IJARSCT
International Journal of Advanced Research in Science, Communication and Technology
International Open-Access, Double-Blind, Peer-Reviewed, Refereed, Multidisciplinary Online Journal
ISSN: 2581-9429
Volume 5, Issue 3, December 2025
Impact Factor: 7.67

Smart Grid Technologies and Their Impact on Power Quality

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Abstract: *As our power systems move away from large centralized plants toward renewable-based, decentralized setups, traditional grids are transforming into smart, connected networks. These smart grids are more efficient, flexible and eco-friendly but they also bring new problems with power quality (PQ). Issues like unstable voltage, frequency changes and unwanted electrical noise (harmonics) are becoming more common, especially with electricity now flowing in both directions between the grid and active consumers who also produce power. This study looks at how distributed energy storage systems (DESS) when paired with smart control methods can make smart grids more stable and reliable. We propose a multi-layer approach that uses grid-forming inverters, smart prediction for when to use storage and coordinated methods to reduce harmonics. All of this works through real-time monitoring and adaptive control, so storage and renewable sources work together smoothly. Our computer simulations show clear benefits i.e. better voltage and frequency stability, lower harmonic distortion and faster recovery when problems occur. On top of that, the system helps manage peak electricity demand, smooths out the ups and downs of renewable power and recovers quickly from short-term disruptions. By combining smart storage with advanced controls, this approach offers a scalable way to make future smart grids more reliable and resilient helping utilities, engineers, and policymakers handle the challenges of our rapidly changing energy world.*

Keywords: Smart grid, Power quality (PQ), Distributed energy storage systems (DESS), Grid-forming inverters, Harmonic suppression, Voltage stability, Frequency stability, Predictive Storage dispatch, Renewable integration, Peak load management, Adaptive control, Real-time monitoring

I. INTRODUCTION

Smart grids make power transmission and distribution more efficient and reliable. These modernised power networks comprise computerised systems capable of automating and managing the increasing complexity of 21st-century power grids [1]. Smart grids are the ultimate goal of power system development. With access to a high proportion of renewable energy, energy storage systems, with their energy transfer capacity, have become a key part of the smart grid construction process [2]. While the adoption of renewable energy sources can bring many benefits in responding to climate change and addressing the energy crisis, high levels of renewable energy penetration in power grids can also cause significant impacts on the grid. For one, the output of renewable energy is unpredictable and intermittent due to uncontrollable external factors, such as weather and the environment, making it difficult to meet the voltage and waveform requirements of an ideal power supply system and resulting in power quality problems. Voltage fluctuations and flicker, voltage imbalance, frequency deviation, a low power factor, and harmonic pollution are among the main impacts of high renewable energy penetration on power quality in a distribution network [3].

Besides achievements in power electronics, sensing, monitoring, and control technology, key Smart Grid enablers are the advances that in the last decade have been made in the area of telecommunications. There is a long list of complementary and sometimes competing wireless and wireline specifications and standards that can be used in Smart Grid deployments [4].

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Smart grids enhance the efficiency of power systems, especially during the integration of renewable energy (RE) systems. Utilising electricity from RES reduces harmful greenhouse gas emissions, provides diversity in the generation mix, and reduces the overdependence on fossil fuels. Various challenges are encountered during the integration and utilisation of such systems. Recent studies have proposed diverse techniques in addressing these challenges, however, there is a lack of research on the current techniques suitable for integrating the recent developments on REs and smart grids [5]

II. FACTS DEVICES (FLEXIBLE AC TRANSMISSION SYSTEMS)

FACTS devices are employed to regulate power flow and enhance the efficiency and stability of electrical power systems. Power lines have losses which make the situation more unfavourable for maximum power transfer. Implementing a flexible AC transmission system (FACTS) is one of the best ways to reduce line losses [6]. There might be various causes of a fault, such as a short circuit, a natural calamity, an overload, or reckless maintenance. System failures may manifest themselves in several ways, such as a triple-phase failure, a single line to ground failure, and a double-line failure. In the present system, the faults contribute to a huge increase in the current level. Damage to power system equipment could cause the whole area to black out [7]. This will negatively impact the power network's reliability and efficiency. Distribution network and transmission system have widely implemented flexible AC transmission system (FACTS) to help improve and regulate credibility as well as exercise power [8]. FACTS devices, such as Static VAR Compensators (SVCs), Static Synchronous Series Compensators (SSSCs), and Unified Power Flow Controllers (UPFCs), can control voltage, current, and phase angle across transmission lines to optimize flow paths and prevent overload [9]. Additionally, distribution STATCOM (DSTATCOM), dynamic voltage re storer (DVR) , and unified power quality conditioner (UPQC)are used in the distribution network. The operation of the FACTS devices is controlled by different controllers such as fuzzy controller, adaptive controller , and PI controller. A perfect placement of these FACTS devices gives maximum power quality improvement. These FACTS devices can also be used to reduce the fault current in the system.[6].

