IJEES

International Journal of Electrical Engineering and Sustainability (IJEES)

ISSN (online): 2959-9229

https://ijees.org/index.php/ijees/index

Volume 1 | Number 2 | April-June 2023 | Pages 38-48

Research Article

Enhancing Microgrid Performance through Hybrid Energy Storage System Integration: ANFIS and GA Approaches

Mohamed Khaleel [1]*, Zıyodulla Yusupov [2], Nassar Yasser [3], Hala J. El-Khozondar [4,5]

[1]Research and Development Department, College of Civil Aviation, Misrata, Libya
[2]Department of Electrical-Electronics Engineering, Faculty of Engineering, Karabuk University, Karabuk, Turkey
[3]Mechanical and Renewable Energy Engineering Department, Faculty of Engineering, Wadi Alshatti University, Libya
[4]Electrical Engineering and smart systems Department, Islamic University of Gaza, Gaza, Palestine
[5]Materials and London Centre for Nanotechnology Department, Imperial College London, United Kingdom

*Corresponding author: lykhaleel@yahoo.co.uk

Received: March 19, 2023 Accepted: May 30, 2023 Published: June 23, 2023

Abstract: Modeling and stability analysis of a battery energy storage system in the Microgrid (MG) is critical for optimizing performance and efficiency and managing power safely and effectively. In this context, the contribution of this work is to propose the combined efforts of the hybrid energy storage system (HESS) including the photovoltaic (PV), fuel cell (FC), and battery to support the demand load. This article of the contribution is interfaced with the PV, FC, and battery with MG. To gain design evaluation, the method incorporates the phasor workable alternative from advanced power systems. In this direction, an adaptive neuro-fuzzy inference system (ANFIS) and Genetic Algorithm (GA) control strategies are applied to collect the system data in electrical power systems. The process of these data provides important information, and knowledge is the result of analyzing this information, which is a key driver to intelligent behavior or action. To conclude, the application of ANFIS in the HESS-MG system results in an injection value of 99.6% at the Single Line-to-Ground Faults Scenario (SLGFS), and the utilization of GA in the HESS-MG yields an injection value of 98.9% at the SLGFS. The reduction of voltage sag without the use of HESS-MG technology is 76.2%, respectively.

Keywords: Microgrid; Photovoltaic; Fuel Cell; MPPT technique; ANFIS; GA

1. Introduction

Microgrids (MGs) have been recognized as a fundamental aspect of smart grids, playing a crucial role in enhancing power reliability, performance, and energy efficiency [1,4]. The integration of renewable energy sources (RES) into the power grid is facilitated by the presence of MGs as the underlying network infrastructure. However, maintaining the stability, reliability, cost-effectiveness, and comprehensive control of MGs is a significant challenge [5,8]. As illustrated in Figure 1, The architecture of the European benchmark low voltage MG system. The ability to effectively manage and control MGs is essential for maximizing their operational efficiency, ensuring reliable power supply, and integrating renewable energy resources into the MG [9-13]. The operation of MGs can occur in either grid-connected or islanded modes, both of which pose significant control challenges. Consequently, various control methods have been proposed for both modes. The task of controlling MGs is further complicated by the presence of multiple RES and loads within the system, leading to issues of coordination and collaboration [14-16].

The Microgrid (MG) system has gained widespread recognition due to its numerous advantages over traditional grid systems. The integration of smaller, more efficient distributed energy resource units into the distribution model and the reduction of damage from bulk power transmission by locating generation closer to load centers are among its key benefits [17,18].

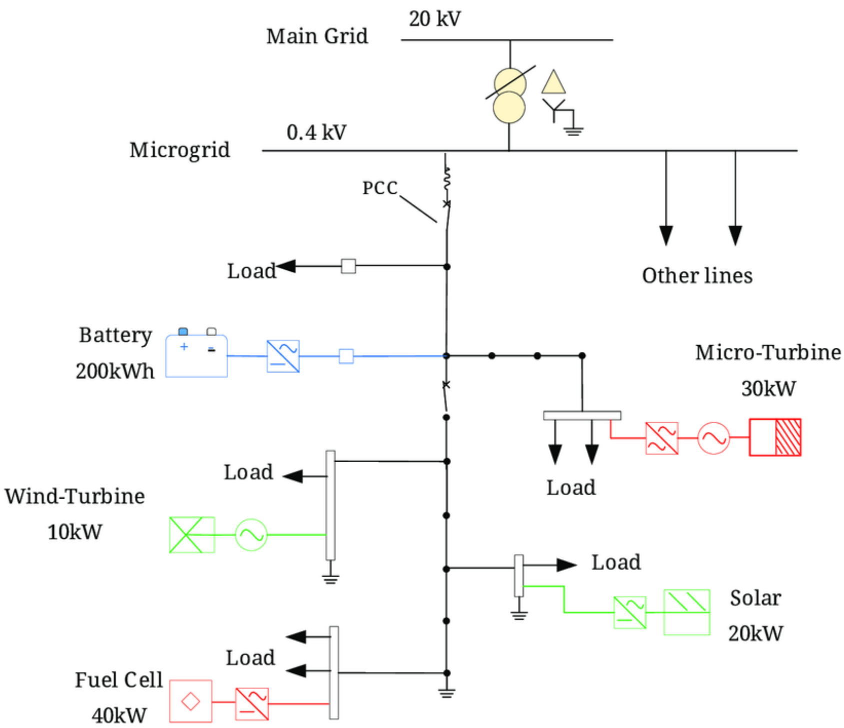

Figure 1. The architecture of the European benchmark low voltage MG system.

Additionally, the increasing global concern over the environmental impacts of traditional power generation has further boosted its popularity. However, the integration of photovoltaic (PV) systems into the electricity network has resulted in fluctuations in energy quality and reliability due to imbalances caused by solar irradiance events. Energy storage systems (ESS) have been widely employed through various operational techniques to mitigate these power fluctuations [20,25]. Figure 2, shows the category of ESS. The ESS block header serves as a crucial component that mitigates the fluctuations in the Photovoltaic (PV) system and brings them down to an acceptable threshold.

