engineering proceedings

MDPI

Proceeding Paper

Power System Transient Stability Analysis Considering Short-Circuit Faults and Renewable Energy Sources †

Amel Brik *, Nour El Yakine Kouba * and Ahmed Amine Ladjici *

Faculty of Electrical Engineering, University of Sciences and Technology Houari Boumediene, Algiers 16111, Algeria

* Correspondence: abrik2022@gmail.com (A.B.); koubanour@gmail.com (N.E.Y.K.); aladjici@usthb.dz (A.A.L.)

† Presented at the 3rd International Electronic Conference on Processes—Green and Sustainable Process Engineering and Process Systems Engineering (ECP 2024), 29–31 May 2024; Available online: https://sciforum.net/event/ECP2024.

Abstract: This paper describes a power system transient stability analysis in the presence of renewable energy sources (RESs), including wind farms and solar photovoltaic (PV) generators. The integration impact of RESs on power system time-domain simulation and transient stability were analyzed using the Western System Coordinating Council (WSCC) IEEE 14 bus system. Through this study, we aimed to analyze the transient stability of an interconnected electrical network by integrating renewable energy for critical clearing time (CCT) enhancement when a short-circuit fault appears. It is important for a power system to remain in a state of equilibrium under normal operating conditions and reach an acceptable state of equilibrium after having been disturbed. With this in mind, the influence of the integration of renewable energy sources such wind turbines and PV generators in an electrical network was envisaged in the case of transient stability. The standard test network IEEE 14 bus was employed for the simulation using the MATLAB software, which is a dedicated tool used for the dynamic analysis and control of electrical networks. Several scenarios that simulated transient stability were reviewed, and an analysis was conducted, including three phases: before, during, and after a three-phase short-circuit fault.

Keywords: power system; transient stability; renewable energy; wind farm; solar photovoltaic (PV) generator

check for updates

Citation: Brik, A.; Kouba, N.E.Y.; Ladjici, A.A. Power System Transient Stability Analysis Considering Short-Circuit Faults and Renewable Energy Sources. *Eng. Proc.* **2024**, *67*, 42. https://doi.org/10.3390/engproc2024067042

Academic Editor: Michael C. Georgiadis

Published: 13 September 2024

1. Introduction

Power system operation and control refers to the management of electricity generation, transmission, and distribution to ensure a reliable supply of energy to consumers. It involves monitoring the system in real time, making adjustments to balance supply and demand, and responding to disturbances or outages. The control strategies include adjusting the generator output, changing the routing of power flows, and implementing protective measures to maintain system stability [1]. This is critical for maintaining the reliability and efficiency of the power grid. Furthermore, transient stability analysis in power systems refers to the study of the system's ability to maintain synchronism and stability following a large disturbance, such as a fault or a sudden change in load. It involves analyzing the dynamic response of generators, loads, and other system components to ensure that the system can quickly recover and continue to operate without losing stability. This type of analysis is essential for preventing widespread blackouts and ensuring the overall reliability of a power system [2].

Presently, modern power systems face many operation and control challenges due to the integration of renewable energy technologies such as solar, wind, hydro, and geothermal power into the existing electricity grid [3]. These clean energy sources generate electricity without producing carbon emissions or other harmful pollutants, making them environmentally friendly alternatives to traditional fossil fuels [4]. The integration of clean energy sources into power systems requires advanced control and management strategies to ensure a reliable and stable supply of electricity while maximizing the use of renewable resources. This shift towards clean energy is essential for reducing greenhouse gas emissions and mitigating the impacts of climate change [5]. The impact of increasing the share of renewable energy production brings the electricity system to conditions of lower reliability, security, and stability [6]. In this context, stability, particularly transient [7], deals with the effects of sudden disturbances of high amplitudes and short durations, such as short-circuit faults, disconnections of lines, production groups, sudden variations in the load, etc. System transient stability issues range from the ability to maintain generator synchronism when subjected to a strong disturbance to the ability to maintain an acceptable voltage profile after having been subjected to a disturbance [8]. The determination of the critical clearing time (CCT) constitutes an important characteristic in the operation of circuit breakers [9]. It is of major importance to the analysis, planning, and operation of electricity networks [10]. The CCT value depends not only on the position and magnitude of the fault, but also on the intrinsic parameters of the electrical network [11].

