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МИНИСТЕРСТВО ВЫСШЕГО ОБРАЗОВАНИЯ, НАУКИ И ИННОВАЦИЙ РЕСПУБЛИКИ УЗБЕКИСТАН
АНДИЖАНСКИЙ МАШИНОСТРОИТЕЛНЫЙ ИНСТИТУТ

НАУЧНО-ТЕХНИЧЕСКИЙ ЖУРНАЛ
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Qishloq xo'jaligi ishlab chiqarishini mexanizatsiyalash texnologiyasi

Transport

Iqtisodiyot

ЭНЕРГЕТИКА ВА ЭЛЕКТРОТЕХНИКА. ҚИШЛОҚ ХЎЖАЛИГИ ИШЛАБ ЧИҚАРИШИНИ ЭЛЕКТРЛАШТИРИШ ТЕХНОЛОГИЯСИ. ЭЛЕКТРОНИКА

SANOAT KORXONALARI ELEKTR TARMOQLARIDA QAYTA TIKLANUVCHI ENERGIYA MANBALARINI YUKLAMA KO‘RSATKICHLARI VA ELEKTR ENERGIYA SIFAT KO‘RSATKICHLARIGA TA’SIRI

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ANNOTATSIYA

Maqolada quyosh elektr stansiyalari elektr tarmoq tizimlariga integratsiyasi va tegishli yechimlar bilan bog'liq muammolarni ko'rib chiqadi va muhokama qiladi. Qayta tiklanuvchi energiya manbalarini sanoat korxonalari elektr tarmog‘ida elektr energiya sifat ko’rsatkichlari, kuchlanish chastota va reaktiv quvvat balansiga ta’siri ko’rib chiqilgan. Shuningdek, u dolzarb ijtimoiy-iqtisodiy, ekologiya va elektr energiyasi bozoriga oid masalalarni ham hal qiladi. Nihoyat, u muhokama qilingan muammolarga qarshi kurashish uchun to'g'ri yechimlar metodologiyalarini, shu jumladan energiyani saqlash tizimlari va qayta tiklanadigan energiya manbalaridan foydalanish istiqbollari keltirilgan.

Kalit so‘zlar: *Elektr energiyaasi sifati, qayta tiklanuvchi energiya manbalari, kuchlanish va chastota og‘ishi, energiya siyosati, energiya saqlash tizimlari.*

АННОТАЦИЯ

В статье рассматриваются и обсуждаются проблемы, связанные с интеграцией солнечных электростанций в электросетевые системы и связанные с этим решения. Рассмотрено влияние возобновляемых источников энергии на показатели качества электроэнергии, частоты напряжения и баланса реактивной мощности в электросетях промышленных предприятий. В нем также рассматриваются текущие социально-экономические, экологические проблемы и проблемы рынка электроэнергии. Наконец, в нем представлены правильные методологии решения обсуждаемых проблем, включая перспективы использования систем хранения энергии и возобновляемых источников энергии.

Ключевые слова: *Качество электроэнергии, возобновляемые источники энергии, отклонение напряжения и частоты, энергетическая политика, системы хранения энергии*

ABSTRACT

The article examines and discusses the problems associated with the integration of solar power plants into electrical grid systems and related solutions. The influence of renewable energy sources on the power quality indicators, voltage frequency and reactive power balance in the power network of industrial enterprises was considered. It also addresses current socio-economic, environmental and electricity market issues. Finally, it presents the right solution methodologies to combat the discussed problems, including the perspectives of using energy storage systems and renewable energy sources.

Key words: *Power quality, renewable energy resourses, voltage and frequency deviation, energy policy, energy storage systems.*

Introduction

In 2020-2030, special attention will be paid to the production of electricity from renewable energy sources, especially the development of solar energy. These projects are implemented only at the expense of investors - independent electricity producers. In order to achieve the development indicators of renewable energy, the target parameters of the annually commissioned capacities of QTEMs are set, with the construction of 3 GW of wind and 5 GW of solar power plants planned for 2020-2030. In wind energy, the main focus is on the establishment of large wind power plants with a capacity of 100-500 MW each, most of which will be located in the North-West region (the Republic of Karakalpakstan and Navoi region). Figure 1 below shows the structure of energy production based on RER until 2030, in MW [1].