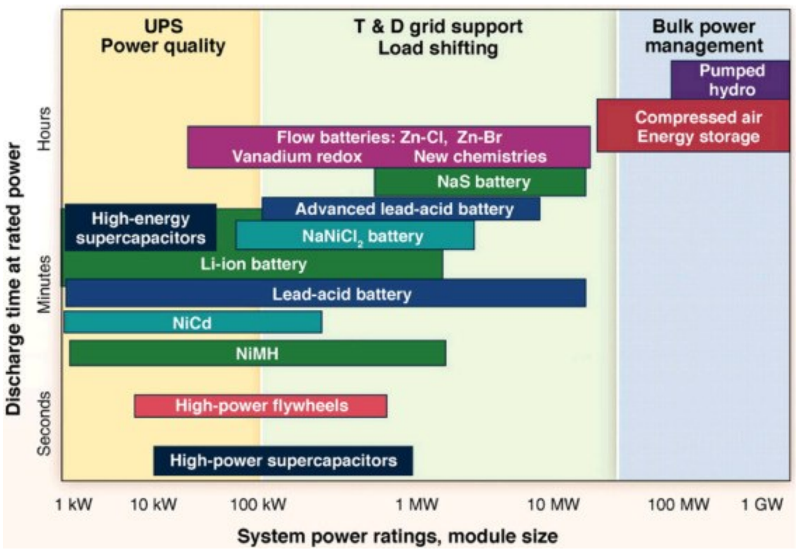

Figure 2. The category of the energy storage system [26,27].

In Figure 3, a PV system is depicted as being connected to a small electrolyze and a fuel cell. This configuration can completely supply power to a household that is connected to the grid. The ESS block header, represented in the diagram, effectively manages and controls the energy flow between the PV system and the home's electrical load. Its primary function is to ensure a stable and consistent power supply by reducing the impact of variations in the PV system's output. By integrating energy storage capabilities, the ESS block header enables excess energy generated by the solar PV array to be stored and utilized when there is insufficient sunlight or high demand from the home [28-35]. This helps to optimize the utilization of renewable energy and provides reliable power

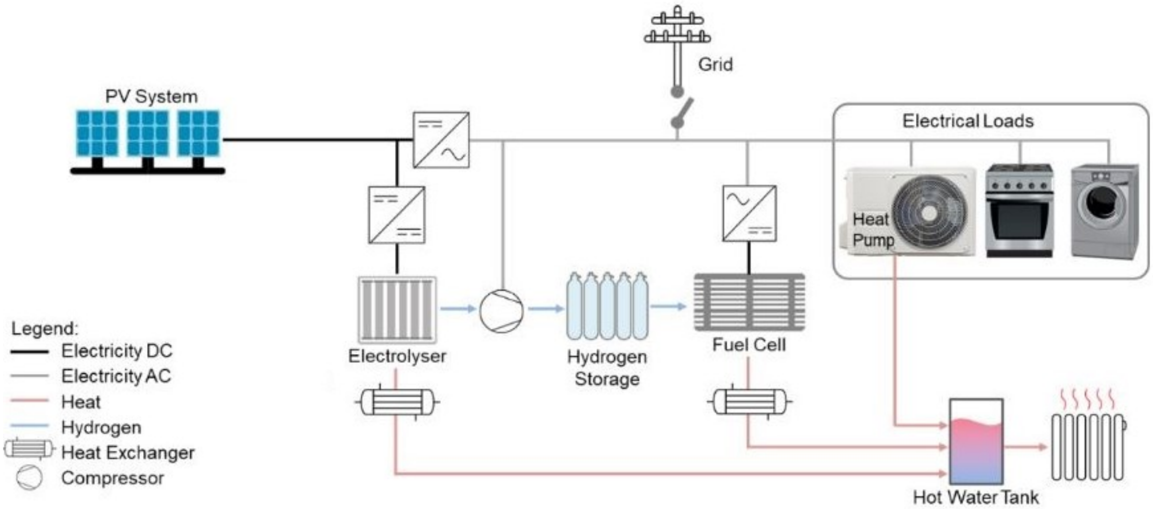

Figure 3. The basic model for grid integration of PV, small electrolyze, and a fuel cell.

The pervasive need for efficient energy sources has led to several comparative studies of different strategies, with a particular focus on battery performance [36]. The battery plays a vital role in various systems, employing diverse methods to cater to different applications. Its versatility and ability to function effectively across a range of contexts are highly appreciated. Whether it is powering electric vehicles, storing renewable energy in grid systems, or providing backup power in residential and commercial settings, the battery's capability to adapt to different requirements is of significant value [37]. Thus, this flexibility allows the battery to be integrated seamlessly into various systems, contributing to improved efficiency, reliability, and sustainability. As the demand for energy storage and portable power solutions continues to grow, the battery's versatility remains a key attribute in meeting the diverse needs of modern applications [38-40].

The literature review conducted by Thirunavukkarasu [41] provided an overview of the relevant works about Microgrids (MGs) discussed in this manuscript. The utilization of optimization algorithms and ESS in MGs has been widely studied, with the mixed integer linear program being the most commonly used optimization algorithm [42]. Additionally, multi-agent systems are considered to be ideal for unit commitment and demand management problems, while cutting-edge machine learning algorithms are utilized for forecasting applications and meta-heuristic algorithms are applied in several economic dispatch applications [43]. In reference [44] presented a comprehensive review of the current advancements in HESSs within the context of MG applications. It offers a broad perspective on the evolving HESS industry. The study [45] delved into crucial aspects of HESS utilization in MGs, covering various topics such as capacity sizing methodologies, power converter topologies for HESS interface, architectural considerations, control strategies, and energy management techniques specifically tailored for HESS in MGs [46]. A recent article [47] presented a comparative study between a single battery system and two alternative HESSs - one utilizing battery-supercapacitor (SC) technology and the other employing battery-flywheel technology - within the framework of an isolated PV power Microgrid. The research [47,48] findings indicate that both the SC-HESS and the flywheel-HESS effectively mitigate the charging and discharging powers of the battery, leading to a significant reduction in the required battery capacity. As a result, this mitigates the operational stresses on the battery and reduces the size requirements, ultimately contributing to an extended battery lifespan.