Enhancing power system stability with renewable energies is a crucial topic in the current energy field [12]. Integrating renewable energy sources like wind and solar power into the grid brings both opportunities and challenges for ensuring a stable and reliable power system [13]. Renewable energies offer a diverse mix of energy sources, reducing dependence on traditional fossil fuels and increasing the resilience of the grid [14]. Some renewable sources, such as hydro and certain types of wind and solar power, can provide a fast response and flexibility to support grid stability during fluctuations [15]. Moreover, improving the critical clearing time for transient stability in the presence of renewable energies is a crucial aspect of ensuring grid reliability and resilience [16]. In addition, incorporating energy storage systems can help mitigate fluctuations in renewable energy output and provide additional support during transient stability events [17]. Also, deploying FACTS devices can improve grid stability by enhancing voltage control and power flow management, especially during transient stability challenges [18]. By focusing on these approaches, the integration of renewable energies can be optimized while maintaining the stability and reliability of the grid during transient stability events [19].

This paper first examines the impact of renewable energy production on a power system's transient stability when RESs (wind turbine, PV generator) are connected. The main objective of this work is to analyze and compare some of the solutions to improve the transient stability after a fault. The IEEE 14 bus was used as a test system by adding a wind turbine and a PV generator. The IEEE 14 bus system was modeled under various scenarios. The rest of this paper is organized as follows. Section 2 presents the power system model, while Section 3 describes the simulation results and, finally, Section 4 brings about the conclusion.

2. System Modeling

In this section, we describe how the IEEE 14 bus test system was modeled for the transient stability analysis of a system including wind turbines and a PV generator, as shown in Figure 1. A three-phase short-circuit fault was considered as the system disturbance, with the calculation of the critical clearing time (CCT) for each fault. During the simulation, a hybrid wind–PV power generation system was installed at bus 11 and bus 12, with a balanced three-phase short-circuit applied at bus 10.