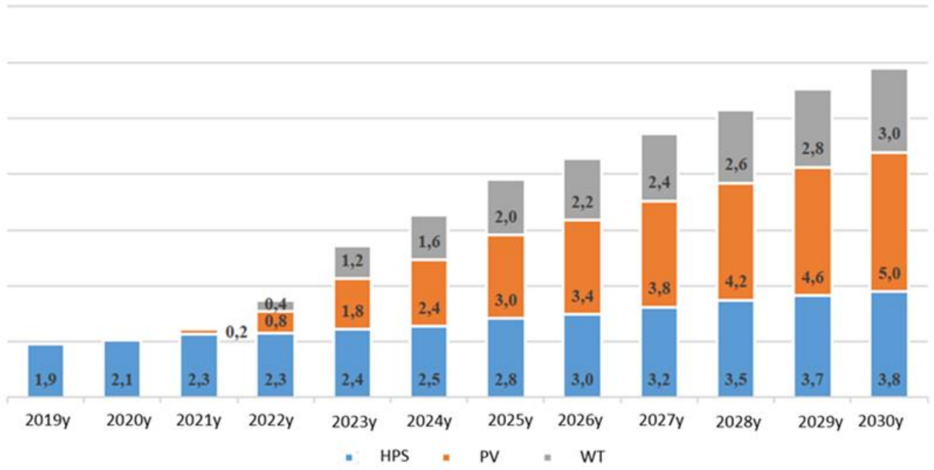


Figure 1. Structure of energy production based on RER until 2030, MW

The modular nature and declining price of solar PV and wind energy technologies drive their comparatively faster growth over other RER [2]. In addition, technological advancement due to continuous investments in research plays a vital role in reducing the Levelized Costs of Energy (LCOE) and their integration into the electric grids. However, the intermittent nature of wind speed and solar irradiation due to climactic conditions can create a wide range of operational and protection challenges for electricity grids. Besides, the networks' power quality, reliability, and stability may be hampered due to the bulk intermittent energy integration if timely appropriate measures are not taken [3,4]. Furthermore, load demand and RER power generation compatibility, transmission infrastructure and congestion, grid flexibility and resiliency, electricity market mechanism, and policies may lead to curtailment of installed RER.

Methodology & empirical analysis. Rigorous research in the enhancement of PV cell efficiency, reduction of PV panel cost, and maximum power extraction from the PV systems pave the way for the rapid growth ofPV power generation [5]. due to the climatic conditions pose operational challenges for PV integration into the grid [6]. Therefore, accurate prediction of PV power has become an essential task for safe and stable power system operation. Prediction can focus on PV power or energy output or their rate of change.

Results. To obtain a flat voltage profile with minor deviations, a con-stant source of power that is adaptable to the changes in the network is required. Unfortunately, solar PV plants do not possess the necessary characteristics, as the average hours (average peak sun-hours) under perfect conditions are from three to six hours [7]. Many studies investigated this issue and suggested solutions. Widen et al. [8] presented a stochastic methodology for simulating PV-system impacts on low-voltage distribution grids via detailed generation and demand models. The authors concluded that there would be an unacceptable voltage variability if the PV penetration level goes beyond a certain threshold. Gaunt et al. [9] analyzed the impact of a PV system on a residential distribution feeder. The adopted probabilistic approach showed that a certain percentage (i.e., 25%) penetration of solar PV in low voltage feeders recommended by the South African grid code could lead to substantial voltage problems. In [10], the optimal penetration level of solar PV power into the Nigerian power system considering voltage stability was addressed. Ref. [11] proposed a three-layer voltage/var control strategy to enhance voltage stability with large-scale PV penetration. Battery energy storage systems (BESS) were used to optimize active and reactive powers for voltage stability [12]. Researches of the three modes of microgrid operation have been conducted. The values of voltage fluctuations, frequency deviations and voltage harmonic composition are investigated. Microgrid operation modes are described by the following equations:

$$P_B + P_{CON} \pm P_{SB} = P_{CEN} + P_{DG} \tag{1}$$

$$Q_B + Q_{CON} \pm Q_{RPS} = Q_{CEN} + Q_{DG} \tag{2}$$

where P, Q – active and reactive power; indexes: B –ballast load, C – consumers load, SB – storage battery, CEN –centralized electrical network, DG – distributed generation,RPC – reactive power compensation.

It has been established that in modes 2 and 3 a brief imbalance of power is possible. This leads to short-term increases in current in modes 2 and 3 - up to 70% of the parameters of the normal mode; and increases in voltage – up to 11.5% of the nominal value (Fig. 2) [49].