III. POWER QUALITY ISSUES IN TRADITIONAL GRIDS

Traditional power grids were designed many decades ago with a simple structure: electricity was generated at large central power plants, transmitted over long lines, and distributed to end-users. While this system worked well in the past, today's electrical environment is very different. The growing use of modern appliances, electronics, and non-linear loads has created challenges that the old grid setup is not well-prepared to handle. As a result, several power quality (PQ) problems are commonly observed.

The main power quality issue in traditional grids are

1. Voltage Fluctuations
2. Harmonics
3. Frequency deviation
4. Flicker
5. Unbalanced Loads
6. Interruptions
7. Low Power Factor

1. Voltage Fluctuations: Voltage fluctuation is one of the key issues on power quality that emerges when RES are integrated with the grid. The significant prevalence of intermittent, uncontrollable RES is the main cause of voltage fluctuation. Voltage flicker is the major effect of voltage fluctuations[10]. They are relatively small (less than +5 or +10 percent) variations in the rms line-voltage. These variations can be caused by static frequency converters, cyclo-converters, arc furnaces, rolling mill drives, main winders and large motors during starting, etc.[11]. voltage fluctuations can be described using two metrics, short-term flicker severity and long-term flicker severity. Although, there are other inherent grid factors capable of causing voltage fluctuations, but are particularly heightened by renewable energy, which has a negative impact on power quality[12].

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2. Harmonics: Harmonics are created when the waveforms deviate from a sinusoidal shape. Such current harmonics change the voltage waveform and disrupt the power supply, which can cause several issues[12]. harmonics are said to be part of a periodic quantity that has a Fourier series of more than one order; for instance, the third harmonic order in a 50 Hz system is 150 Hz. Harmonics are capable of resulting in overheating and overcurrent, with impacts such as supply voltage distortion and rapid circuit breaker tripping[13]. Harmonics can reduce the overall efficiency of a power system. The presence of harmonics means more current is required to deliver the same amount of real power, leading to increased transmission losses. Harmonics can lead to a reduction in the power factor, which can increase the apparent power in the system and result in higher energy costs. The presence of harmonics in a power system is primarily due to non-linear loads. Linear loads, such as resistive heaters or incandescent lights, draw sinusoidal current at the same frequency as the voltage. Non-linear loads, on the other hand, draw current in a non-sinusoidal manner. Harmonics in the power grid can cause various adverse effects, such as overheating in electrical equipment, misoperation of protective devices, and communication interference.[14].

3. Frequence Fluctuations: Frequency fluctuation is the deviation from the nominal frequency. Frequency fluctuation is a significant problem to power quality in the grid as a result of the large penetration of RES [15]. This is a result of the fluctuating output power of RES. Frequency deviation in the grid often happens when the demand is less than or more than the generation. And as more RES are used, this divergence gets worse [12]. This may lead to equipment damage, load performance degradation, and power system instability. The deviation of the frequency from the reference value must never be too large, otherwise, it becomes a serious problem. Normal conditions are often observed when a system works within a frequency deviation range of 0.1 Hz, while abnormal conditions occur when the frequency ranges from 47.5 to 51.5 Hz.[16].