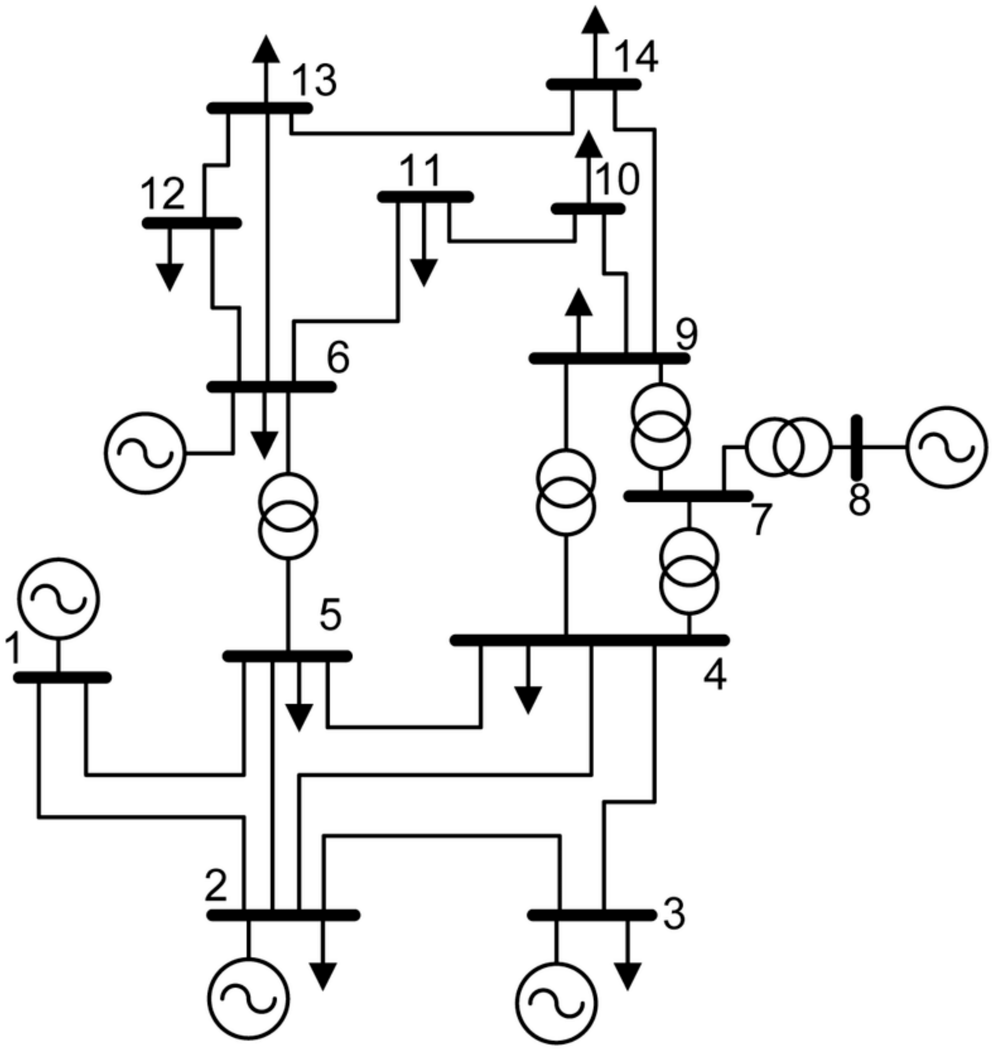

Figure 1. IEEE 14-bus test network.

2.1. Generator Model

The synchronous machine was connected to the grid trough a generator bus. During transient operation, it was represented by its simple model, which consisted of an internal voltage behind a transient reactance, as presented in Figure 2 and Equation (1).

$$E' = E_t + j \cdot Xd' \cdot I_g \quad (1)$$

where

I_g: Machine current in *pu*;
E_t: Terminal voltage at the generator node in *pu*;
E': Internal voltage behind the transient reactance Xd'.

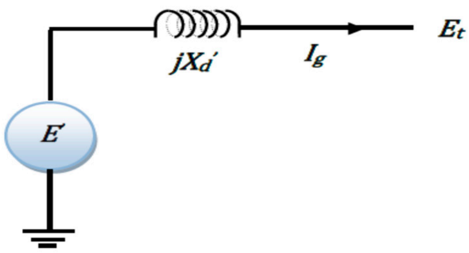

Figure 2. Equivalent diagram of a transient synchronous machine.

2.2. Transformer Model

A transformer is used to raise the voltage amplitude for economical long-distance transmission and lower the voltage for distribution to consumers, as shown in Figure 3.

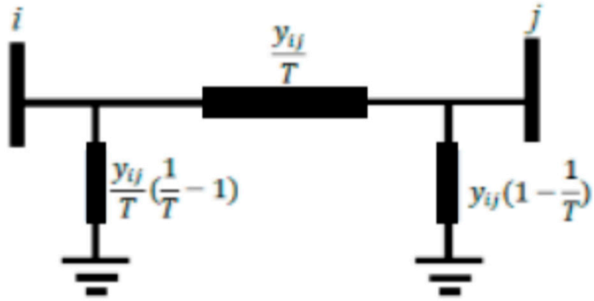

Figure 3. Simplified transformer model.

2.3. Transmission Line Model

The transmission line was modeled by a π-equivalent diagram, which consisted of a series impedance (resistance R in series with an inductive reactance X), and a shunt admittance, which consisted of a capacitive susceptance B (due to the capacitive effect of the line with the Earth), in parallel with an insulating conductance G, as shown in Figure 4.

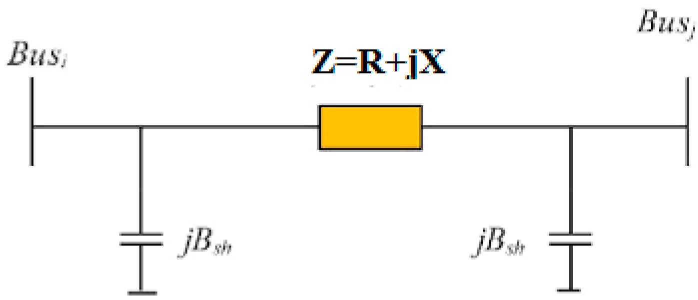

Figure 4. Equivalent diagram of a Π transmission line model.