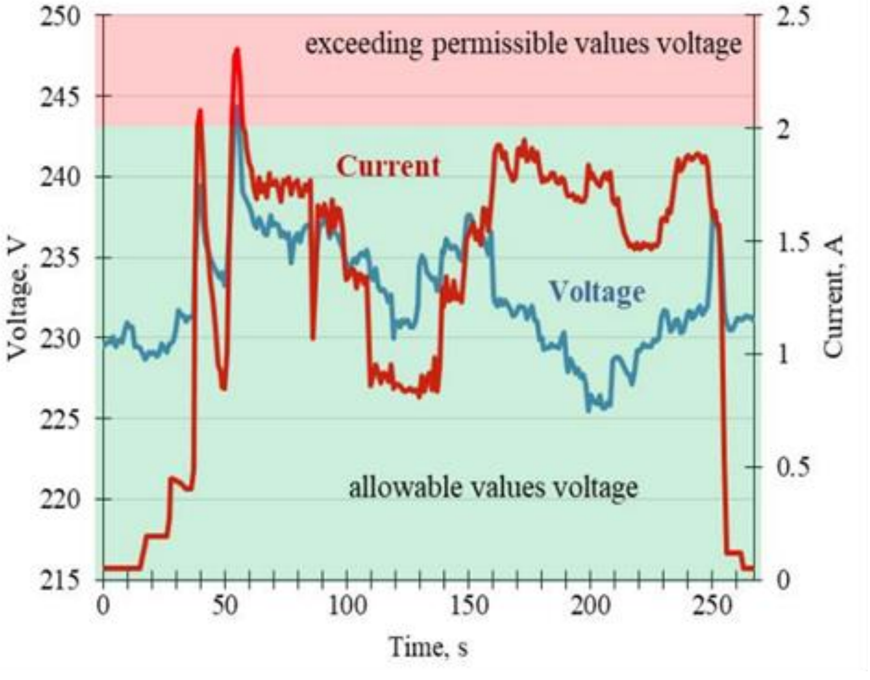


Fig.2. *Oscillograms of current and voltage at the connection point ofconsumer to the microgrid at the start of power output from the DG* [49]

The suitability of various flexible AC transmission systems (FACTS) devices for optimal voltage profiles was investigated in [14]. However, voltage stability with bulk PV penetration remains a prime concern, necessitating further studies to quantify the impact and develop appropriate solutions [14].

The integration of PV systems into the grids increases the probability of an imbalance between generation and demand due to their intermittent nature. This mismatch may lead to frequency fluctuations, causing partial or total loss of electrical supply. It was found that increased PV share accelerates the rate of change of frequency (ROCOF), potentially leading to system collapse during natural overloads [14]. Additionally, studies on IEEE benchmark transmission networks showed that more than 40% penetration of solar PV generation can lead to system collapse during the worst contingency case due to the loss of inertia [15]. The frequency response of a 20 kV distribution grid due to the incorporation of PV generation was investigated, suggesting that more than 20% PV generation integration leads to network collapse [16]. This can be clearly seen from actual frequency event occurred in the Irish power system in 2017 as shown in Fig. 3. During the event displayed a 379 MW synchronous generator tripped resulting in a frequency nadir of 49.4 Hz in which the system experienced large RoCoF of 0.42 Hz/s [48].