This paper aims to further explore and demonstrate the properties of MGs based on PV and Fuel Cell (FC) systems in supporting demand load. The MG system is comprised of a single-phase alternating current network, solar power generation technology, PEMFC, and a rechargeable battery. The battery bank is managed by a rechargeable battery controller, which stores surplus power and provides backup power during outages. The system is connected to the electricity network via a transformer that reduces the voltage from 6.6 kV to 200 V. Both the solar PV power generation, PEMFC, and storage battery are DC forms of energy that are converted to single-phase AC. The following sections of the article are presented in the subsequent sections of the article. **Section 2** provides an overview of intelligent control strategies, including artificial neural network-based intelligent systems (ANIS) and genetic algorithms (GA). **Section 3** deals with the model of MG based on PV, PEMFC, and Battery. The results and discussion are depicted in **Section 4**. Finally, **Section 5** provides the concluding remarks of the article.

2. Intelligent Control Strategy

With the advancement in power electronics, microprocessors, and electrical engineering technologies, the development of superior, compact, and cost-effective sensors have been facilitated. As a result, control strategies based on an adaptive neuro-fuzzy inference system (ANFIS) and genetic algorithms (GA) have been extensively utilized in the collection of system data in Microgrid (MG) applications [49-55]. The analysis of these data provides valuable information, which is the basis of informed behaviour or actions and plays a crucial role in the realization of intelligent behaviour.

A. Adaptive neuro-fuzzy inference system (ANFIS)

The Adaptive Neuro-Fuzzy Inference System (ANFIS) is a form of multi-valued logic that operates through approximate reasoning, as opposed to exact reasoning. This approach involves assigning a value ranging from 0 to 1 to represent the level of truth for an element, rather than simply determining it to be true or false. The concept of fuzzy logic was first formalized through the Fuzzy Set Theory in 1965, and ANFIS architecture is depicted in Figure 4. The widespread utilization of fuzzy logic techniques in electrical power systems is attributed to its ability to model non-linear processes, such as the performance of electrical power systems, as well as complex energy storage management control strategies.

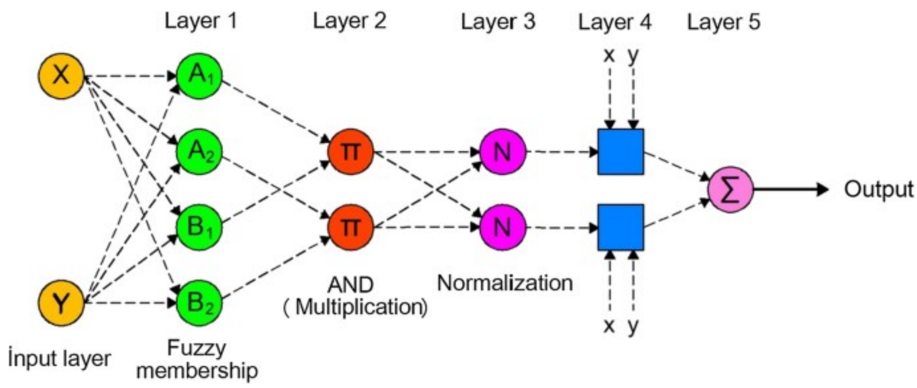

Figure 4. ANFIS architecture

B. Genetic Algorithm (GA)

The genetic algorithm (GA) has been implemented to address stability and power quality considerations within the Microgrid (MG) context. The process begins with the establishment of an initial population, followed by the identification of solutions with superior fitness and the elimination of suboptimal solutions. This results in a population with a higher probability of producing better solutions for MG applications. In this framework, each solution within GA is referred to as a gene. The initial step involves the random generation of a population of chromosomes, ensuring that budget constraints are not violated. The second step is the evaluation of the fitness of the initial population of chromosomes. The third step involves a tournament selection procedure, which continues until the selected parent population matches the population size, and the same chromosome can be selected more than once. Furthermore, the performance of the "parent chromosome" is evaluated against that with the highest fitness level. Lastly, the fourth step involves the utilization of two types of crossover mechanisms, each of which has been employed to optimize different aspects.

3. Model of MG based on PV, PEMFC, and battery

The Microgrid (MG) is a single-phase alternating current computer system, where energy sources such as an electric utility network, PV, PEMFC, and a storage battery, as depicted in Figure 5, are integrated to sustain the micro-network. The rechargeable battery controller manages the battery bank and facilitates the absorption of surplus power and provision of additional power during power outages in the micro-network. Three ordinary residences consume substantial energy (up to 2.5 kW) due to electrostatic repulsion, while the PEMFC can generate a capacity of 20 KW at a cell temperature of 25 degrees Celsius. The MG is connected to the electricity network through a transformer mounted on a pole, which reduces the voltage from 6.6 kV to 200 V. Solar PV power generation, PEMFC, and storage batteries being DC forms of energy are transformed into single-phase AC. Eq. (1) provides the voltage-current I_{ph} characteristic of a PV, and Eq. (2) describes the module saturation current I_0.

$$I_{ph} = \left[I_{sc} + k_i\,(T - 298) * \frac{I_r}{1000}\right] \tag{1}$$

$$I_0 = \left[I_{rs}\left[\frac{T}{T_r}\right]^3 exp\left[\frac{(q * E_{g0})}{n\,k}\right]\left(\frac{1}{T} - \frac{1}{T_r}\right) + k_i\,(T - 298) * \frac{I_r}{1000}\right] \tag{2}$$

where, I_{ph} refers to light-generated current. I_{sc} represents short-circuit current. I_0 is well-known as the saturation current of a diode. E_g shows a band gap. n indicates the ideality factor of the diode.