2.4. Load Model

The load characteristics have a major influence on a system's stability and dynamics. The equivalent load model is shown in Figure 5 and Equation (2).

$$S_{L1} = P_{L1} + Q_{L1} \tag{2}$$

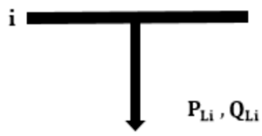

Figure 5. Load model.

2.5. Wind Power Conversion System

The mechanical power output of a wind turbine is generally described as follows [20–25]:

$$p_w = \frac{1}{2} c_p(\lambda, \beta) \rho \, A \, v_{wind}^3 \tag{3}$$

where

p_w: mechanical output power of the turbine (W);
c_p: performance coefficient of the turbine;
λ: tip speed ratio of the rotor blade tip speed to wind speed;
β: blade pitch angle (deg);

ρ: air density (kg/m^3);
A: turbine swept area (m^2);
v_{wind}: wind speed (m/s).

2.6. Solar PV Generator Model

The energy produced by a photovoltaic generator is estimated based on the total irradiance data on the slope, the ambient temperature, and the constructive data of the photovoltaic modules used [20–25].

$$E_{pv} = \eta_{ge} S_{pv} P_f H \quad (4)$$

$$\eta_{gen} = \eta \left\{ 1 - \gamma \left(T_J - 25 \right) \right\} \quad (5)$$

$$T_c = T_a + \left(\frac{NOCT - 20}{800} \right) G \quad (6)$$

$$P_{MPPT} = N_{PV} \frac{G}{G_{réf}} \left[P_{0max} + \mu_{pm} \left(T_c - T_{créf} \right) \right] = N_{PV} P_{max} \quad (7)$$

where

η_{ge}: the efficiency of the photovoltaic generator;
S_{pv}: represents the total surface of the photovoltaic generator (m^2);
P_f: module filling factor equal to 0.9;
H: solar irradiation on an inclined plane ($kWh/m^2 \cdot month$).
The efficiency of a photovoltaic generator is determined as follows:
γ: represents the coefficient, taking into account the variation in the efficiency of the photovoltaic module as a function of temperature, which is taken at (0.0045/°C);
η: the reference efficiency of the photovoltaic generator;
T_c: PV module junction temperature (°C);
T_a: ambient temperature of the location considered (°C);
$NOCT$: operating temperature of PV cells under reference conditions.
The total power supplied is the following:
P_{MPPT}: power supplied by the PV field (W);
N_{PV}: number of modules making up the PV;
G: overall solar irradiation of the location considered (W/m^2);
$G_{réf}$: 1000 (W/m^2): solar irradiation under standard reference conditions;
$P_{0\ max}$: maximum power of the module under standard conditions (W);
μ_{pm}: coefficient of variation in power as a function of temperature;
$T_{c\ réf}$: junction temperature in the reference conditions of the PV module (25 °C).

3. Simulation Results

In this section, the transient stability simulation results of the IEEE 14 bus test system are presented, considering the integration of wind turbines and a PV generator. The network consists of 20 lines, 14 buses, 2 generators, 3 synchronous compensators, and 10 loads as shown in Figure 1. This system was simulated for stable and unstable scenarios. A three-phase short-circuit fault was considered as the system disturbance, with a calculation of the critical clearing time (CCT) conducted for each fault, and, the transient responses for the voltage were presented. Table 1 summarizes the technical data of the IEEE 14 bus system used in the simulation.

When analyzing transient stability in IEEE 14 bus power systems with renewable energies, the calculation of the critical clearing time (CCT) is a crucial issue. The CCT refers to the time it takes for a power system to stabilize after a disturbance, such as a fault or the sudden loss of generation or load isolation. Also, in the case of the integration of renewable energy sources like wind or solar power, their intermittent nature can affect the overall system's stability. In this context, the simulation scenarios in this section presents the impact of wind and solar power plants on transient stability analysis before and after integration, aiming to enhance the CCT.

Table 1. Technical data for the IEEE 14 bus.