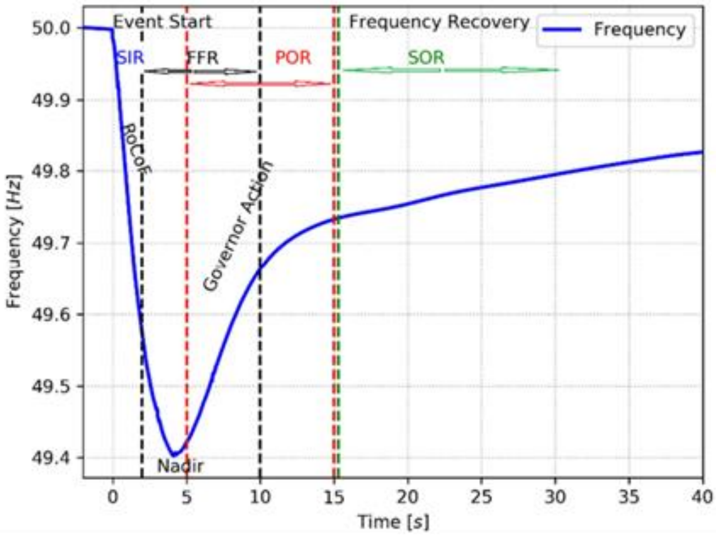


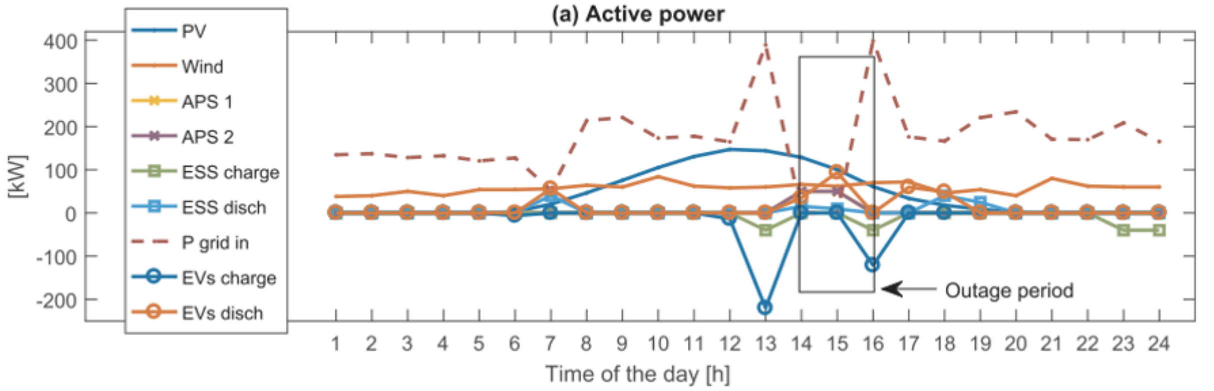
Fig. 3. ***Frequency services in the Irish power system*** [48]

The study also explored using energy storage systems (ESS) to enhance system frequency response under bulk PV penetration. As future intermittent renewable energy resource (RER) penetration increases, system inertia will decrease, making impact analysis and control strategies for frequency response improvement crucial. Therefore, further investigation for proper mitigation in this field is necessary [14].

PV power is produced as direct current (DC) and lacks the capability to provide reactive power, a characteristic of AC sources [17]. Innovative technologies are needed to provide reactive power capability. It was indicated that variable generation plants like wind and solar could contribute to the reactive power capability of the network [18]. One of the two APS units is activated to provide both active and reactive power support as illustrated in Fig. 4a and Fig. 4b, respectively[50].

Strategies for injecting reactive power into the grid from PV power plants were investigated, including various control methods [19]. A proposed reactive power compensation technique enhanced the system voltage profile, minimized voltage variation, and reduced total harmonic distortion of the PV power plant connected to the grid [108]. Additionally, a distributed reactive power compensation scheme was developed to enhance the voltage profile by reducing voltage imbalances in an unbalanced distribution grid [109]. Efficient management of reactive power in electricity grids improves network voltage profiles, enhances system stability, and reduces power quality issues. Therefore, different control strategies for reactive power management and the deployment of FACTS and ESS devices for reactive power support require further attention for sustainable integration of renewable energy resources (RER). Moreover, Pereira et al. [22] introduced a dynamic approach to offset harmonic currents caused by nonlinear loads by utilizing power electronic converters utilized for integrating PV systems as additional services. They suggested that system operators offer incentives to PV system owners utilizing inverters to enhance power quality via harmonic compensation. However, the multifunctional nature of PV inverters could potentially compromise overall system efficiency [23]. Consequently, further in-depth examination and analysis in this domain are warranted.

(a) Active power



(b) Reactive power

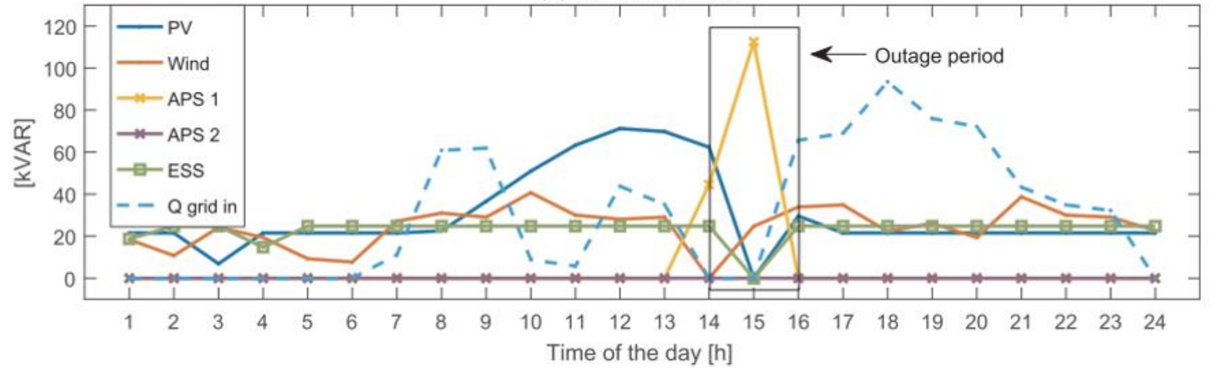


Fig. 4. *Active (a) and reactive (b) power for the existing distribution network generator*