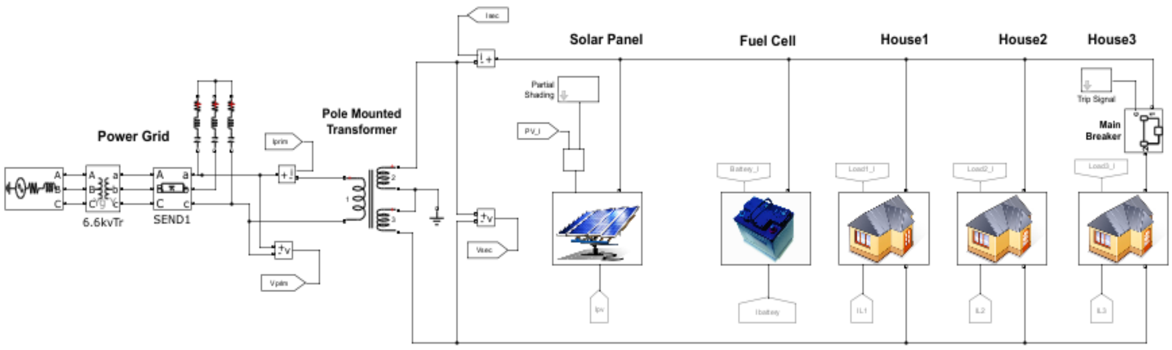

Figure 5. The modeling of MG-based on PV and FC

4. Simulation Parameters

This paper focuses on the design variables of the Microgrid (MG) that are based on Photovoltaic (PV), Proton Exchange Membrane Fuel Cell (PEMFC), and battery. In this context, this case study illustrates the behavior and performance of the MG system as modeled and simulated through a typical 24-hour period. The parameters of the MG based on PV, PEMFC, and battery are presented in Table 1, which was obtained through simulations conducted using MATLAB software.

Table 1. The PV, PEMFC, and parameters in the MATLAB simulation software [56-62].

	Parameters	Unite	Value
Electrical Utility	Three-Phase Source	kV	66
	Maximum Power	kW	5
	Sun irradiance	W/m^2	1000
	Cells per module (Ncell)	-	96
PV	Short-circuit current Isc	Amps	6.14

Array	Open Circuit Voltage (Voc)	Volts	64.6
	Short Circuit Current (Isc)	Amps	9.34
	Maximum System Voltage	kV	1
	Operating Temperature	°C	25
PEMFC	Maximum Power (W)	kW	6.5
DC-DC Converter	Voltage level	V	500
Inverter	Nominal Maximum voltage	V	240
	Efficiency	%	95
	Life span time	10	Years
Pole Mounted Transformer	Nominal power and	VA	$75*10^3$
	frequency	Hz	60
	Magnetization resistance	Rm (pu)	50
	inductance	Lm (pu)	50
Microgrid load	Amount of electric power load at 9h	kW	6.5
	Amount of electric power load at 19h to 22h	kW	7.5

5. Result and Discussion

In this segment of the discourse, the interconnection of the photovoltaic (PV), proton exchange membrane fuel cell (PEMFC), and battery to the MG is discussed. The methodology encompasses the application of phasor-based solutions from advanced energy systems to derive optimal solutions, with consideration given to the effect of electricity consumption demand on the extended utilization of the MG, which exhibits a standard load variation of 6.5 kW at 9.0h, 7,500 W at 19.0 h and 22.0 h in typical households. The battery controller is utilized to regulate the battery between 0 to 12 h and 18.0 to 24.0h, utilizing a control algorithm that reduces the flow of active power into the system from the secondary winding of the pole transformer to zero. The secondary component of the pole-mounted transformer has consistently maintained close to zero active power. In instances where the power in the Microgrid is inadequate, the battery storage system draws surplus current from the Microgrid and provides sufficient current when power exceeds the electricity usage.

Three ordinary residences consume electricity (up to 2.5 kW) as electrically charged particles. The electrical power network is connected to the Microgrid via a post-mounted transformer, which reduces the voltage from 6.6 kV to 200.0 V. Solar-PV panels, PEMFC, and energy storage systems are all DC power sources that are converted to single-phase AC. The control scheme operates under the premise that the MG is not solely dependent on electricity from the electric grid, but also on power generated from the solar panels and the storage system, which are always sufficient.

The outcome of the integration of HESS technology with the MG to eliminate voltage sag is discussed. The results of the MATLAB/Simulink simulations of the MG under Single Line-to-Ground Faults Scenario (SLGFS), Double Line-to-Ground Faults Scenario (DLGFS), and Three Line-to-Ground Faults Scenario (TLGFS) are presented, both with and without the implementation of the HESS-MG technology. Figure 6, illustrates the elimination of voltage sag through the application of the HESS-MG technology in the TLGFS. This section presents the results of the integration of HESS technology with the MG to mitigate voltage sag. The study assesses the performance of the HESS-MG during three fault scenarios through simulations in MATLAB/Simulink, specifically the Single Line-to-Ground Faults Scenario (SLGFS), Double Line-to-Ground Faults Scenario (DLGFS), and Three Line-to-Ground Faults Scenario (TLGFS), both with and without the implementation of HESS-MG technology. Figure 8 illustrates the improvement of the MG voltage sag, with a duration of time ranging from 0.3 to 0.7 seconds. The study employs ANFIS to the HESS-MG, which results in an injection value of 93.3% at TLGFS. Additionally, the study utilizes GA to the HESS-MG and achieves an injection value of 90.0% at the TLGFS. In comparison, the voltage sag drops by 68.6% without the use of HESS-MG. Figure 7, presents the results of the voltage sag elimination through the HESS-MG at DLGFS.

