Q(t) H(t)$

bu yerda: η_{turb} - turbina samaradorligi (Q va H ga bog‘liq), ρ - suv zichligi (≈1000 kg/m^3), g - yerning tortishish tezlanishi (9.81 m/s^2), Q(t) - vaqtiga qarab chiquvchi suv sarfi [m^3/s], H(t) - suv ustuni balandligi (netto napor) [m].



4-rasm. Suv omboridagi suvxajmining o‘zgarishi asosida turbinadan olinadigan quvvat o‘zgarishi modeli

Agar generator samaradorligi η_{gen} va invertor/elektronika isroflari η_{elek} hisobga olinsa, elektr chiqish:

$$P_{gidro}(t) = \eta_{gen}\eta_{elek} \cdot \eta_{turb}(Q(t), H) \cdot \rho g Q(t) H(t)$$

Odatda η_{gen} va η_{elek} doimiylarga yaqin (masalan, 0.9–0.98 orasi), lekin yuqori aniqlik talab qilinsa dinamik jarayonlar ham modellanadi.

Battareya (energiya saqlash) — ekvivalent elektr sxemasi

Ko‘p ishlatiladigan model - single-RC equivalent yoki Thevenin model:

$$\left.\begin{aligned} V_{bat}(t)\} &= V_{oc}(SOC) - I(t)R_{int} - V_{RC}(t) \\ \dot{V}_{RC}(t) &= -\frac{1}{R_{RC}C_{RC}} \cdot V_{RC}(t) + \frac{1}{C_{RC}} I(t) \\ SOC(t) &= SOC(0) - \frac{1}{Q_{nom}} \int_0^1 I(t)dt \end{aligned}\right\}$$

bu yerda: Voc(SOC) - ochiq sxemada kuchlanish (SOCga bog‘liq); Rint - ichki qarshilik; V_{RC}, R_{CR}, C_{RC} - dinamik impedans tarkibi; Q_{nom} - nominal quvvat (Ah).

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Batareya samaradorligi (energetik): $\eta_{bat} \approx \frac{E_{out}}{E_{in}}$, odatda 85–95%.

Misol 4 - Battareya va SOC hisob (energiya saqlash)

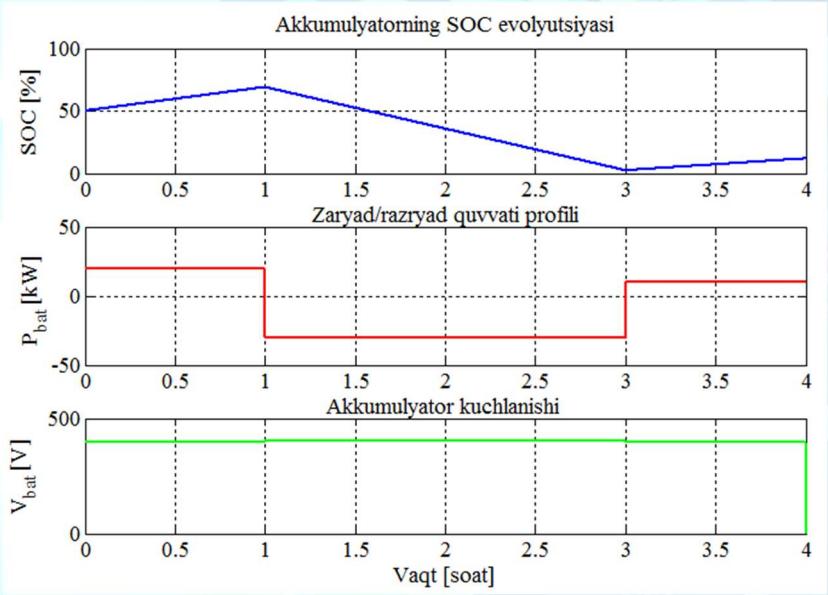
Berilgan: batareya paketi - 48 V, 200 Ah nominal.

1. Energiya: $E_{nom}=V\times Q=48\ V\times 200\ Ah$.

Amper×coatni-vatt×soatga o‘tkazish: 200 Ah=200 A×1 h.

$E_{nom}=48\times 200=9600\ Wh=9.6\ kWh$.

2. Agar SOC(0)=0.8 (80%), energiya mavjud: $E_{avail}=0.8\times 9.6\ kWh=7.68\ kWh$



5-rasm. Aakkumulyator (BESS – Battery Energy Storage System) va uning **SOC (State of Charge)** dinamikasi modeli

Agar yuk 3.5 kW bo‘lib 2 soat ishlashi kerak bo‘lsa, talab: 3.5 kW×2 h=7.0 kWh. Bu batareya 7.68 kWh mavjudligi bilan uni qoplaydi (SOC qoladi ≈ 7.68−7.0 = 0.68 kWh, yoki SOC ≈ 7.68−7.0 = 0.68 kWh ekvivalent ≈ 0.068/9.6 = 0.00708 → haqiqiy SOC% hisoblash aniqlashtirilishi kerak; batafsil: yangi SOC energiyasi = 7.68 − 7.0 = 0.68 kWh. Yang SOC% = (0.68 / 9.6) × 100% = 7.0833% ≈ 7.08% (bu juda past) - ammo e’tibor bering, bu yerda biz yukni batareya to‘liq qamrab olgan deb hisobladik; real tizimda yuk bo‘ladigan vaqtlar, invertor yo‘qotishlari va batareya samaradorligi hisobga olinmaydi).