Large solar PV projects are usually located in deserts, mountainous areas, or places far from the city center, necessitating significant investment in new transmission lines [24]. Remote monitoring and control solutions are also required for their efficient integration into the grids. The high concentrations of rooftop PV systems in distribution grids result in network congestions [25], potentially causing malfunctioning and unwanted curtailment of PV generation. Various series of compensated FACTS devices were proposed to enhance power transfer capability in response to congestion issues [26]. In [27], the PV inverter was transformed into a STATCOM to improve network power transfer capability, also enhancing power system stability under contingency cases. To address communication challenges, the use of the internet of things (IoT) for system monitoring, fault diagnosis, event forecasting, and preventive maintenance was suggested [28]. Finally, Qi et al. [28] proposed a holistic attack-resilient framework to protect grid-integrated RER and overall grid infrastructure from cyberattacks, emphasizing the need for further exploration of methodologies to ensure safe and secure grid operation amidst transmission, communication, and security challenges.

This section summarizes critical and advanced technologies in grid-integrated PV systems. Techniques for power fluctuation smoothing were reviewed [29], including geographical dispersion, principal component analysis, fuzzy wavelet filtering, ramp-rate control, GA-based feedback control, wavelet transform based ANN, Elman neural network, and deep neural network [30]. Two control strategies with and without ESS received attention for providing primary frequency response [31], while frequency control strategies without ESS were proposed as de-loading techniques [32]. Frequency control strategies with ESS were presented [33], along with other strategies such as active power control, fuzzy logic control, and adaptive neuro-fuzzy inference system (ANFIS) [34]. Various voltage control strategies were proposed, including decentralized and centralized techniques [35]. Researchers also explored ESS, tap changing transformers, and FACTS devices for voltage profile enhancement [36].

Advanced control strategies for optimal reactive power dispatch were proposed, classified into graphical, analytical, numerical, heuristic, and dynamic planning methods [37]. Ansari et al. presented a Holonic architecture-based reactive power control strategy [38], while a PI controller was illustrated for reactive power capability control [39]. Other strategies included adaptive droop control, index-based reactive power control, prosumer-owned control, fuzzy-based reactive power control, and system of system-based control [40]. Al-Shetwi reviewed control approaches to enhance grid-integrated PV systems' FRT capability [41], including external devices and improved controller-based strategies [42.]. However, these strategies are still in their early stages and require further investigation for effective, intelligent, and robust control techniques.

As discussed earlier, integrating renewable energy resources (RER) into the grid poses operational challenges due to their lack of dispatchability, which can be addressed through the deployment of energy storage systems (ESS) [43]. ESS technology aids in integrating intermittent RER, reducing peak load demand, and stabilizing electricity prices in competitive markets. While pumped hydroelectric ESS (PHESS) and compressed air ESS (CAESS) are the most deployed large-scale systems, they only represent 3% of global electricity generation capacity [44]. Battery ESS (BESS) has gained attention for its cost reduction and improved efficiency [45]. Other technologies such as flywheel ESS (FESS), super-capacitor ESS (SCESS), and superconducting magnetic ESS (SMESS) have also garnered interest. Additionally, hydrogen fuel cell ESS (FCESS) offers emission-free electricity generation and finds applications in the power system.

Conclusions

This paper reviewed such grid integration challenges of PV systems along with available solution technologies. The reviewed significant challenges are the accurate voltage, frequency, angular stabilities, injection of harmonics, and system fault ride-through capability. Other reviewed challenges include the up-gradation of the protection schemes of the traditional power systems, transmission congestion management, penetration into the electricity markets, and socio-economic and environmental issues due to the incorporation of PV systems into the grids. Finally, this article discussed available methodologies investigated and explored by the researchers and scientists to combat the reviewed challenges.

References

1. “2020-2030 йилларда Ўзбекистон Республикасини электр энергияси билан таъминлаш концепцияси” https://minenergy.uz/uz/lists/view/28.

2. M. R. Patel, Wind and Solar Power Systems: Design, Analysis, and Operation. Boca Raton, FL, USA: CRC Press, 2005..

3. V. Telukunta, J. Pradhan, A. Agrawal, M. Singh, and S. G. Srivani, ‘‘Protection challenges under bulk penetration of renewable energy resources in power systems: A review,’’ CSEE J. Power Energy Syst., vol. 3, no. 4, pp. 365-379, Dec. 2017, doi: 10.17775/CSEEJPES. 2017.00030.