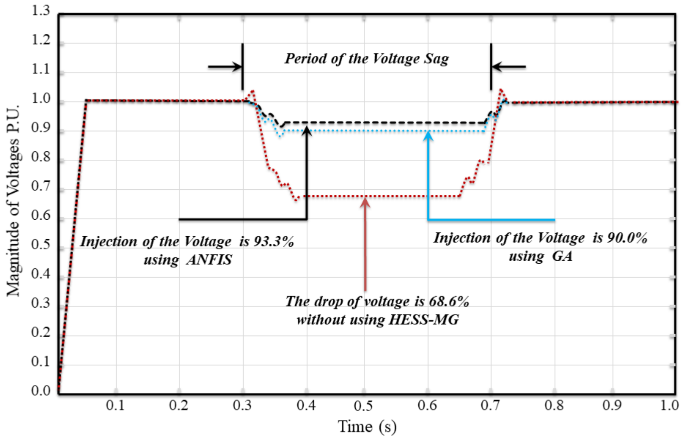

Figure 6. Voltage sag elimination using HESS-MG at the TLGFS

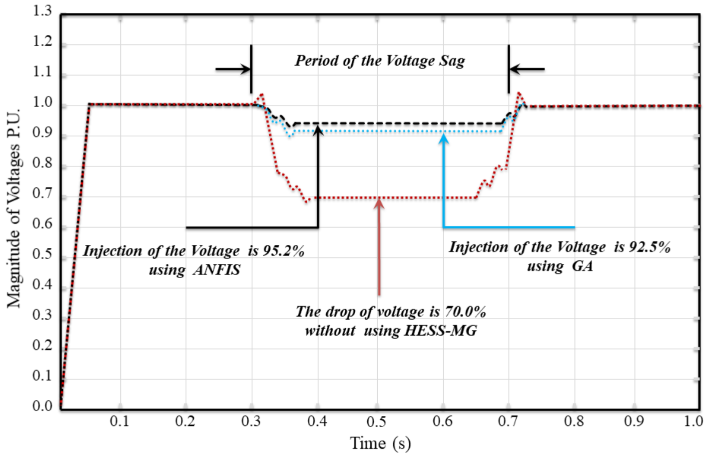

Figure 7. Voltage sag elimination using HESS-MG at the DLGFS.

The results of this paper are depicted in Figure 7, which demonstrates the improvement in the voltage sag of the MG achieved through the integration of HESS technology. Specifically, it is shown that the voltage sag has been mitigated for a time range of 0.3 to 0.7 seconds. The use of the Adaptive Neuro-Fuzzy Inference System (ANFIS) at the HESS-MG resulted in an injection value of 95.2% at the DLGFS, while the utilization of Genetic Algorithm (GA) at the HESS-MG led to an injection value of 92.5% at the DLGFS. Without the HESS-MG, the voltage sag reduction was only 70.0%. Figure 8, illustrates the elimination of voltage sag through the HESS-MG technology during the Single Line-to-Ground Faults Scenario (SLGFS).

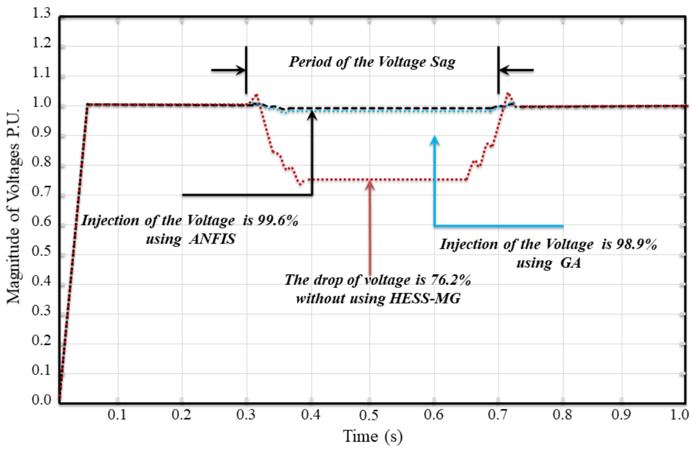

Figure 8. Voltage sag elimination using HESS-MG at the SLGFS.

Figure 8, presents the results of the enhancement of the MG voltage sag by the proposed scheme, with a duration ranging from 0.3 to 0.7 seconds. The utilization of ANFIS in the HESS-MG system results in an injection value of 99.6% at the SLGFS. Additionally, the application of the Genetic Algorithm (GA) to the HESS-MG yields an injection value of 98.9% at the TLGFS. The reduction of voltage sag without the utilization of the HESS-MG technology is 76.2%.

6. Conclusion

An adaptive neuro-fuzzy inference system (ANFIS) and Genetic Algorithm (GA) control strategies have been widely applied to collect the system data in electrical power systems. The process of these data provides important information, and knowledge is the result of analyzing this information, which is a key driver to intelligent behavior or action. In this context, the power system is rapid technological advancements change at the moment. In addition to that, massive power plants are now becoming the path to the smart grid in the long term. In this sense, the MG principle is the strongest method for combining distributed production, particularly with sources of renewable energy. The paper provides a comprehensive review of MG control and the most recent advancements in the field, both typically and across several different perspectives. The control system investigated using a centralized-decentralized structure, which distinguishes multiple aspects of decentralization and outlines the key features of any of the frequently used control structures. This paper also illustrates the interfaces of the PV, PEMFC, and battery with MG, the method incorporates the phasor workable alternative from advanced power systems. In this direction, the study employs the ANFIS in the HESS-MG and obtains an injection value of 93.3% at the TLGFS. Moreover, the paper implements the GA in the HESS-MG and achieves an injection value of 90.0% at the TLGFS. In comparison, the reduction of voltage sag without the use of HESS-MG is 68.6%. Moreover, the utilization of ANFIS in the HESS-MG system leads to an injection value of 95.2% at the DLGFS, while the implementation of GA in the HESS-MG yields an injection value of 92.5% at the DLGFS. The reduction of voltage sag without the use of HESS-MG is only 70.0%. To conclude, the application of ANFIS in the HESS-MG system results in an injection value of 99.6% at the SLGFS, and the utilization of GA in the HESS-MG yields an injection value of 98.9% at the SLGFS. The reduction of voltage sag without the use of HESS-MG technology is 76.2%, respectively.

