2024 32nd Southern African Universities Power Engineering Conference (SAUPEC) | 979-8-3503-7134-5/24/$31.00 ©2024 IEEE | DOI: 10.1109/SAUPEC60914.2024.10445051

Review of Adaptive Load Frequency Control Strategies for Improving Wind Power Plant Integration

Ntanganedzeni Tshinavhe, Mukovhe Ratshitanga, Nomzamo Tshemese-Mvandaba
Department of Electrical, Electronic, and Computer Engineering
Cape Peninsula University of Technology
Cape Town, South Africa
tshinavhen@cput.ac.za, RatshitangaM@cput.ac.za, Tshemesen@cput.ac.za

Abstract— **The integration of renewable energy sources into the power grid is increasing globally to meet the increasing demand for clean and sustainable energy. The integration introduces challenges to the power system due to the varying nature of renewable energy sources. The purpose of this study is to investigate the load frequency control methods in the developing setting of modern power systems with renewable energy integration, with a focus on wind power. While traditional load frequency control methods have been efficient in maintaining the stability of the grid, the introduction of wind power has added a new layer of complexity. The paper analyzes the benefits and challenges of various adaptive control techniques, which include the classic Proportional, Integral and Derivative controller, fuzzy logic, and neural network based on adapting to the changes. It is also anticipated that given the availability of solar photovoltaic energy particularly in residential and commercial settings, the next area of focus will focus on investing the potential to contribute to maintaining the grid stability.**

Keywords—Load frequency control, wind farm, adaptive control algorithms, renewable energy

I. INTRODUCTION

There has been a rise in the use of renewable energy sources around the world to fulfil the growing need for clean and sustainable energy as well as for environmental benefits. Amongst the sources, the use of wind and solar photovoltaic (PV) power has rapidly increased and contributes a larger portion of the energy portfolio [1]. Because of its fluctuation and intermittent nature, the increasing penetration of renewable energy sources has presented a challenge to the power grid's stability and reliability. Compared to conventional energy sources such as coal, wind power generation is subjected to fluctuations that are caused by the change in wind speed and direction [2]–[5]. These challenges have motivated a new area of research opportunities for researchers to design adaptive control schemes that will be capable of maintaining the balance between the generated power and the load to maintain the stability of the power grid. Considering this, the primary objective of this paper is to conduct a comprehensive review of the various adaptive load frequency control (LFC) strategies that are capable of maintaining system stability.

It becomes necessary to create control systems that can keep the power system's stability and dependability. LFC plays a crucial role in the dependability and efficiency of modern power systems. It plays a role in maintaining the balance between the generated electricity and consumption, ensuring that the grid is operating within the acceptable frequency range. LFC systems have historically been designed with a well-defined control mechanism based on traditional power generation sources.

With the rapid integration of renewable energy sources and increasing demand, the power generation landscape is changing significantly, which is a challenge to operators. Since renewable energy sources are naturally varying, integrating them into the grid adds to the uncertainty and complexity. These challenges require flexible and adaptive strategies to ensure grid stability and sustainability.

This paper reviews the concept of adaptive load frequency control techniques, which have the potential to overcome the challenges posed by renewable energy sources and the evolving grid infrastructure, this will include the challenges of those control strategies. The research will also explore future directions.

II. WIND POWER GENERATION IN SOUTH AFRICA

South Africa has significantly advanced the development of infrastructure for wind power generation [6]. Several challenges persist particularly in regulation, market and energy storage systems and overcoming them requires cooperation between the various stakeholders [7]. The country has great potential for harnessing wind energy due to the availability of wind resources, particularly along the coastal areas of the Western Cape and Eastern Cape and in the Northern Cape [8], [9]. The availability of wind resources has led to onshore and offshore wind farms that contribute to the nation's renewable energy capacity being built. Fig. 1 shows the renewable energy technologies in South African provinces. The data shows the highest ranking of wind energy in the Eastern Cape and Western Cape, followed by the Northern Cape.

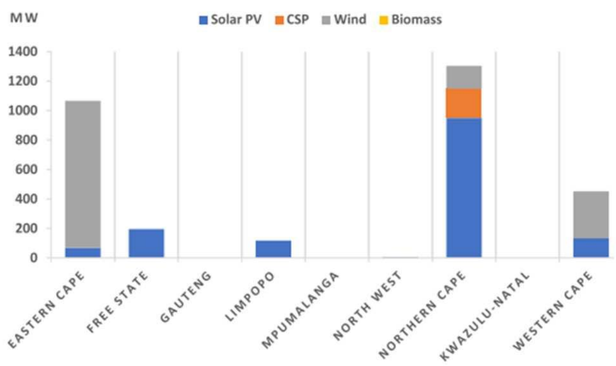

Fig. 1. Electricity generation by different technologies in South Africa [8]

This research was partly funded by the ESKOM Tertiary Education Support Programme (TESP)

With the integration of wind farms into the power, the standards and the requirements of the grid code must be adhered to [10]. With the challenges such as voltage and frequency deviation caused by the variable nature of wind farms, the South African Grid Code specify that the tolerance of voltage and frequency deviation be as per Fig. 2 under normal conditions.