IV. ROLE OF REAL-TIME MONITORING AND CONTROL

Monitoring and controlling power quality is become crucial to ensure the power system runs steadily as smart grids have developed quickly. Issues related to conventional power quality monitoring techniques include insufficient real-time performance and limited monitoring accuracy.[17] Monitoring and managing power quality is a crucial criterion for developing a smart grid. The electricity system's operational condition and other indicator metrics must be continuously monitored to make use of smart grid technology[18,19]. Real-time power quality monitoring is an essential component of current power management systems. This feature enables continuous monitoring and analysis of the characteristics of electrical power. This technology significantly aids in the identification, diagnosis, and mitigation of power quality issues, preventing them from affecting system performance or causing damage to electrical equipment. In order to continually monitor a wide range of electrical parameters, including voltage, current, frequency, harmonics, and power factor, real-time power quality monitoring systems make use of sophisticated sensors and meters[20]. Advanced control systems can step in immediately to fix problems as they occur, whether by switching capacitor banks, adjusting generation levels, or redirecting power to balance the grid. This role becomes even more critical with renewable sources like solar and wind, which are unpredictable and can cause sudden changes in supply. Real-time monitoring helps utilities deliver electricity that is both steady and clean, while also providing useful data for maintenance and future planning. In simple terms, it works like the nervous system of the power grid constantly sensing, reacting, and keeping everything stable to ensure good power quality and reliable service.

V. RENEWABLE INTEGRATION CHALLENGES

A sustainable energy future depends on the grid's ability to integrate renewable energy sources (RES), but doing so presents substantial power quality difficulties. Due to differences in power generation, the usage of power electronics in RES can result in problems such voltage instability, harmonic distortion, frequency oscillations, and reactive power imbalance. This study looks into how integrating renewable energy affects power quality[21]. The use of power electronics to connect renewable energy sources to the grid also inevitably introduces harmonic components to the grid[22]. The integration of new energy generation into the grid can exacerbate the problem of voltage imbalance in the grid, leading to additional power losses and reducing the capacity of transformers and lines[23]. Due to the intermittent

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nature of renewable energy output and the uncertainty of load demand, the mismatch between power generation and load demand leads to deviations in grid frequency[24]. When uncontrollable renewable energy units are connected to the system, the power-dispatching process becomes more complicated[25].

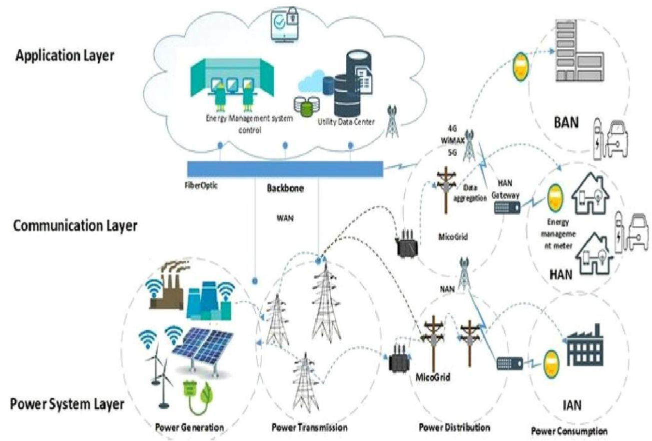

Fig. 1.. Concept of smart grid architecture [26]

Fig.1. Illustrates a typical concept of a smart grid with several Renewable Energies (REs) and Distributed Energy Resources (DERs) integrated. The key aspect of the modern smart grid architecture is its ability to communicate with each component of the power system. Smart grids integrate both traditional and renewable energy-generating technologies into a single network. It facilitates the operation of distributed generation, energy storage systems, and residential micro-generation[27].

Amid growing concerns over climate change and energy security, the deployment of power from renewable energy sources (RES) has attracted significant global interest due to its potential to address these critical challenges. In this context, smart grids offer a promising pathway for the effective integration of RES into power systems, thereby contributing to the reduction of greenhouse gas emissions [5]. ectric power from RES is generated close to the load centres, thereby limiting the burden placed on long transmission systems [28]. Despite the numerous benefits associated with renewable energy sources (RES), their integration into power systems presents significant challenges. In particular, incorporating RES into smart grids introduces complex dynamics that can affect the stability, reliability, and operation of conventional energy networks. The intermittency associated with RES, such as wind and solar energy contributes to voltage and frequency fluctuations, which leads to grid instability [29]. Furthermore, the variability and uncertainty associated with renewable energy sources such as wind and solar can reduce system inertia and cause real-time imbalances between load and generation, leading to frequency instability and grid management challenges [30]. Given these challenges, different techniques have been proposed by various studies to optimise the integration of RE into smart grids. These techniques are normally borne out of the impacts associated with the RE system and the smart grid system [5].