Bus	V [p.u.]	Phase [rad]	P Gen [p.u.]	Q Gen [p.u.]	P Load [p.u.]	Q Load [p.u.]
Bus 1	1.0625	11.9952	3.5203	−0.28197	0	0
Bus 2	1.0495	11.8729	0.4	0.9486	0.3038	0.1778
Bus3	1.0064	11.6342	0	0.59736	1.3188	0.266
Bus 4	0.97871	11.6661	0	0	0.6692	0.056
Bus 5	0.98813	11.7258	0	0	0.1064	0.0224
Bus 6	1.0619	11.5751	0	0.44433	0.1568	0.105
Bus 7	1.0233	11.5949	0	0	0	0
Bus 8	1.083	11.595	0	0.33402	0	0
Bus 9	0.99993	11.5573	0	0	0.413	0.2324
Bus 10	1.0001	11.5535	0	0	0.126	0.0812
Bus 11	1.0254	11.5615	0	0	0.049	0.0252
Bus 12	1.0379	11.5535	0	0	0.0854	0.0224
Bus 13	1.0279	11.5521	0	0	0.189	0.0812
Bus 14	0.98612	11.529	0	0	0.2086	0.07

3.1. Case 1: Without RES Integration and a Fault

In this part, the first scenario is analyzed without the integration of wind turbines, a PV generator, and a short-circuit fault, with the aim of showing the operating behavior of a normal network. The voltage profile results are shown in Figure 6.

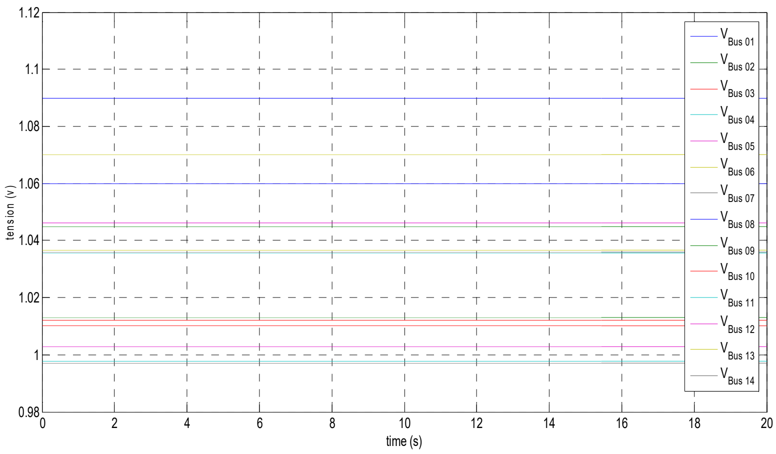

Figure 6. Bus voltage without RESs and faults.

3.2. Case 2: Without RES Integration and with a Three-Phase Short-Circuit Fault

As a reference, we carried out simulations on the network above to determine the CCT at each bus. In this case, the short-circuit fault was the base event, applied at the 1 s timepoint. A balanced three-phase short-circuit was applied at bus 10 before the integration of a wind turbine and a PV generator, as shown in Figure 7.

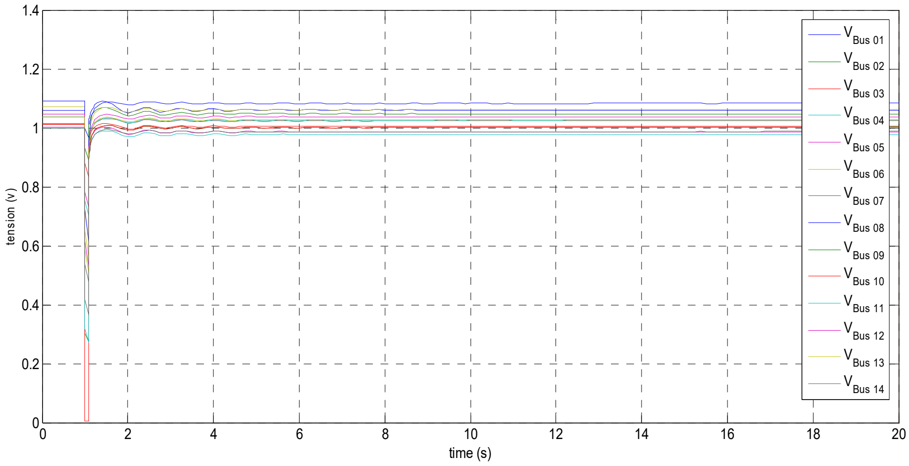

Figure 7. Bus voltage with a three-phase short-circuit fault.