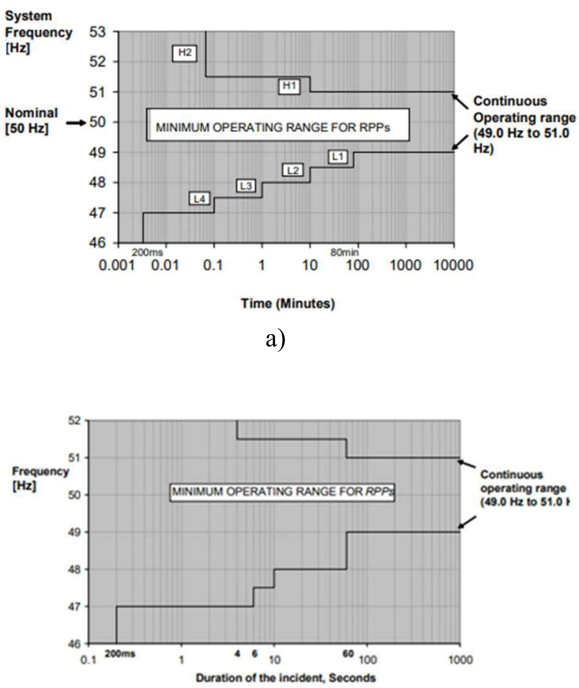

Fig. 2. Minimum frequency operating range a) under normal conditions. b) under frequency disturbance [10]

It is critical to adhere to the grid code standards and requirements when developing and implementing control algorithms as failure to comply could result in operational issues, instability, disconnection from the grid, and damage to equipment.

III. INTEGRATION OF WIND POWER AND CHALLENGES

Wind energy stands out among renewable energy sources, which is mainly because of its technological advancement, infrastructure, and competitive cost when compared to other renewable energy sources[11]. One key part of maintaining the power grid's reliability is ensuring that the amount of power generated at any given time closely reflects the amount of power used. When there is an excess of electricity produced, the grid frequency increases, when there is insufficient power generation, the frequency will decrease the turbine function [12]. Traditional turbines typically have a constant rotational speed that is synced with the frequency of the grid. Wind turbines, on the other hand, do not function synchronously with the frequency of the grid, they instead are controlled to optimize their active power generation.

Morden wind power plants use complex plant control systems which can modify the active power output responding to the changes in grid frequency [12]. This adaptability is essential for ensuring the grid's overall performance and stability. The wind farm can assist in maintaining a balance between power generation and consumption by participating in grid frequency control.

The integration of wind power generation, however, introduces challenges in areas that are key for the system reliability. The integration issues for onshore and offshore may differ depending on the wind speed and environment.

IV. FREQUENCY CONTROL AND RESPONSE OF POWER SYSTEMS

The power system frequency response is crucial to ensuring a stable electric grid. The system should be able to react to changes in load and generation to maintain that stability under various conditions [13], [14]. Depending on the region, the nominal frequency could be 50 Hz or 60 Hz. The frequency change indicates the balance between the supply and demand. The frequency response is divided into regions, which are the inertial, primary, secondary, and tertiary responses, as shown in Fig. 3.

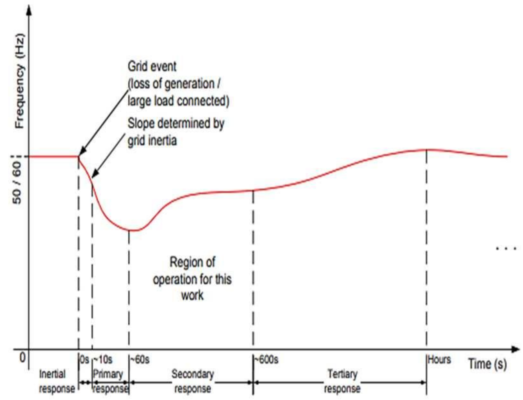

Fig. 3. Frequency response

Frequency control techniques are at three different levels, the primary or droop-based control[15] provides fast power support in events of sudden power imbalance, usually within seconds [16]–[19]. The secondary, known as the LFC restores the system's frequency to the nominal frequency[20], [21]. The tertiary control, which is referred to as reserve control is important for system stabilization[22], [23]. The control mechanism can further be categorized as demand control, emergency control, and control support which contains regulation support from energy storage systems (ESS), and virtual synchronous generators [24]. Fig. 4 further shows the analysis of a study of frequency control.

V. LOAD FREQUENCY CONTROL STRATEGIES

Adaptive controllers are designed to maintain the frequency of the power system to its nominal value. There are common controllers used for this purpose, including the classic Proportional (P), Integral (I), and Derivative (D) controllers, intelligent controllers such as fuzzy logic controllers [25], [26], sliding mode [27], [28] Adaptive Neuro-Fuzzy Interference (ANFIS) [29], and Artificial Neural Network (ANN) controllers[30], [31].

P, I, and D controllers are commonly used in power systems because of their simplicity, effectiveness, and ease of implementation in many applications[32]. PIDs use a control loop to continuously monitor the frequency of the power system and adjust the power output of the generators to maintain frequency within the desired range[30]. These controllers consider the overshoot/undershoot which refers to the point to which the frequency deviates from its desired value and the settling time as the objective functions for optimization in LFC[31].