VI. USE OF SMART DEVICES TO MITIGATE PQ ISSUES

Various techniques are used to improve the power quality, such as passive filters, tuned passive harmonic filters, and active filters. the use of a series active filter on the DC side of grid-connected PV systems to improve their power quality, stability, and dynamic performance[33]. Power system reliability can be improved with the use of energy storage. Energy storage systems, with their energy transfer capacity, have become a key part of the smart grid construction process[2,34]. The fast frequency control in bulk power systems using embedded networks of grid-forming energy storage resources. Further, the grid-forming inverter systems interfacing with the storage resources, are augmented with fast-acting safety controls designed to contain frequency transients within a prescribed tolerance band[35].Some of the smart device for PQ Mitigation are : Smart Meters & Power Quality Monitors, Dynamic

Voltage Restorer (DVR), Static VAR Compensator (SVC)/ Static Synchronous Compensator (STATCOM),Energy Storage Systems (ESS).

Smart Meters & Power Quality Monitors: Smart meters and PQ monitors are digital devices installed at the consumer or distribution side to measure and record power system parameters such as voltage, current, harmonics, flicker, frequency, and power factor. These devices follow standards like IEC 61000-4-30 for PQ measurement. Enable real-time detection of sags, swells, harmonics, and unbalance. Provide trend analysis to utilities for preventive action. Support demand response and corrective switching of compensators. Help enforce regulatory compliance by monitoring customers' harmonic injections and power factor.[36,37,38].

Dynamic Voltage Restorer (DVR): A DVR is a series-connected power electronic device that injects controlled voltage to compensate for disturbances. It uses a Voltage Source Converter (VSC) and a DC link for short-term energy storage. Compensates voltage sags and swells by injecting the missing or excess voltage. Provides phase balancing for unbalanced voltages. Maintains clean sinusoidal waveform for sensitive loads.[39,40].

Static VAR Compensator (SVC)/ Static Synchronous Compensator (STATCOM): SVC: Shunt-connected compensator using thyristor-controlled capacitors/reactors. STATCOM: Advanced shunt device using a VSC, capable of faster and more precise reactive power compensation than SVC. Provide dynamic reactive power to stabilize voltage .Suppress voltage flicker and fluctuations .Improve power factor and mitigate unbalance. In renewable integration, STATCOM supports voltage ride-through and grid stability[41,42].

Energy Storage Systems (ESS) : An energy storage system, often abbreviated as ESS, is a device or group of devices assembled together, capable of storing energy in order to supply electrical energy at a later time. Battery ESS are the most common type of new installation and are the focus of our free fact sheet[43]. Provide ride-through support during voltage sags/interruptions. Smooth renewable energy intermittency. Improve frequency stability by balancing demand–generation. Supply reactive power through converter control, supporting PQ like a STATCOM. Reduce harmonics if converters are programmed as active filters[44].

VII. APPLICATIONS

IoT + ANFIS for Real-time PQ Enhancement: Use of Internet of Things (IoT) sensors, wireless sensor networks, and adaptive neuro-fuzzy inference systems (ANFIS) to continuously monitor PQ parameters (voltage fluctuations, harmonics etc.) and automatically adjust control responses. Enables early detection of disturbances (sags, swells, flicker), adaptive controller can compensate dynamically, improving stability and reducing downtime. In addition, renewable sources (solar, wind) performance improves when their disturbances are managed in real time[45].

Volt/Var Management & Distribution Automation (DA) for Voltage Regulation and Reactive Power Control: Systems that use smart metering, real-time data, automated control devices (capacitor banks, voltage regulators, LTCs), communication networks, and software (VVM - Volt/Var management, DA) to control voltage profiles across feeders, balance phases, minimize reactive losses.Reduces voltage sags/swells, reduces unbalance, lowers reactive power flow (improves efficiency), flattens voltage profile so end customers get more stable voltage. It can reduce harmonic-related problems by keeping voltage in desired limits.[46]

Power Quality Compensators under Smart Grid / Microgrid Settings: Use of active and passive compensators, such as APFs (Active Power Filters), UPQC (Unified Power Quality Conditioners), STATCOM/D-STATCOM, DVRs in grids with distributed generation (DGs) or microgrids. Smart control and coordination among these devices using communication, local measurement, and digital controllers. Mitigates harmonics, reactive imbalance; improves waveform quality; provides local correction of distortions; helps in handling fluctuating loads and intermittent generation. In microgrids the compensators collaborate to maintain PQ even when grid is islanded[47].