Author Contributions: All authors listed have made a substantial, direct, and intellectual contribution to the work and approved it for publication.

Funding: This research received no external funding.

Data Availability Statement: Not applicable.

Acknowledgements: Authors would like to express our sincere gratitude and appreciation to Karabuk University for its invaluable support and assistance in the successful completion of our article.

Conflicts of Interest: The authors declare no conflict of interest.

References

[1] A. Etxeberria, I. Vechiu, H. Camblong, and J.-M. Vinassa, “Comparison of three topologies and controls of a hybrid energy storage system for microgrids,” *Energy Convers. Manag.*, vol. 54, no. 1, pp. 113–121, 2012.

[2] V. V. S. N. Murty and A. Kumar, “RETRACTED ARTICLE: Multi-objective energy management in microgrids with hybrid energy sources and battery energy storage systems,” *Prot. Control Mod. Power Syst.*, vol. 5, no. 1, 2020.

[3] M. M. Khaleel, M. R. Adzman, and S. M. Zali, “An integrated of hydrogen fuel cell to distribution network system: Challenging and opportunity for D-STATCOM,” *Energies*, vol. 14, no. 21, p. 7073, 2021.

[4] K. A. Khan and M. Khalid, “Improving the transient response of hybrid energy storage system for voltage stability in DC microgrids using an autonomous control strategy,” *IEEE Access*, vol. 9, pp. 10460–10472, 2021.

[5] W. Jing, C. Hung Lai, S. H. W. Wong, and M. L. D. Wong, “Battery-supercapacitor hybrid energy storage system in standalone DC microgrids: areview,” *IET Renew. Power Gener.*, vol. 11, no. 4, pp. 461–469, 2017.

[6] Y. Sahri *et al.*, "Energy management system for hybrid PV/wind/battery/fuel cell in microgrid-based hydrogen and economical hybrid battery/super capacitor energy storage," *Energies*, vol. 14, no. 18, p. 5722, 2021.

[7] X. Feng, J. Gu, and X. Guan, "Optimal allocation of hybrid energy storage for microgrids based on multi-attribute utility theory," *J. Mod. Power Syst. Clean Energy*, vol. 6, no. 1, pp. 107–117, 2018.

[8] M. M. Khaleel, A. Alsharif, and I. I. K. Imbayah, "Renewable energy technologies: Recent advances and future predictions," *AJAPAS*, pp. 58–64, 2022.

[9] C. R. Arunkumar, U. B. Manthati, and P. Srinivas, "Accurate modelling and analysis of battery–supercapacitor hybrid energy storage system in DC microgrid systems," *Energy Syst.*, vol. 13, no. 4, pp. 1055–1073, 2022.

[10] S. Tabassum *et al.*, "Solar energy in the United States: Development, challenges and future prospects," *Energies*, vol. 14, no. 23, p. 8142, 2021.

[11] J. Li *et al.*, "Design and real-time test of a hybrid energy storage system in the microgrid with the benefit of improving the battery lifetime," *Appl. Energy*, vol. 218, pp. 470–478, 2018.

[12] R. Sepehrzad, M. E. Hassanzadeh, A. R. Seifi, and M. Mazinani, "An efficient multilevel interconnect control algorithm in AC/DC micro-grids using hybrid energy storage system," *Electric Power Syst. Res.*, vol. 191, no. 106869, p. 106869, 2021.

[13] Q. Xu *et al.*, "A decentralized dynamic power sharing strategy for hybrid energy storage system in autonomous DC microgrid," *IEEE Trans. Ind. Electron.*, vol. 64, no. 7, pp. 5930–5941, 2017.

[14] N. Korada and M. K. Mishra, "Grid adaptive power management strategy for an integrated microgrid with hybrid energy storage," *IEEE Trans. Ind. Electron.*, vol. 64, no. 4, pp. 2884–2892, 2017.

[15] M. M. Khaleel, "Intelligent Control Techniques for Microgrid Systems," *Brilliance: Research of Artificial Intelligence*, vol. 3, no. 1, pp. 56–67, 2023.

[16] R. Liu, S. Wang, G. Liu, S. Wen, J. Zhang, and Y. Ma, "An improved virtual inertia control strategy for low voltage AC microgrids with hybrid energy storage systems," *Energies*, vol. 15, no. 2, p. 442, 2022.

[17] Y. Zhu, Q. Fan, L. Xiong, G. Zhang, and X. Qian, "Coordination control strategy for battery- ultracapacitor hybrid energy storage system in microgrids with unbalanced and nonlinear loads," *IEEE Access*, vol. 7, pp. 111577–111591, 2019.

[18] M. M. Khaleel, S. A. Abulifa, and A. A. Abulifa, "Artificial intelligent techniques for identifying the cause of disturbances in the power grid," *Brilliance: Research of Artificial Intelligence*, vol. 3, no. 1, pp. 19–31, 2023.

[19] R. Georgious, R. Refaat, J. Garcia, and A. A. Daoud, "Review on energy storage systems in microgrids," *Electronics (Basel)*, vol. 10, no. 17, p. 2134, 2021.