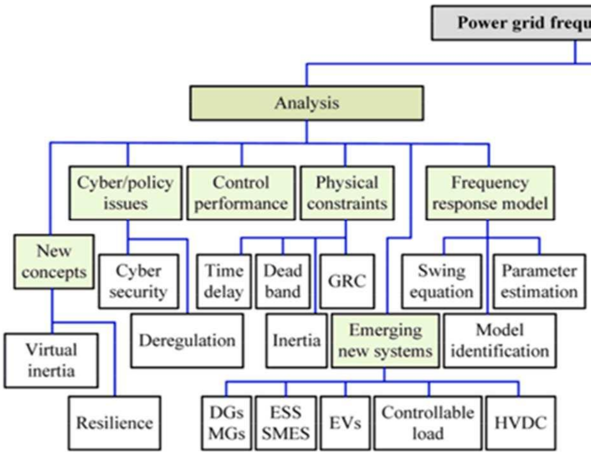

Fig. 4. Analysis of power system grid frequency control

The main issues associated with PID controllers are low accuracy, might not provide ideal performance in systems especially those with complex dynamics, and a high settling time[33]. The use of intelligent controllers/soft computing has also increased within power systems. Controllers such as the ANN use neural networks to model the behaviours of the power system and predict the optimal power output adjustments needed to maintain the frequency. These controllers are trained using historical data from the wind power plant [34]–[36]. They are commonly used because they can handle complex and nonlinear systems and can learn from historical data without the need for mathematical modelling which makes them more adaptable to changing conditions[37]. The disadvantage of the types of controllers is that they require a large amount of data to accurately train the network, and it is time-consuming.

VI. FREQUENCY CONTROL METHODS

A. *Fuzzy logic control*

Controllers that take advantage of the fuzzy logic's ability to handle non-linear systems have an increasing application in [29], and [34] within the application of power systems. To handle the non-linearity of power systems, caused by the variable nature of wind power, intelligent controllers such as the fuzzy logic controller [39], [41], [44] are being proposed as the most efficient control mechanisms. In [42] the authors proposed an adaptive fuzzy logic controller to improve the performance of a wind power integrated system. The controller proposed was effective in achieving a faster response and reducing fluctuations. [40] presented the load frequency control of a hydro-electrical power plant that is manipulated by a fuzzy logic system. The results also showed that the proposed controller performs better than the conventional controllers.

B. *Fuzzy PI control*

Conventional controllers such as the PI have the advantage of simplicity and less complexity, hence have always been utilized in applications of power systems with the help of different optimization methods. [32], [45] used the PI controller for LFC to take advantage of these benefits. [46] proposed a fuzzy PI controller, where the fuzzy logic is used to choose the P and I gains. Even though [47]–[49] have presented fuzzy PI, they made use of optimizing strategies such as Particle Swarm Optimization (PSO) to improve the performance of the controller. Though they are capable of handling nonlinear and complex power systems, the drawback is that their complexity usually makes them less capable. This is also evident in [50]–[52]. [53], [54] demonstrated that apart from regulating voltage and frequency in wind power plants, it can also be utilized for PV systems. The results show that voltage and frequency can still be maintained with minimal deviations in events of load changes.

C. *Fuzzy-based PID*

PID controllers are often used in applications in power systems. One such application is for LFC in systems that consist of hydro units, nuclear units, and thermal units[30]. [59]–[61] presented a fuzzy-based PID controller for better robust control and flexibility in tuning nonlinear gains. They are also applicable in hybrid systems[62], [65]. In [65], the author also demonstrated the effectiveness of a conventional PID controller optimized by a Particle Swarm Optimization (PSO) algorithm for a hybrid PV, wind turbine and BESS connected to a microgrid LFC. The PSO-optimized PI was also investigated by [42] to compare the performance of the two controllers. Although in [65] the author was able to obtain satisfactory results, the fuzzy logic-based was superior to the study in [42]. What can be observed from this is how authors use optimization methods in their designs for either tuning, tracking or minimizing the setting time to improve the performance and reduce frequency deviations.

D. *Artificial Neural Network (ANN)*

In [35], the authors used an optimized PI controller and artificial neural network to train the data of the area to be controlled. It was shown that the ANN proposed outshined the integral controller in terms of setting time. In [36] the authors introduce an adaptive controller which uses the combination of fuzzy logic, neural networks, and PID controller, which allows for learning the behaviour of the system, ensuring asymptotic stability, and tracking of the reference signals. [37] also presented the PID controller for LFC and how optimization techniques can be used to improve the performance of the controller, considering that a large quantity of data is required to train the network, this was also demonstrated in [73], where the authors presented a neural network-based controller optimized by PSO to adjust main parameters or the neural network model.

E. Adaptive Sliding Mode Controller (ASMC)

Sliding mode controllers require full-state feedback, meaning that all unmeasured system states and disturbances must be estimated. It is mostly preferred for its robustness to uncertainties and instability. This allows it to handle variations in the power system. [74] , [27] presented the LFC strategy that is based on the sliding mode control theory to address the intermittency of renewable energy sources. Controller in a single area power system. The method involves selecting the right switching surface to manage frequency deviations caused by parameter uncertainty [28].