Smart Microgrids Integrating Distributed Renewable Generation: Local (microgrid) systems with solar, wind, storage, loads, managed via smart controllers, smart meters, energy management systems. They can operate in grid-connected or island mode, switching modes during disturbances.Helps limit the propagation of PQ disturbances from distributed generation to the main grid; voltage fluctuations due to renewable intermittency are mitigated by local

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ISSN: 2581-9429

Volume 5, Issue 3, December 2025

Impact Factor: 7.67

storage / local control; when islanded, the microgrid can maintain PQ for its loads. Also mitigates voltage drop and THD under different load and generation conditions[48].

VIII. CONCLUSION

Smart grid technologies are reshaping the way modern power systems operate by directly addressing long-standing challenges in power quality. Unlike traditional grids which struggle with instability when integrating renewable energy, smart grids leverage advanced devices such as smart meters, FACTS controllers, energy storage, and adaptive monitoring systems to create a more reliable and resilient network. These innovations help minimize disturbances like voltage sags, harmonic distortion, and frequency fluctuations while also ensuring smoother renewable integration and better load management. Beyond technical improvements, the adoption of smart grids represents a step toward a cleaner, more sustainable energy future. By combining intelligent control with distributed energy storage and real-time monitoring, smart grids can adapt quickly to disturbances, recover faster from faults, and optimize resource use. This makes them not only a solution for today's PQ challenges but also a foundation for future energy systems that are flexible, efficient, and environmentally responsible.

REFERENCES

[1]. A.M. Prostejovsky, C. Brosinsky, K. Heussen, D. Westermann, J. Kreusel, M. Marinelli, The future role of human operators in highly automated electric power systems, Electr. Power Syst. Res. 175 (2019) 105883..

[2]. Fan Li 1, Dan Wang1, DongLiu 1, Songheng Yang 2,*, Ke Sun 1, Zhongjian Liu 1, Haoyang Yu 1 and Jishuo Qin 1, AComprehensive Review on Energy Storage System Optimal Planning and Benefit Evaluation Methods in Smart Grids, Sustainability 2023, 15, 9584. https://doi.org/10.3390/su15129584.

[3]. Shafiullah, G.; Arif, M.T.; Oo, A.M. Mitigation strategies to minimize potential technical challenges of renewable energy integration. Sustain. Energy Techn. 2018, 25, 24–42.

[4]. M. Burns, "NIST SGIP catalog of standards," October 2010, http://collaborate.nist.gov/twiki-sggrid/bin/view/SmartGrid SGIPCatalogOfStandards

[5]. Samuel Jonas Yeboah a,b William Duodu Asihene , Solomon Nunoo c a , Joseph Cudjo Attachie , Emmanuel Yeboah Asuamah a d, Impact and integration techniques of renewable energy sources on smart grid operations:Asystematicreview,https://doi.org/10.1016/j.sciaf.2025.e02845

[6]. IbrahimM.Mehedi Ubaid M. Al-Saggaf ,1,2JahinAlHasanJoy ,3Md.RafiqulIslam ,1,2 Ahmad H. Milyani ,3NayeemaHasan ,1AhmedI. Iskanderani Abdullah Abusorrah ,1,4 Muhyaddin Rawa ,1,4 and Hussain Bassi, Reducing Fault Current by Using FACTS Devices to Improve Electrical Power Flow Hindawi Mathematical Problems in Engineering Volume 2021, Article ID 8116816, 9 pages https://doi.org/10.1155/2021/8116816

[7].] L.Kovalsky,X.Yuan,K.Tekletsadik,A.Keri, J.Bock, and F. Breuer, "Applications of superconducting fault current limiters in electric power transmission systems," IEEE Transactions onAppiled Superconductivity, vol. 15, no. 2, pp.2130–2133,2005.

[8]. R. K. Padiyar, FACTS Controllers in Power Transmission and Distribution, Anshan Publishers, Anshan, China, 1st edition, 2007

[9]. Mehrdad Tarafdar Hagh a , Mohammad Ali Jabbary Borhany Kamran Taghizad-Tavana a a,* , Morteza Zare Oskouei, A comprehensive review of flexible alternating current transmission system (FACTS): Topologies,applications, optimal placement, and innovative models, https://doi.org/10.1016/j.heliyon.2024.e41001.