Invertor va elektronika

Invertorlar DC→AC konversiyada samaradorligi ηinv\eta_{inv}ηinv (~94–98%) va anti-aylanding, MPPT, fazo kontrol kabi funksiyalarni bajaradi. Modelda invertorni statik samaradorlik koeffisiyenti sifatida yoki dinamik PWM model sifatida ifodalash mumkin.

Invertorning vazifalari:

Invertorlar - **DC (doimiy tok)** manbalaridan olingan energiyani **AC (o‘zgaruvchan tok)** ko‘rinishiga aylantiradi. Ular gibrid energiya tizimlarida:

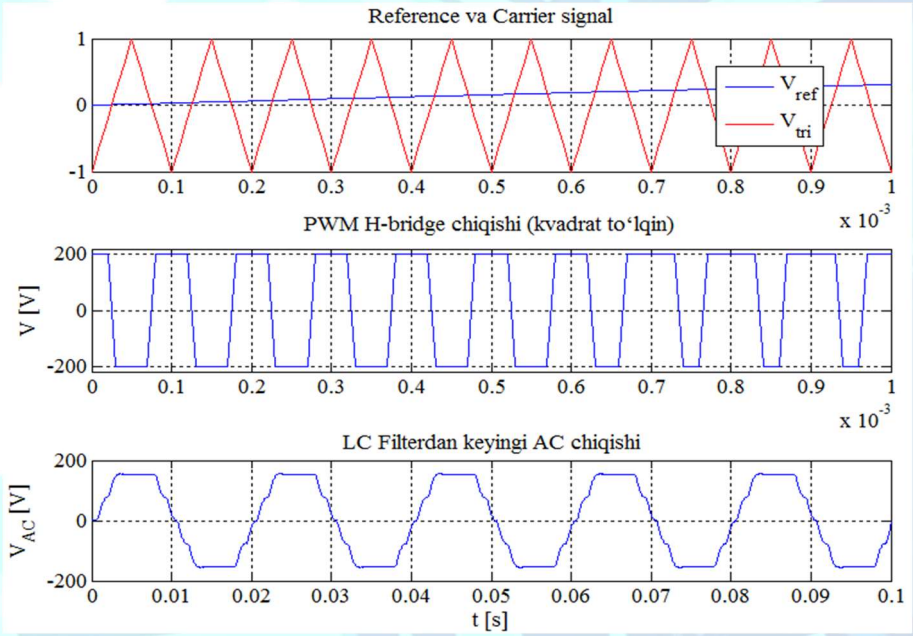
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- Fotoelektrik panellardan chiquvchi,
- DC quvvatni AC tarmoqqa uzatish,
- Batareya (BESS) bilan integratsiyada zaryad/razryad boshqaruvi.
- Shamol generatori va mikroGES invertorlari orqali sinxronlash **vazifalarini** bajaradi.

Invertor samaradorligi. Invertorning samaradorligi η_{inv} odatda **94–98%** orasida bo‘ladi:

$$\eta_{inv} = \frac{P_{AC}}{P_{DC}} \times 100\%$$

bu yerda: P_{AC} – chiqish quvvati (AC), P_{DC} – kirish quvvati (DC)



6-rasm. PWM asosida dinamik invertor modeli natijalari. V_{ref} – AC sinusoida (reference signal). V_{tri} – tashuvchi uchburchak (PWM carrier).

Samaradorlik yuklanishga bog‘liq bo‘lib, maksimal qiymatga 40–80% yuklanish oralig‘ida yetishiladi.

PWM simulyasiyasi **MATLAB/Simulink**da **Universal Bridge** blogi va **SPWM generator** orqali amalga oshiriladi.

Xulosa

Muqobil gibrid energiya manbalarining ish rejimlarini matematik modellashtirish natijalari ularning barqaror ishlashini ta’minlash va optimal ekspluatatsiya qilishda muhim ahamiyatga ega. Olib borilgan tahlillar asosida quyidagi ilmiy xulosalar shakllantirildi:

1. **Kompleks modelning zarurligi** - gibrid tizim tarkibidagi fotoelektrik stansiya, shamol turbinasi, mikro-GES, akkumulyator batareyalari va tarmoq bilan integratsiya jarayonlarini birgalikda hisobga olgan holda ish rejimlari tahlil qilindi.

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2. **Matematik modelning asosiy vazifasi** – energiya manbalarining turli ish rejimlarini (kunduz-tugun davriy o‘zgarishlari, shamol tezligi va gidroresurslar fluktuatsiyasi, yuklamalarning dinamik talablari) hisobga olish va ularning optimal taqsimotini ta’minlashdan iborat ekanligi ko‘rsatildi.

Xulosa sifatida aytish mumkinki, matematik modellashtirish – muqobil gibrid energiya manbalarining ish rejimlarini aniq baholash, ularning energetik parametrlarini optimallashtirish va istiqbolli qo‘llanilishini ta’minlash uchun muhim ilmiy-amaliy vosita hisoblanadi.

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