In [75], the authors presented an Adaptive Sliding Mode Controller (ASMC) for managing the power flow of a wind turbine that is equipped with a DFIG system. The proposed controller with the combination of an Optimal Power Maximum Power Point Tracking (OP-MPPT) strategy can enhance the power quality generated by the wind turbine. It was effective in handling variations in machine parameters and disturbances and offers no overshoot, zero steady state and fast transient response compared to a conventional PI controller. On the other hand, the OP-MPPT has shown poor capabilities in dealing with high variations of wind speed

VII. Discussion and Future Work

Various methods are discussed in solving LFC in power systems, like the use of classical controllers such as the PID, and intelligent methods/soft computing as well as fuzzy logic and artificial neural networks. Emphasis is placed on the need to design controllers that are flexible and adaptive to the changing conditions of the power system. Traditional control methods are not flexible enough to handle the complexity of modern power systems, hence the emergence of adaptive methods. The has been an increase in the use of hybrid methods, such as fuzzy-based PI or PID controllers. This is mainly to take advantage of the characteristics of each method, such as the simplicity, ease of implementation, cost, and ability to handle nonlinear systems. This combination has improved the performance of LFC such as removing steady state error and fast response under conditions such as change in load and generated power.

While the focus of this review has mostly been on adaptive load frequency control strategies in the context of wind power generation into the grid, the next area of focus in the growing power landscape will most likely be on solar photovoltaic (PV) energy. This is because of its widespread availability, existing installations in both the residential and commercial sectors, and the potential to contribute to grid stability through surplus energy injection

VIII. Conclusion

Wind power due to its variable nature presents a challenge to power system operations. Different adaptive load frequency control strategies have been reviewed with a focus on the integration of wind power. The various LFC strategies reviewed include the classic P, I, D, fuzzy logic, neural network-based and a hybrid of classical P, I, and D controllers with intelligent controllers. They provide a flexible and adaptive solution to the challenges and enable the power system to respond to the fluctuations caused by the variable nature of wind power. These strategies enhance the stability of the grid and mitigate the impact caused by the variation in wind power generation. However, these strategies do come with challenges such as the ability to handle linear or nonlinear systems, and the amount of data required especially in neural networks which require large quantities of historical data to predict future patterns. Continuous technology and research developments provide the potential to improve adaptive control systems, increasing their ability to handle wind power fluctuations and add to the sustainability of wind energy generation.

Acknowledgement

The authors would like to express their gratitude to the ESKOM Tertiary Education Support Programme (TESP) for partly funding this research.

References

[1] B. Rona and Ö. Güler, “Power system integration of wind farms and analysis of grid code requirements,” *Renewable and Sustainable Energy Reviews*, vol. 49, pp. 100–107, 2015, doi: 10.1016/j.rser.2015.04.085.

[2] A. Gupta, “Integration Challenges of Wind Power on Power System Grid A Review,” *2018 International Conference on Advanced Computation and Telecommunication, ICACAT 2018*, vol. 2, no. 4, 2018, doi: 10.1109/ICACAT.2018.8933741.

[3] X. Liang, “Emerging Power Quality Challenges Due to Integration of Renewable Energy Sources,” *IEEE Trans Ind Appl*, vol. 53, no. 2, pp. 855–866, 2017, doi: 10.1109/TIA.2016.2626253.

[4] Á. Fleury, F. Arteiro, D. Brasil, P. Gomes, and A. Franceschi, “Integration of wind power plants into the electric system - The Brazilian experience,” *Proceedings of the 2012 6th IEEE/PES Transmission and Distribution: Latin America Conference and Exposition, T and D-LA 2012*, pp. 1–6, 2012, doi: 10.1109/TDC-LA.2012.6319134.

[5] P. Van Aarde, A. Dalton, and B. Bekker, “Balancing wind and solar power variability through spatial deployment informed by weather regimes: A review and roadmap ahead,” *Proceedings - 30th Southern African Universities Power Engineering Conference, SAUPEC 2022*, 2022, doi: 10.1109/SAUPEC55179.2022.9730687.

[6] N. Mararakanye, B. Bekker, N. Mararakanye, and B. Bekker, “Investigating renewable energy curtailment as a flexibility resource in the future South African Grid,” no. January 2019, 2019, [Online]. Available: https://www.researchgate.net/publication/342170833

[7] O. Apata, A. V. Adebayo, and K. O. Awodele, “Grid Integration of Wind Energy: The South African Challenge,” *2020 IEEE PES/IAS PowerAfrica, PowerAfrica 2020*, 2020, doi: 10.1109/PowerAfrica49420.2020.9219813.

[8] O. M. Akinbami, S. R. Oke, and M. O. Bodunrin, “The state of renewable energy development in South Africa: An overview,” *Alexandria Engineering Journal*, vol. 60, no. 6, pp. 5077–5093, 2021, doi: 10.1016/j.aej.2021.03.065.

[9] J. De Bruyn, B. Bekker, and A. Dalton, “A Review of Load Flow Methodologies for Constrained Networks: A South African Case Study,” *International Conference on Electrical, Computer, Communications and Mechatronics Engineering, ICECCME 2022*, no. November, pp. 1–6, 2022, doi: 10.1109/ICECCME55909.2022.9988460.

[10] RSA Grid Code Secretariat, “Grid Connection Code for Renewable Power Plants Connected to the Electricity Transmission System or the Distribution System in South Africa,” vol. 8, no. July, p. 17, 2014.