[10]. OLADAPO T. IBITOYE, MOSES O. ONIBONOJE, JOSEPH O. DADA, Analysis of Power Quality and Technical Challenges in Grid-Tied Renewable Energy, Volume 18, 2023

[11]. https://www.electricalindia.in/which-factors-affect-the-power-supply-quality/

[12]. N. Medepalli, M. Joy, and R. Gorre, "Mitigation of Power Quality Issues in Grid Integrated Renewable Energy Resources," no. November, 2020, 10.13140/RG.2.2.35224.21764.

DOI: 10.48175/IJARSCT-30434

[13]. G. Carpinelli, F. Mottola, D. Proto, and A. Russo, "A Decision Theory Approach for the Multi-objective Optimal Allocation of Active Filters in Smart Grids," in 2022 20th International Conference on Harmonics \& Quality of Power (ICHQP), 2022, pp. 1–6

[14]. https://www.monolithicpower.com/en/learning/mpscholar/power-electronics/power-quality-and-harmonics/introduction-to-power-quality-and-harmonics#:~:text=The%20presence%20of%20harmonics%20means,result%20in%20higher%20energy%20costs.

[15]. M. A. Majeed et al., "Adaptive Dynamic Control Based Optimization of Renewable Energy Resources for Grid-Tied Microgrids," Sustain., vol. 14, no. 3, 2022, doi: 10.3390/su14031877.

[16]. S. Impram, S. Varbak Nese, and B. Oral, "Challenges of renewable energy penetration on power system flexibility: A survey," Energy Strategy Reviews, vol. 31, no. August. Elsevier Ltd, p. 100539, 2020. doi: 10.1016/j.esr.2020.100539.

[17]. Dr.Amitvikram C Nawalagatti1, Dr.D.Obulesu2, Pramodhini R3, Dr.Preethi D4, P.Uma Maheshwara Rao5*, Dr. R. Senthamil Selvan6, Dr. M. Prabha, Enhancing Power Quality and Grid Control with Real-Time Monitoring Sensors, Metall. Mater. Eng. Vol 31(1) 2025p. 501-510

[18]. Bubshait, Abdullah S., et al. "Power quality enhancement for a grid connected wind turbine energy system." IEEE Transactions on Industry Applications 53.3 (2017): 2495-2505.

[19]. Qureshi, Kashif Naseer, Raza Hussain, and Gwanggil Jeon. "A distributed software defined networking model to improve the scalability and quality of services for flexible green energy internet for smart grid systems." Computers & Electrical Engineering 84 (2020): 106634.-505101520368.917Flicker Frequency (Hz)Voltage fluctuation %Relative error %

[20]. https://www.monolithicpower.com/en/learning/mpscholar/ac-power/power-conditioning-systems/power-monitoring-and-control-systems#:~:text=Real%2DTime%20Power%20Quality%20Monitoring,causing%20damage%20to%20electrical%20equipment.

[21]. Pradeep Kumar 1 , Dr Suresh Chand2 , Rohit Kumar Gupta3 , Amar Bahadur Singh4, Impact of Renewable Energy Integration on Power Quality Challenges and Solutions, ISSN (Online): 2350-0557, Volume-11, Issue-4, August 2024

[22]. Shi, L.L.; Jia, Q.Q.; Lin, L.J.; Wang, N.; Tian, G. Distributed Global Optimal Harmonic Mitigation Strategy for Power Electronics High Penetrated Distribution Networks. Proc. CSEE 2020, 40, 2914–2924.

[23]. Meersman, B.; Renders, B.; Degroote, L.; Vandoorn, T.; Vandevelde, L. Three-phase inverter-connected DG-units and voltage unbalance. Electr. Power Syst. Res. 2011, 81, 899–906.

[24]. Xu, Y.; Li, C.; Wang, Z.; Zhang, N.; Peng, B. Load frequency control of a novel renewable energy integrated micro-grid containing pumpedhydropower energy storage. IEEE Access 2018, 6, 29067–29077

[25]. Das, T.; Roy, R.; Mandal, K.K. Impact of the penetration of distributed generation on optimal reactive power dispatch. Protect. Control. Mod. Power Syst. 2020, 5, 31

[26]. S.S. Al-Azzawi, N.A. Qarabash, N.A. Qarabsh, S.S. Sabry, H.A. Qarabash, Smart grid in the context of industry 4.0 : an overveiw of communictions technologies and challenges smart grid in the context of industry 4.0: an overview of communications technologies and challenges, Indones. J. Electr. Eng. Comput. Sci. 18 (2) (2020) 656–665, https://doi.org/10.11591/ijeecs.v18.i2.pp%25p.