[20] A. Cansiz, C. Faydaci, M. T. Qureshi, O. Usta, and D. T. McGuiness, "Integration of a SMES–battery-based hybrid energy storage system into microgrids," *J. Supercond. Nov. Magn.*, vol. 31, no. 5, pp. 1449–1457, 2018.

[21] M. Khaleel, N. El-Naily, H. Alzargi, M. Amer, T. Ghandoori, and A. Abulifa, "Recent progress in synchronization approaches to mitigation voltage sag using HESS D-FACTS," *2022 International Conference on Emerging Trends in Engineering and Medical Sciences (ICETEMS),* pp. 186–190, 2023.

[22] M. Moncecchi, C. Brivio, S. Mandelli, and M. Merlo, "Battery energy storage systems in microgrids: Modeling and design criteria," *Energies*, vol. 13, no. 8, p. 2006, 2020.

[23] R. Kandari, N. Neeraj, and A. Micallef, "Review on recent strategies for integrating energy storage systems in microgrids," *Energies*, vol. 16, no. 1, p. 317, 2022.

[24] M. M. Khaleel, A. A. Ahmed, and A. Alsharif, "Artificial Intelligence in Engineering," *Brilliance: Research of Artificial Intelligence*, vol. 3, no. 1, pp. 32–42, 2023.

[25] L. Al-Ghussain, A. Darwish Ahmad, A. M. Abubaker, and M. A. Mohamed, "An integrated photovoltaic/wind/biomass and hybrid energy storage systems towards 100% renewable energy microgrids in university campuses," *Sustain. Energy Technol. Assessments*, vol. 46, no. 101273, p. 101273, 2021.

[26] Y. Wang, L. Wang, M. Li, and Z. Chen, "A review of key issues for control and management in battery and ultra-capacitor hybrid energy storage systems," *eTransportation*, vol. 4, no. 100064, p. 100064, 2020.

[27] A. O. Gbadegesin, Y. Sun, and N. I. Nwulu, "Techno-economic analysis of storage degradation effect on levelised cost of hybrid energy storage systems," *Sustain. Energy Technol. Assessments*, vol. 36, no. 100536, p. 100536, 2019.

[28] Q. Li, R. Li, Y. Pu, S. Li, C. Sun, and W. Chen, "Coordinated control of electric-hydrogen hybrid energy storage for multi-microgrid with fuel cell/ electrolyzer/ PV/ battery," *J. Energy Storage*, vol. 42, no. 103110, p. 103110, 2021.

[29] M. M. Khaleel, A. A. Ahmed, and A. Alsharif, “Energy Management System Strategies in Microgrids: A Review,” *The North African Journal of Scientific Publishing (NAJSP)*, vol. 1, no. 1, pp. 1–8, 2023.

[30] L. Al-Ghussain, R. Samu, O. Taylan, and M. Fahrioglu, “Sizing renewable energy systems with energy storage systems in microgrids for maximum cost-efficient utilization of renewable energy resources,” *Sustain. Cities Soc.*, vol. 55, no. 102059, p. 102059, 2020.

[31] A. Aktas, K. Erhan, S. Özdemir, and E. Özdemir, “Dynamic energy management for photovoltaic power system including hybrid energy storage in smart grid applications,” *Energy (Oxf.)*, vol. 162, pp. 72–82, 2018.

[32] M. M. Khaleel, T. Mohamed Ghandoori, A. Ali Ahmed, A. Alsharif, A. J. Ahmed Alnagrat, and A. Ali Abulifa, “Impact of mechanical storage system technologies: A powerful combination to empowered the electrical grids application,” in *2022 IEEE 2nd International Maghreb Meeting of the Conference on Sciences and Techniques of Automatic Control and Computer Engineering (MI-STA)*, 2022, pp. 628–636.

[33] X. Lin and R. Zamora, “Controls of hybrid energy storage systems in microgrids: Critical review, case study and future trends,” *J. Energy Storage*, vol. 47, no. 103884, p. 103884, 2022.

[34] A. Traore, A. Taylor, M. A. Zohdy, and F. Z. Peng, “Modeling and simulation of a hybrid energy storage system for residential grid-tied solar microgrid systems,” *J. Power Energy Eng.*, vol. 05, no. 05, pp. 28–39, 2017.

[35] C. Ju, P. Wang, L. Goel, and Y. Xu, “A two-layer energy management system for microgrids with hybrid energy storage considering degradation costs,” *IEEE Trans. Smart Grid*, vol. 9, no. 6, pp. 6047–6057, 2018.

[36] N. R. Tummuru, U. Manandhar, A. Ukil, H. B. Gooi, S. K. Kollimalla, and S. Naidu, “Control strategy for AC-DC microgrid with hybrid energy storage under different operating modes,” *Int. J. Electr. Power Energy Syst.*, vol. 104, pp. 807–816, 2019.

[37] X. Li, C. Dong, W. Jiang, and X. Wu, “An improved coordination control for a novel hybrid AC/DC microgrid architecture with combined energy storage system,” *Appl. Energy*, vol. 292, no. 116824, p. 116824, 2021.

[38] M. Khaleel, M. R. Adzman, S. M. Zali, M. M. Graisa, and A. A. Ahmed, “A review of fuel cell to distribution network interface using D-FACTS: Technical challenges and interconnection trends,” *Int. J. Electr. Electron. Eng. Telecommun.*, vol. 10, no. 5, pp. 319–332, 2021.

[39] S. Jithin and T. Rajeev, “Novel adaptive power management strategy for hybrid AC/DC microgrids with hybrid energy storage systems,” *J. Power Electron.*, vol. 22, no. 12, pp. 2056–2068, 2022.

[40] M. Khaleel, Z. Yusupov, N. Yasser, H. Elkhozondar, and A. A. Ahmed, “An integrated PV farm to the unified power flow controller for electrical power system stability,” *International Journal of Electrical Engineering and Sustainability (IJEES)*, vol. 1, no. 1, pp. 18–30, 2023.