4. J. G. Ndirangu, J. N. Nderu, A. M. Muhia, and C.M. Maina, ‘‘Power quality challenges and mitigation measures in grid integra¬tion of wind energy conversion systems,’’

in Proc. IEEE Int. Energy Conf. (ENERGYCON), Jun. 2018, pp. 1-6, doi: 10.1109/ENERGYCON. 2018.8398823.4. Соловьев, А.Л. Шабад М.А. Релейная защита городских электрических сетей 6 и 10 кВ / Учебное пособие. – Санкт-Петербург: Политехника, 2007. – 175 с.

5. D. S. Pillai and N. Rajasekar, ‘‘A comprehensive review on protection challenges and fault diagnosis in PV systems,’’ Renew. Sustain. Energy Rev., vol. 91, pp. 18-40, Aug. 2018, doi: 10.1016/j.rser.2018.03.082.

6. L.-L. Li, S.-У. Wen, M.-L. Tseng, and C.-S. Wang, ‘‘Renewable energy prediction: A novel short-term prediction model of photovoltaic out¬put power,’’ J. Cleaner Prod., vol. 228, pp. 359-375, Aug. 2019, doi: 10.1016/j.jclepro.2019.04.331.7. Козлов, В.Л. Электроснабжение городов. / В.Л. Козлов. – Ленинград: Энергоатомиздат, Ленинградское отделение, 1988. – 264 с.

7. Sun Hours/Day Zone Solar Insolation Map, Solar Wholesale, Orlando, FL, USA, 2013.

8. J. Widen, E. Wackelgard, J. Paatero, and P. Lund, ‘‘Impacts of dis¬tributed photovoltaics on network voltages: Stochastic simulations of three Swedish low-voltage distribution grids,’’ Electr. Power Syst. Res., vol. 80, no. 12, pp. 1562-1571, Dec. 2010, doi: 10.1016/j.epsr. 2010.07.007.

9. C. T. Gaunt, E. Namanya, and R. Herman, ‘‘Voltage modelling of LV feeders with dispersed generation: Limits of penetration of randomly connected photovoltaic generation,’’ Electr. Power Syst. Res., vol. 143, pp. 1-6, Feb. 2017, doi: 10.1016/j.epsr. 2016.08.042.

10. O. B. Adewuyi, R. Shigenobu, T. Senjyu, M. E. Lotfy, and A. M. Howlader, ‘‘Multiobjective mix generation planning considering utility-scale solar PV system and voltage stability: Nigerian case study,’’ Electr. Power Syst. Res., vol. 168, pp. 269-282, Mar. 2019, doi: 10.1016/j.epsr.2018.12.010.

11. H. Li, L. Zhou, M. Mao, and Q. Zhang, ‘‘Three-layer voltage/var control strategy for PV cluster considering steady-state voltage sta¬bility,’’ J. Cleaner Prod., vol. 217, pp. 56-68, Apr. 2019, doi: 10.1016/j.jclepro.2019.01.163.

12. O. B. Adewuyi, R. Shigenobu, K. Ooya, T. Senjyu, and A. M. Howlader, ‘‘Static voltage stability improvement with battery energy storage considering optimal control of active and reactive power injection,’’ Electr. Power Syst. Res., vol. 172, pp. 303-312, Jul. 2019, doi: 10.1016/j.epsr.2019.04.004.

13. S. Gasperic and R. Mihalic, ‘‘Estimation of the efficiency of FACTS devices for voltage-stability enhancement with PV area criteria,’’ Renew. Sustain. Energy Rev., vol. 105, pp. 144-156, May 2019, doi: 10.1016/j.rser.2019.01.039.

14. Shafiullah M., Ahmed S. D., Al-Sulaiman F. A. Grid integration challenges and solution strategies for solar PV systems: a review //IEEE Access. – 2022. – Т. 10. – С. 52233-52257.

15. K. A. Qaid, C. Kim Gan, N. Bin Salim, and M. Shamshiri, ‘‘Impacts of large-scale solar photovoltaic generation on power system frequency response,’’ in Proc. 5th IET Int. Conf. Clean Energy Technol. (CEAT), 2018, pp. 1-16, doi: 10.1049/cp.2018.1309.

16. R. Darussalam and I. Garniwa, ‘‘The effect of photovoltaic pene¬tration on frequency response of distribution system,’’ in Proc. Int. Conf. Sustain. Energy Eng. Appl. (ICSEEA), Nov. 2018, pp. 81-85, doi: 10.1109/ICSEEA.2018.8627080.

17. Photovoltaics and Electricity—Energy Explained, Your Guide To Under-standing Energy—Energy Information Administration, Energy Inf. Admin., Washington, DC, USA, 2022.

18. A. Ellis, R. Nelson, E. Von Engeln, R. Walling, J. McDowell, L. Casey, E. Seymour, W. Peter, C. Barker, and B. Kirby, ‘‘Reac¬tive power interconnection requirements for PV

and wind plants- recommendations to NERC,'' Sandia Nat. Lab., Albuquerque, NM, USA, Tech. Rep. SAND2012-1098, 2012, doi: 10.2172/1039006.