[11] T. R. Ayodele, A. A. Jimoh, J. L. Munda, and J. T. Agee, “Challenges of grid integration of wind power on power system grid integrity: A review,” *International Journal of Renewable Energy Research*, vol. 2, no. 4. pp. 618–626, 2012.

[12] N. W. Miller, K. Clark, and M. Shao, “Frequency responsive wind plant controls: Impacts on grid performance,” *IEEE Power and Energy Society General Meeting*, pp. 1–8, 2011, doi: 10.1109/PES.2011.6039137.

[13] H. Haes Alhelou, M. E. H. Golshan, and P. Siano, “Frequency response models and control in smart power systems with high penetration of renewable energy sources,” *Computers and Electrical Engineering*, vol. 96, no. PA, p. 107477, 2021, doi: 10.1016/j.compeleceng.2021.107477.

[14] N. Mararakanye and B. Bekker, “Renewable energy integration impacts within the context of generator type, penetration level and grid

characteristics,” *Renewable and Sustainable Energy Reviews*, vol. 108, no. April, pp. 441–451, 2019, doi: 10.1016/j.rser.2019.03.045.

[15] M. Dreidy, H. Mokhlis, and S. Mekhilef, “Inertia response and frequency control techniques for renewable energy sources: A review,” *Renewable and Sustainable Energy Reviews*, vol. 69, no. July 2016, pp. 144–155, 2017, doi: 10.1016/j.rser.2016.11.170.

[16] M. Mditshwa, M. E. S. Mnguni, and M. Ratshitanga, “Integration of Wind Power Plant (WPP) for primary frequency regulation,” *2021 IEEE PES/IAS PowerAfrica, PowerAfrica 2021*, pp. 1–5, 2021, doi: 10.1109/PowerAfrica52236.2021.9543391.

[17] U. Datta, J. Shi, and A. Kalam, “Primary frequency control of a microgrid with integrated dynamic sectional droop and fuzzy based pitch angle control,” *International Journal of Electrical Power and Energy Systems*, vol. 111, no. December 2018, pp. 248–259, 2019, doi: 10.1016/j.ijepes.2019.04.001.

[18] S. I. Nanou, A. G. Papakonstantinou, and S. A. Papathanassiou, “A generic model of two-stage grid-connected PV systems with primary frequency response and inertia emulation,” *Electric Power Systems Research*, vol. 127, pp. 186–196, 2015, doi: 10.1016/j.epsr.2015.06.011.

[19] Y. Fu, X. Zhang, Y. Hei, and H. Wang, “Active participation of variable speed wind turbine in inertial and primary frequency regulations,” *Electric Power Systems Research*, vol. 147, pp. 174–184, 2017, doi: 10.1016/j.epsr.2017.03.001.

[20] M. Mditshwa, M. Elvis, S. Mnguni, and R. Mukovhe, “The Benefits of Automatic Generation Control in Interconnected Power The Benefits of Automatic Generation Control in Interconnected Power System Under Various System Conditions,” no. October, 2021.

[21] M. S. H. Choudhury, I. Hossain, A. Hossain, and A. Ullah, “Energies-16-00812-V2.Pdf,” pp. 1–31, 2023.

[22] H. Bevrani, H. Golpîra, A. R. Messina, N. Hatziargyriou, F. Milano, and T. Ise, “Power system frequency control: An updated review of current solutions and new challenges,” *Electric Power Systems Research*, vol. 194, no. February 2021, doi: 10.1016/j.epsr.2021.107114.

[23] A. Fernández-Guillamón, E. Gómez-Lázaro, E. Muljadi, and Á. Molina-García, “Power systems with high renewable energy sources: A review of inertia and frequency control strategies over time,” *Renewable and Sustainable Energy Reviews*, vol. 115, no. September, p. 109369, 2019, doi: 10.1016/j.rser.2019.109369.

[24] H. Bevrani, H. Golpîra, A. R. Messina, N. Hatziargyriou, F. Milano, and T. Ise, “Power system frequency control: An updated review of current solutions and new challenges,” *Electric Power Systems Research*, vol. 194. Elsevier Ltd, May 01, 2021. doi: 10.1016/j.epsr.2021.107114.

[25] F. F. Mammadov, “Fuzzy Logic Controller Application in Hybrid Solar and Wind Energy System,” *2019 International Conference on Artificial Intelligence and Data Processing Symposium, IDAP 2019*, 2019, doi: 10.1109/IDAP.2019.8875960.

[26] S. Mansour *et al.*, “Fuzzy Logic Controller Equilibrium Base to Enhance AGC System Performance with Renewable Energy Disturbances,” *Energies (Basel)*, vol. 15, no. 18, 2022, doi: 10.3390/en15186709.

[27] Y. Mi, Y. Fu, D. Li, C. Wang, P. C. Loh, and P. Wang, “The sliding mode load frequency control for hybrid power system based on disturbance observer,” *International Journal of Electrical Power and Energy Systems*, vol. 74, pp. 446–452, 2016, doi: 10.1016/j.ijepes.2015.07.014.

[28] J. Guo, “Application of a novel adaptive sliding mode control method to the load frequency control,” *Eur J Control*, vol. 57, pp. 172–178, 2021, doi: 10.1016/j.ejcon.2020.03.007.