[27]. I Diahovchenko, M. Kolcun, Z. ˇ Conka, V. Savkiv, R. Mykhailyshyn, Progress and challenges in smart grids: distributed generation, smart metering, energy storage and smart loads, Iran. J. Sci. Technol. Trans. Electr. Eng. 44 (2020) 1319–1333.

[28]. T. Adefarati, R. Bansal, Energizing renewable energy systems and distribution generation. Pathways to a Smarter Power System, Elsevier, 2019, pp. 29–65.

[29]. B. Kroposki, Achieving a 100% renewable grid: operating electric power systems with extremely high levels of variable renewable energy, IEEE Power Energy Mag. 15 (2) (2017) 61–73.

[30]. J. Hu, R. Harmsen, W. Crijns-Graus, E. Worrell, M. Broek, Identifying barriers to large-scale integration of variable renewable electricity into the electricity market: a literature review of market design, Renew. Sustain. Energy Rev. 81 (2018) 2181–2195.

[31]. https://www.nfpa.org/education-and-research/electrical/energy-storage-systems

[32]. N. Florin, E. Dominish, Sustainability evaluation of energy storage technologies, Inst. Sustain. Futur. 78 (2017)

[33]. Husam Ali Hadi a a , Abdallah Kassem Ecole Doctoral, Improve power quality and stability of grid - Connected PV system by using series filter, https://doi.org/10.1016/j.heliyon.2024.e39757

[34]. Sushita K a a b , Shanmugasundaram N b , Kannadhasan Suriyan c , Nagarajan R d and Kanagaraj Venusamy, Impacts of residential energy storage system modeling on power system, SUSTAINABLE ENVIRONMENT 2022, VOL. 8, NO. 1, 2125905 https://doi.org/10.1080/27658511.2022.2125905

[35]. Kaustav Chatterjee, Ramij Raja Hossain, Sai Pushpak Nandanoori, Soumya Kundu, Diane Baldwin, and Ronald Melton, Frequency Control and Disturbance Containment Using Grid-Forming Embedded Storage Networks, arXiv:2410.14892v1 [eess.SY] 18 Oct 2024

[36]. Cavalcante, D. et al., "Low-cost smart meter for monitoring of power quality disturbances applied in smart grid," *Measurement*, 146: 873–885, 2019.

[37]. Mocanu, B. et al., "PQ and Harmonic Assessment Issues on Low-Cost Smart Metering Platforms: A Case Study," *Sensors*, 20(21): 6361, 2020.

[38]. University of Ruhuna, "Smart meters for monitoring power quality in distribution grids," 2020.

[39]. Haldar, R., & Ghosh, A., "Voltage Sag Mitigation in a Three-Phase Induction Motor using DSTATCOM and DVR," *CPRI Journal*, 13(2): 223–231, 2017.

[40]. Gour, R., & Verma, P., "Comparative Performance of DVR and STATCOM for Voltage Regulation in Radial Microgrid with High Penetration of RES," *International Journal of Electrical and Computer Engineering Systems*, 14(1), 2023.

[41]. Nair, N. et al., "Power Quality Issues and Mitigation for Electric Grids with Wind Power Penetration," *Applied Sciences*, 10(24): 8852, 2020.

[42]. Khadem, S. K., et al., "A Comparative Study of Direct Power Control Strategies for STATCOM Using Three-Level and Five-Level Diode-Clamped Inverters," *Energies*, 18(13): 3582, 2023.

[43]. https://www.nfpa.org/education-and-research/electrical/energy-storage-systems

[44]. *Zhu et al. (2022)* optimized ESS sizing for PQ services, including reactive compensation and sag mitigation [IET RPG].

[45]. Tabassum, S., Vijay Babu, A. R., & Kumar Dheer, D. "Real-time power quality enhancement in smart grids through IoT and adaptive neuro-fuzzy systems," *Science & Technology for Energy Transition*, 79:89, 2024.

[46]. Mehrdad Boloorchi, "Smart Grid and Power Quality Management," IEEE Smart Grid Bulletin, June 2019. smartgrid.ieee.org

[47]. "Overview of power quality analysis and control technology for the smart grid," *Journal of Modern Power Systems and Clean Energy*, Vol. 4, 2016.

[48]. Khan, Shahanawaz, "A Review on Enhancing Smart Grid Power Quality," *Journal of Sensor Research and Technologies*. Harvard Business Review Press