19. У. Yang, H. Wang, and F. Blaabjerg, ''Reactive power injection strategies for single-phase photovoltaic systems considering grid requirements,'' IEEE Trans. Ind. Appl., vol. 50, no. 6, pp. 4065-4076, Nov./Dec. 2014, doi: 10.1109/TIA.2014.2346692.

20. A. Samir, M. Taha, M. M. Sayed, and A. Ibrahim, ''Efficient PV-grid system integration with PV-voltage-source converter reactive power support,'' J. Eng., vol. 2018, no. 2, pp. 130-137, Feb. 2018, doi: 10.1049/joe.2017.0877.

21. M. Zeraati, M. E. H. Golshan, and J. M. Guerrero, ''Voltage quality improvement in low voltage distribution networks using reactive power capability of single-phase PV inverters,'' IEEE Trans. Smart Grid, vol. 10, no. 5, pp. 5057-5065, Sep. 2019, doi: 10.1109/TSG.2018.2874381.

22. H. A. Pereira, G. L. E. da Mata, L. S. Xavier, and A. F. Cupertino, ''Flexible harmonic current compensation strategy applied in single and three-phase photovoltaic inverters,'' Int. J. Electr. Power Energy Syst., vol. 104, pp. 358-369, Jan. 2019, doi: 10.1016/j.ijepes.2018.07.017.

23. G. L. E. Mata, R. C. de Barros, W. V. Ribeiro, L. S. Xavier, A. F. Cupertino, and H. A. Pereira, ''LCL filter losses due to harmonic compensation in a photovoltaic system,'' in Proc. IEEE 8th Int. Symp. Power Electron. Distrib. Gener. Syst. (PEDG), Apr. 2017, pp. 1-7, doi: 10.1109/PEDG.2017.7972523.

24. Challenges for 100% Renewable Energy, Life: Powered, Texas Public Policy Found., Austin, TX, USA, 2018.

25. G. Tevar, A. Gomez-Exposito, A. Arcos-Vargas, and M. Rodriguez-Montanes, ''Influence of rooftop PV generation on net demand, losses and network congestions: A case study,'' Int. J. Elect. Power Energy Syst., vol. 106, pp. 68-86, Mar. 2019, doi: 10.1016/j.ijepes.2018.09.013.

26. S. Sreejith, S. S. Rangarajan, M. Ambili, P. Sujyothi, and V. G. Nithya, ''Enhancing the power transfer capability in a power system network using series connected FACTS devices for increased renewable penetra¬tion,'' in Proc. Int. Conf. Adv. Electr. Eng. (ICAEE), Jan. 2014, pp. 1-6, doi: 10.1109/ICAEE.2014.6838509.

27. R. Nivedha, R. N. Banu, and A. O. Prakash, ''Enhancement of grid power transmission limits using photovoltaic solar farm as STATCOM (PV-STATCOM),'' in Proc. Int. Conf. Comput. Technol. Intell. Data Eng. (ICCTIDE), Jan. 2016, pp. 1-6, doi: 10.1109/ICCTIDE.2016.7725325.

28. C. Zedak, A. Lekbich, A. Belfqih, J. Boukherouaa, T. Haidi, and F. E. Mariami, ''A proposed secure remote data acquisition architecture of photovoltaic systems based on the Internet of Things,'' in Proc. 6th Int. Conf. Multimedia Comput. Syst. (ICMCS), May 2018, pp. 1-5, doi: 10.1109/ICMCS.2018.8525902.

29. S. Shivashankar, S. Mekhilef, H. Mokhlis, and M. Karimi, ''Mitigating methods of power fluctuation of photovoltaic (PV) sources—A review,'' Renew. Sustain. Energy Rev., vol. 59, pp. 1170-1184, Jun. 2016, doi: 10.1016/j.rser.2016.01.059.

30. J. Marcos, L. Marroyo, E. Lorenzo, and M. Garrfa, ''Smoothing of PV power fluctuations by geographical dispersion,'' Prog. Photovolt., Res. Appl., vol. 20, no. 2, pp. 226-237, Mar. 2012, doi: 10.1002/pip.1127.

31. M. Dreidy, H. Mokhlis, and S. Mekhilef, ''Inertia response and fre¬quency control techniques for renewable energy sources: A review,'' Renew. Sustain. Energy Rev., vol. 69, pp. 144-155, Mar. 2017, doi: 10.1016/j.rser.2016.11.170.