[29] A. Fathy and A. M. Kassem, “Antlion optimizer-ANFIS load frequency control for multi-interconnected plants comprising photovoltaic and wind turbine,” *ISA Trans*, vol. 87, pp. 282–296, 2019, doi: 10.1016/j.isatra.2018.11.035.

[30] S. R. Basa Varajappa and M. S. Nagaraj, “Load frequency control of three area interconnected power system using conventional PID, fuzzy logic and ANFIS Controllers,” *2021 2nd International Conference for Emerging Technology, INCET 2021*, pp. 1–6, 2021, doi: 10.1109/INCET51464.2021.9456120.

[31] R. Umrao, S. Kumar, M. Mohan, D. K. Chaturvedi, and S. Member, “Load Frequency Control Methodologies for Power System,” no. March 2015, 2012, doi: 10.1109/ICPCES.2012.6508133.

[32] S. Ayasun, “Stability Region in the Parameter Space of PI Controller for a Single-Area Load Frequency Control System With Time Delay,” vol. 31, no. 1, pp. 2015–2016, 2016, doi: 10.1109/TPWRS.2015.2412678.

[33] M. M. Gulzar, M. Iqbal, S. Shahzad, H. A. Muqeet, M. Shahzad, and M. M. Hussain, “Load Frequency Control (LFC) Strategies in Renewable Energy-Based Hybrid Power Systems: A Review,” *Energies (Basel)*, vol. 15, no. 10, pp. 1–23, 2022, doi: 10.3390/en15103488.

[34] S. Cong and Y. Liang, “PID-like neural network nonlinear adaptive control for uncertain multivariable motion control systems,” *IEEE Transactions on Industrial Electronics*, vol. 56, no. 10, pp. 3872–3879, 2009, doi: 10.1109/TIE.2009.2018433.

[35] S. Khadarvali, V. Madhusudhan, and R. Kiranmayi, “Artificial Neural Network Controller in Two-Area and Five-Area System with Security Attack and Game-Theory Based Defender Action,” *Energies (Basel)*, vol. 15, no. 15, 2022, [Online]. Available: https://www.mdpi.com/1996-1073/15/15/5715

[36] K. Sabahi, M. Teshnehlab, and M. Aliyari, “Recurrent fuzzy neural network by using feedback error learning approaches for LFC in interconnected power system,” *Energy Convers Manag*, vol. 50, no. 4, pp. 938–946, 2009, doi: 10.1016/j.enconman.2008.12.028.

[37] G. A. R. Ibraheem, A. T. Azar, I. K. Ibraheem, and A. J. Humaidi, “A Novel Design of a Neural Network-Based Fractional PID Controller for Mobile Robots Using Hybridized Fruit Fly and Particle Swarm Optimization,” *Complexity*, vol. 2020, 2020, doi: 10.1155/2020/3067024.

[38] L. Suganthi, S. Iniyan, and A. A. Samuel, “Applications of fuzzy logic in renewable energy systems - A review,” *Renewable and Sustainable Energy Reviews*, vol. 48, pp. 585–607, 2015, doi: 10.1016/j.rser.2015.04.037.

[39] F. F. Mammadov, “Fuzzy Logic Controller Application in Hybrid Solar and Wind Energy System; Fuzzy Logic Controller Application in Hybrid Solar and Wind Energy System,” 2019. [Online]. Available: http://www.azerenerji.gov.az

[40] E. Çam, “Application of fuzzy logic for load frequency control of hydro electrical power plants,” *Energy Convers Manag*, vol. 48, no. 4, pp. 1281–1288, 2007, doi: 10.1016/j.enconman.2006.09.026.

[41] O. Zamzoum, A. Derouich, S. Motahhir, Y. El Mourabit, and A. El Ghzizal, “Performance analysis of a robust adaptive fuzzy logic controller for wind turbine power limitation,” *J Clean Prod*, vol. 265, Aug. 2020, doi: 10.1016/j.jclepro.2020.121659.

[42] M. A. Soliman, H. M. Hasanien, H. Z. Azazi, E. E. El-Kholy, and S. A. Mahmoud, “An adaptive fuzzy logic control strategy for performance enhancement of a grid-connected PMSG-Based wind turbine,” *IEEE Trans Industr Inform*, vol. 15, no. 6, pp. 3163–3173, Jun. 2019, doi: 10.1109/TII.2018.2875922.

[43] T. Hinokuma, H. Farzaneh, A. Shaqour, and M. Sorrentino, “Techno-Economic Analysis of a Fuzzy Logic Control Based Hybrid Renewable Energy System to Power a University Campus in Japan,” 2021, doi: 10.3390/en.

[44] A. Ghafouri, J. Milimonfared, and G. B. Gharehpetian, “Fuzzy-adaptive frequency control of power system including microgrids, wind farms, and conventional power plants,” *IEEE Syst J*, vol. 12, no. 3, pp. 2772–2781, 2018, doi: 10.1109/JSYST.2017.2715819.

[45] G. Anil, “PI Controller based MPPT for a PV System,” *IOSR Journal of Electrical and Electronics Engineering*, vol. 6, no. 5, pp. 10–15, 2013, doi: 10.9790/1676-0651015.

[46] C. F. Juang and C. F. Lu, “Power system load frequency control by evolutionary fuzzy PI controller,” *IEEE International Conference on Fuzzy Systems*, vol. 2, pp. 715–719, 2004, doi: 10.1109/FUZZY.2004.1375486.