3.3. Case 3: With RES Integration and without a Fault

In this part, we describe how a hybrid wind–PV power generation system was installed in the IEEE 14 bus at the bus 11 and bus 12 positions. In this case, the system was simulated without short-circuit faults. A small change was observed in the voltage profile, as shown in Figure 8.

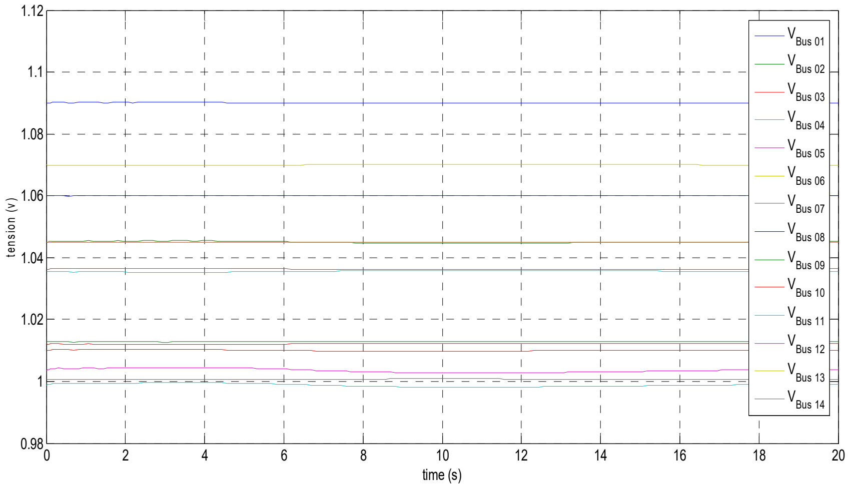

Figure 8. Bus voltage with RES integration.

3.4. Case 4: With RES Integration and a Three-Phase Short-Circuit Fault

In the simulation described in this section, we used the same source location as Case 3 and the short-circuit fault simulated at the bus 10 location. The obtained result are listed in Figure 9.

We deduce from Figure 9 that the network is able to maintain stability during a fault. It can be seen that there is a significant improvement in the voltage profile when a wind farm, PV source, or both sources are integrated at the bus level, compared to the other voltages in the initial state. RESs' impact on the power system's transient stability depends on the integration rate. It can be concluded that the optimal placement of distributed power generation units will play an increasingly important role in the future in improving power system performance (network quality, damping and oscillation, and power flow distribution).

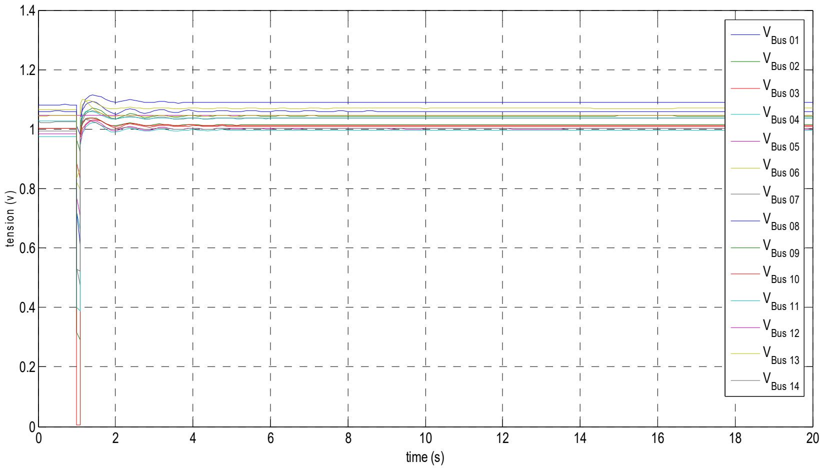

Figure 9. Bus voltage with RES integration and a three-phase short-circuit fault.