[41] A. Latorre, W. Martinez, and C. A. Cortes, “Average current control with internal model control and real-time frequency decoupling for hybrid energy storage systems in microgrids,” *J. Mod. Power Syst. Clean Energy*, vol. 11, no. 2, pp. 511–522, 2023.

[42] G. S. Thirunavukkarasu, M. Seyedmahmoudian, E. Jamei, B. Horan, S. Mekhilef, and A. Stojcevski, “Role of optimization techniques in microgrid energy management systems—A review,” *Energy Strat. Rev.*, vol. 43, no. 100899, p. 100899, 2022.

[43] M.-H. Khooban, T. Niknam, M. Shasadeghi, T. Dragicevic, and F. Blaabjerg, “Load frequency control in microgrids based on a stochastic noninteger controller,” *IEEE Trans. Sustain. Energy*, vol. 9, no. 2, pp. 853–861, 2018.

[44] M. F. Zia, E. Elbouchikhi, and M. Benbouzid, “Microgrids energy management systems: A critical review on methods, solutions, and prospects,” *Appl. Energy*, vol. 222, pp. 1033–1055, 2018.

[45] S. Hajiaghasi, A. Salemnia, and M. Hamzeh, “Hybrid energy storage system for microgrids applications: A review,” *J. Energy Storage*, vol. 21, pp. 543–570, 2019.

[46] A. S. Jacob, R. Banerjee, and P. C. Ghosh, “Sizing of hybrid energy storage system for a PV based microgrid through design space approach,” *Appl. Energy*, vol. 212, pp. 640–653, 2018.

[47] T. M. Amirthalakshmi *et al.*, “A novel approach in hybrid energy storage system for maximizing solar PV energy penetration in microgrid,” *Int. J. Photoenergy*, vol. 2022, pp. 1–7, 2022.

[48] Y. Jiao and D. Mansson, “Analysis of two hybrid energy storage systems in an off-grid photovoltaic microgrid: A case study,” in *2020 IEEE PES Innovative Smart Grid Technologies Europe (ISGT-Europe)*, 2020.

[49] L. W. Chong, Y. W. Wong, R. K. Rajkumar, and D. Isa, “Hybrid energy storage systems and control strategies for stand-alone renewable energy power systems", Renewable Sustain, ” Renewable Sustain,” *Renewable Sustain,” Renewable Sustain. Energy Rev*, vol. 66, pp. 174–189, 2016.

[50] M. Khaleel *et al.*, "Effect of fuel cells on voltage sag mitigation in power grids using advanced equilibrium optimizer and particle swarm optimization," *Jordan Journal of Electrical Engineering*, vol. 9, no. 2, p. 175, 2023.

[51] J. Marqusee, W. Becker, and S. Ericson, "Resilience and economics of microgrids with PV, battery storage, and networked diesel generators," *Advances in Applied Energy*, vol. 3, no. 100049, p. 100049, 2021.

[52] A. Saxena and R. Shankar, "Improved load frequency control considering dynamic demand regulated power system integrating renewable sources and hybrid energy storage system," *Sustain. Energy Technol. Assessments*, vol. 52, no. 102245, p. 102245, 2022.

[53] H. Armghan, M. Yang, A. Armghan, N. Ali, M. Q. Wang, and I. Ahmad, "Design of integral terminal sliding mode controller for the hybrid AC/DC microgrids involving renewables and energy storage systems," *Int. J. Electr. Power Energy Syst.*, vol. 119, no. 105857, p. 105857, 2020.

[54] A. Chakraborty and S. Ray, "Operational cost minimization of a microgrid with optimum battery energy storage system and plug-in-hybrid electric vehicle charging impact using slime mould algorithm," *Energy (Oxf.)*, vol. 278, no. 127842, p. 127842, 2023.

[55] F. Alasali, A. S. Saidi, N. El-Naily, O. Alsmadi, M. Khaleel, and I. Ghirani, "Assessment of the impact of a 10-MW grid-tied solar system on the Libyan grid in terms of the power-protection system stability," *Clean Energy*, vol. 7, no. 2, pp. 389–407, 2023.

[56] G. V. Brahmendra Kumar and K. Palanisamy, "Review of energy storage system for microgrid," *Microgrid Technologies*. Wiley, pp. 57–90, 11-Mar-2021.

[57] M. Khalid, "A review on the selected applications of battery-supercapacitor hybrid energy storage systems for microgrids," *Energies*, vol. 12, no. 23, p. 4559, 2019.

[58] R. Hemmati and H. Saboori, "Emergence of hybrid energy storage systems in renewable energy and transport applications – A review," *Renew. Sustain. Energy Rev.*, vol. 65, pp. 11–23, 2016.

[59] J. M. Lujano-Rojas, R. Dufo-López, J. L. Atencio-Guerra, E. M. G. Rodrigues, J. L. Bernal-Agustín, and J. P. S. Catalão, "Operating conditions of lead-acid batteries in the optimization of hybrid energy systems and microgrids," *Appl. Energy*, vol. 179, pp. 590–600, 2016.

[60] P. Dhar and N. Chakraborty, "A dual mode wind turbine operation with hybrid energy storage system for electricity generation at constant voltage in an islanded microgrid," *Int. J. Energy Res.*, vol. 45, no. 13, pp. 18885–18902, 2021.

[61] J. Duan, Z. Yi, D. Shi, C. Lin, X. Lu, and Z. Wang, "Reinforcement-learning-based optimal control of hybrid energy storage systems in hybrid AC–DC microgrids," *IEEE Trans. Industr. Inform.*, vol. 15, no. 9, pp. 5355–5364, 2019.

[62] Q. Li, X. Zou, Y. Pu, and W. Chen, "A real-time energy management method for electric-hydrogen hybrid energy storage microgrid based on DP-MPC," *CSEE J. Power Energy Syst.*, pp. 1–13, 2020.