[47] I. Sefa, N. Altin, S. Ozdemir, and O. Kaplan, “Fuzzy PI controlled inverter for grid-interactive renewable energy systems,” *IET Renewable Power Generation*, vol. 9, no. 7, pp. 729–738, 2015, doi: 10.1049/iet-rpg.2014.0404.

[48] T. Mohammed, J. Momoh, and A. Shukla, “Single area load frequency control using fuzzy-tuned PI controller,” *2017 North American Power Symposium, NAPS 2017*, pp. 1–6, 2017, doi: 10.1109/NAPS.2017.8107352.

[49] M. Abedini, E. Mahmodi, M. R. Mousavi, and I. Chaharmahali, “A novel Fuzzy PI controller for improving autonomous network by considering uncertainty,” *Sustainable Energy, Grids and Networks*, vol. 18, Jun. 2019, doi: 10.1016/j.segan.2019.100200.

[50] C. S. Chang, W. Fu, and F. Wen, “LOAD FREQUENCY CONTROL USING GENETIC- ALGORITHM BASED FUZZY GAIN SCHEDULING OF PI CONTROLLERS,” no. May 2007, doi: 10.1080/07313569808955806.

[51] A. M. Yousef, F. K. Abo-Elyousr, A. Elnozohy, M. Mohamed, and S. A. M. Abdelwahab, “Fractional order pi control in hybrid renewable power generation system to three-phase grid connection,” *International Journal on Electrical Engineering and Informatics*, vol. 12, no. 3, pp. 470–493, 2020, doi: 10.15676/ijeei.2020.12.3.5.

[52] M. U. Jan, A. Xin, M. A. Abdelbaky, H. U. Rehman, and S. Iqbal, “Adaptive and Fuzzy PI Controllers Design for Frequency Regulation