32. P. P. Zarina, S. Mishra, and P. C. Sekhar, ''Exploring frequency con¬trol capability of a PV system in a hybrid PV-rotating machine-without storage system,'' Int. J. Elect. Power Energy Syst., vol. 60, pp. 258-267, Sep. 2014, doi: 10.1016/j.ijepes.2014.02.033.

33. R. Bhatt and B. Chowdhury, ‘‘Grid frequency and voltage support using PV systems with energy storage,’’ in Proc. North Amer. Power Symp., Aug. 2011, pp. 1-6, doi: 10.1109/NAPS.2011.6025112.

34. A. Q. Al-Shetwi, W. K. Issa, R. F. Aqeil, T. S. Ustun, H. M. K. Al-Masri, K. Alzaareer, M. G. M. Abdolrasol, and M. A. Abdullah, ‘‘Active power control to mitigate frequency deviations in large-scale grid-connected PV system using grid-forming single-stage inverters,’’ Energies, vol. 15, no. 6, p. 2035, Mar. 2022, doi: 10.3390/en15062035.

35. A. Arshad and M. Lehtonen, ‘‘A comprehensive voltage control strategy with voltage flicker compensation for highly PV penetrated distribution networks,’’ Electr. Power Syst. Res., vol. 172, pp. 105-113, Jul. 2019, doi: 10.1016/j.epsr.2019.02.019.

36. У. Wang, K. T. Tan, X. У. Peng, and P. L. So, ‘‘Coordinated control of distributed energy-storage systems for voltage regulation in distribution networks,’’ IEEE Trans. Power Del., vol. 31, no. 3, pp. 1132-1141, Jun. 2016, doi: 10.1109/TPWRD.2015.2462723.

37. M. Hashemi and M. H. Zarif, ‘‘A novel two-stage distributed structure for reactive power control,’’ Eng. Sci. Technol., Int. J., vol. 23, no. 1, pp. 168-188, Feb. 2020, doi: 10.1016/j.jestch.2019.03.003.

38. J. Ansari, A. Gholami, and A. Kazemi, ‘‘Multi-agent systems for reactive power control in smart grids,’’ Int. J. Electr. Power Energy Syst., vol. 83, pp. 411-425, Dec. 2016, doi: 10.1016/j.ijepes.2016.04.010.

39. E. M. Darwish, H. M. Hasanien, A. Atallah, and S. El-Debeiky, ‘‘Reac¬tive power control of three-phase low voltage system based on voltage to increase PV penetration levels,’’ Ain Shams Eng. J., vol. 9, no. 4, pp. 1831-1837, Dec. 2018, doi: 10.1016/j.asej.2017.01.006.

40. M. A. Ghasemi and M. Parniani, ‘‘Prevention of distribution network overvoltage by adaptive droop-based active and reactive power control of PV systems,’’ Electr. Power Syst. Res., vol. 133, pp. 313-327, Apr. 2016, doi: 10.1016/j.epsr.2015.12.030.

41. A. Q. Al-Shetwi, M. Z. Sujod, F. Blaabjerg, and У. Уang, ‘‘Fault ride-through control of grid-connected photovoltaic power plants: A review,’’ Sol. Energy, vol. 180, pp. 340-350, Mar. 2019, doi: 10.1016/j.solener.2019.01.032.

42. S. C. Уang, A. Ukil, S. Dasgupta, A. K. Gupta, and V. S. K. M. Balijepalli, ‘‘LVRT capability enhancement for grid connected distributed syn¬chronous generators using switch-in braking resistors,’’ in Proc. Asian Conf. Energy, Power Transp. Electrific. (ACEPT), Oct. 2017, pp. 1-5, doi: 10.1109/ACEPT.2017.8168551.

43. M. Уousif, Q. Ai, W. A. Wattoo, Z. Jiang, R. Hao, and У. Gao, ‘‘Least cost combinations of solar power, wind power, and energy storage system for powering large-scale grid,’’ J. Power Sources, vol. 412, pp. 710-716, Feb. 2019, doi: 10.1016/j.jpowsour.2018.11.084.

44. W. Wu and B. Lin, ‘‘Application value of energy storage in power grid: A special case of China electricity market,’’ Energy, vol. 165, pp. 1191-1199, Dec. 2018, doi: 10.1016/j.energy.2018.09. 202.

45. K. E. Forrest, B. Tarroja, L. Zhang, B. Shaffer, and S. Samuelsen, ‘‘Charging a renewable future: The impact of electric vehicle charging intelligence on energy storage requirements to meet renewable portfo¬lio standards,’’ J. Power Sources, vol. 336, pp. 63-74, Dec. 2016, doi: 10.1016/j.jpowsour.2016.10.048.