of Isolated Microgrid Integrated with Electric Vehicles," *IEEE Access*, vol. 8, pp. 87621–87632, 2020, doi: 10.1109/ACCESS.2020.2993178.
[53] H. C. Mohanta *et al.*, "An Optimized PI Controller-Based SEPIC Converter for Microgrid-Interactive Hybrid Renewable Power Sources," *Wirel Commun Mob Comput*, vol. 2022, 2022, doi: 10.1155/2022/6574825.
[54] P. B. Nempu, N. S. Jayalakshmi, K. Shaji, and M. Singh, "Fuzzy-PI Controllers for Voltage and Frequency Regulation of a PV-FC Based Autonomous Microgrid," *2019 IEEE International Conference on Distributed Computing, VLSI, Electrical Circuits and Robotics, DISCOVER 2019 - Proceedings*, 2019, doi: 10.1109/DISCOVER47552.2019.9008093.
[55] J. Zhang, L. Li, D. G. Dorrell, and Y. Guo, "Modified PI controller with improved steady-state performance and comparison with PR controller on direct matrix converters," *Chinese Journal of Electrical Engineering*, vol. 5, no. 1, pp. 53–66, 2019, doi: 10.23919/CJEE.2019.000006.
[56] P. J. Krishna, V. P. Meena, and V. P. Singh, "Load Frequency Control in Four-Area Interconnected Power System Using Fuzzy PI Controller with Penetration of Renewable Energies," *ICPC2T 2022 - 2nd International Conference on Power, Control and Computing Technologies, Proceedings*, pp. 4–9, 2022, doi: 10.1109/ICPC2T53885.2022.9777076.
[57] C. Pradhan, C. N. Bhende, and A. K. Samanta, "Adaptive virtual inertia-based frequency regulation in wind power systems," *Renew Energy*, vol. 115, pp. 558–574, 2018, doi: 10.1016/j.renene.2017.08.065.
[58] M. Kumar and Y. V. Hote, "Robust PIDD2 Controller Design for Perturbed Load Frequency Control of an Interconnected Time-Delayed Power Systems," *IEEE Transactions on Control Systems Technology*, vol. 29, no. 6, pp. 2662–2669, 2021, doi: 10.1109/TCST.2020.3043447.
[59] S. M. Sam and T. S. Angel, "Performance optimization of PID controllers using fuzzy logic," *2017 IEEE International Conference on Smart Technologies and Management for Computing, Communication, Controls, Energy and Materials, ICSTM 2017 - Proceedings*, no. August, pp. 438–442, 2017, doi: 10.1109/ICSTM.2017.8089200.
[60] J. Wang and J. R. Jordan, "Robust step performance of PID and fuzzy logic controlled SISO systems," *IEEE International Conference on Fuzzy Systems*, vol. 1, pp. 325–330, 1995, doi: 10.1109/fuzzy.1995.409699.
[61] H. X. Li, L. Zhang, K. Y. Cai, and G. Chen, "An improved robust fuzzy-PID controller with optimal fuzzy reasoning," *IEEE Transactions on Systems, Man, and Cybernetics, Part B: Cybernetics*, vol. 35, no. 6, pp. 1283–1294, 2005, doi: 10.1109/TSMCB.2005.851538.
[62] M. Regad, M. Helaimi, R. Taleb, A. M. Othman, and H. A. Gabbar, "Control of hybrid power system based renewable energy generations using PID controller," *International Journal of Power Electronics and Drive Systems*, vol. 11, no. 4, pp. 1775–1784, Dec. 2020, doi: 10.11591/ijpeds.v11.i4.pp1775-1784.
[63] A. Kumar and S. Pan, "Design of fractional order PID controller for load frequency control system with communication delay," *ISA Trans*, vol. 129, pp. 138–149, Oct. 2022, doi: 10.1016/j.isatra.2021.12.033.
[64] M. Regad, M. Helaimi, R. Taleb, A. M. Othman, and H. A. Gabbar, "Control of hybrid power system based renewable energy generations using PID controller," *International Journal of Power Electronics and Drive Systems*, vol. 11, no. 4, pp. 1775–1784, 2020, doi: 10.11591/ijpeds.v11.i4.pp1775-1784.
[65] B. Saleh *et al.*, "Design of PID Controller with Grid Connected Hybrid Renewable Energy System Using Optimization Algorithms," *Journal of Electrical Engineering and Technology*, vol. 16, no. 6, pp. 3219–3233, Nov. 2021, doi: 10.1007/s42835-021-00804-7.
[66] A. M. Yousef, M. Ebeed, F. K. Abo-Elyousr, A. Elnozohy, M. Mohamed, and S. A. Mohamed Abdelwahab, "Optimization of PID controller for Hybrid Renewable Energy System using Adaptive Sine Cosine Algorithm," *International Journal of Renewable Energy Research*, vol. 10, no. 2, pp. 669–677, 2020, doi: 10.20508/ijrer.v10i2.10685.g7938.
[67] B. Saleh *et al.*, "Design of PID Controller with Grid Connected Hybrid Renewable Energy System Using Optimization Algorithms," *Journal of Electrical Engineering and Technology*, vol. 16, no. 6, pp. 3219–3233, 2021, doi: 10.1007/s42835-021-00804-7.
[68] S. Dettori, V. Iannino, V. Colla, and A. Signorini, "An adaptive Fuzzy logic-based approach to PID control of steam turbines in solar applications," *Appl Energy*, vol. 227, no. April 2017, pp. 655–664, 2018, doi: 10.1016/j.apenergy.2017.08.145.
[69] S. Padhy and S. Panda, "Simplified grey wolf optimisation algorithm tuned adaptive fuzzy PID controller for frequency regulation of interconnected power systems," *International Journal of Ambient Energy*, vol. 43, no. 1, pp. 4089–4101, 2022, doi: 10.1080/01430750.2021.1874518.
[70] S. Tiacharoen, "2-DOF PID controller of a wind turbine and synchronous generator for load frequency control optimization by PSO," in *ECTI-CON 2021 - 2021 18th International Conference on Electrical Engineering/Electronics, Computer, Telecommunications and Information Technology: Smart Electrical System and Technology, Proceedings*, Institute of Electrical and Electronics Engineers Inc., May 2021, pp. 746–749. doi: 10.1109/ECTI-CON51831.2021.9454771.
[71] A. Kumar, R. K. Khadanga, and S. Panda, "Reinforced modified equilibrium optimization technique-based MS-PID frequency regulator for a hybrid power system with renewable energy sources," *Soft Comput*, vol. 26, no. 11, pp. 5437–5455, 2022, doi: 10.1007/s00500-021-06558-8.
[72] S. Padhy and S. Panda, "Application of a simplified Grey Wolf optimization technique for adaptive fuzzy PID controller design for frequency regulation of a distributed power generation system," *Protection and Control of Modern Power Systems*, vol. 6, no. 1, Dec. 2021, doi: 10.1186/s41601-021-00180-4.
[73] D. A.-M. Sadeq, A.-N. Mohammed Kh, A. J. Mohammed, A. M. Dakhil, M. F. Abbod, and A.-R. Hamed S, "Design of a Load Frequency Controller Based on an Optimal Neural Network," *Energies (Basel)*, vol. 15, no. 17, 2022, [Online]. Available: https://www.mdpi.com/1996-1073/15/17/6223
[74] Z. Deng, C. Xu, Z. Huo, X. Han, and F. Xue, "Sliding Mode Based Load Frequency Control and Power Smoothing of Power Systems with Wind and BESS Penetration," *Machines*, vol. 10, no. 12, Dec. 2022, doi: 10.3390/machines10121225.
[75] O. Zamzoum, Y. El Mourabit, M. Errouha, A. Derouich, and A. El Ghzizal, "Active and reactive power control of wind turbine based on doubly fed induction generator using adaptive sliding mode approach," *International Journal of Advanced Computer Science and Applications*, vol. 10, no. 2, pp. 397–406, 2019, doi: 10.14569/ijacsa.2019.0100252.
[76] O. Zamzoum, Y. El Mourabit, M. Errouha, A. Derouich, and A. El Ghzizal, "Active and reactive power control of wind turbine based on doubly fed induction generator using adaptive sliding mode approach," *International Journal of Advanced Computer Science and Applications*, vol. 10, no. 2, pp. 397–406, 2019, doi: 10.14569/ijacsa.2019.0100252.
[77] A. T. Tran *et al.*, "Adaptive integral second-order sliding mode control design for load frequency control of large-scale power system with communication delays," *Complexity*, vol. 2021, 2021, doi: 10.1155/2021/5564184.