4. Conclusions

The study of transient stability is important for testing the reliability and resistivity of the elements constituting an electrical system and providing future solutions in the event of an electrical safety problem in the same system. Network stability is a very important parameter. By studying this parameter, we can determine the maximum fault isolation time and avoid network instability and its collapse (blackout). The optimal location of renewable energy sources in electrical production influences the fault isolation time. The results obtained show that wind farms and photovoltaic generators clearly improve the transient stability; however, they can severely worsen the transient stability during periods of intermittent power, with strong penetration.

In future works, the optimal placement and size of RES sources in a storage system will be studied and applied. A comparison will be made using artificial intelligence and nature-inspired optimization algorithms.

Author Contributions: Conceptualization, A.B., N.E.Y.K. and A.A.L.; methodology, A.B., N.E.Y.K. and A.A.L.; software A.B., N.E.Y.K. and A.A.L.; validation, A.B., N.E.Y.K. and A.A.L.; formal analysis, A.B.; investigation, A.B.; resources, N.E.Y.K.; data curation, A.B.; writing—original draft preparation, A.B.; writing—review and editing, A.B., N.E.Y.K. and A.A.L.; visualization, A.B.; supervision, N.E.Y.K. and A.A.L.; project administration, N.E.Y.K.; funding acquisition, N.E.Y.K. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: No new data were reated.

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

References

1. Tina, G.M.; Maione, G.; Licciardello, S. Evaluation of technical solutions to improve transient stability in power systems with wind power generation. *Energies* **2022**, *15*, 7055. [CrossRef]
2. Flynn, D.; Rather, Z.; Ardal, A.; D'Arco, S.; Hansen, A.D.; Cutululis, N.A.; Wang, Y. Technical impacts of high penetration levels of wind power on power system stability. *Wiley Interdiscip. Rev. Energy Environ.* **2017**, *6*, e216. [CrossRef]
3. Kundur, P.; Paserba, J.; Ajjarapu, V.; Andersson, G.; Bose, A.; Canizares, C.; Vittal, V. Definition and classification of power system stability IEEE/CIGRE joint task force on stability terms and definitions. *IEEE Trans. Power Syst.* **2004**, *19*, 1387–1401.
4. Kaur, R.; Kumar, D. Transient stability improvement of IEEE 9 bus system using power world simulator. *MATEC Web Conf.* **2016**, *57*, 01026. [CrossRef]
5. Djemai, N. Optimization of the Integration of Decentralized Energy Resources (DER) into Distribution Networks in a Deregulated Electricity Market. Ph.D. Thesis, University of Mohamed Khider Biskra, Biskra, Algiers, 2016.

6. Boubakeur, M.H. Contribution to Improving the Efficiency of Electricity Networks through the Integration and Flexible Control of Wind Energy and FACTS Systems. Ph.D. Thesis, University of Mohamed Khider Biskra, Biskra, Algiers, 2017.
7. Alhamrouni, I.; Abdul Kahar, N.H.; Salem, M.; Swadi, M.; Zahroui, Y.; Kadhim, D.J.; Mohamed, F.A.; Alhuyi Nazari, M. A Comprehensive Review on the Role of Artificial Intelligence in Power System Stability, Control, and Protection: Insights and Future Directions. *Appl. Sci.* **2024**, *14*, 6214. [CrossRef]
8. Shahzad, S.; Jasińska, E. Renewable Revolution: A Review of Strategic Flexibility in Future Power Systems. *Sustainability* **2024**, *16*, 5454. [CrossRef]
9. Abdelaal, A.K.; El-Hameed, M.A. Application of Robust Super Twisting to Load Frequency Control of a Two-Area System Comprising Renewable Energy Resources. *Sustainability* **2024**, *16*, 5558. [CrossRef]
10. Hernández-Mayoral, E.; Madrigal-Martínez, M.; Mina-Antonio, J.D.; Iracheta-Cortez, R.; Enríquez-Santiago, J.A.; Rodríguez-Rivera, O.; Martínez-Reyes, G.; Mendoza-Santos, E. A comprehensive review on power-quality issues, optimization techniques, and control strategies of microgrid based on renewable energy sources. *Sustainability* **2023**, *15*, 9847. [CrossRef]
11. Alam, S.; Chowdhury, T.A.; Dhar, A.; Al-Ismail, F.S.; Choudhury, M.S.H.; Shafiullah, M.; Hossain, I.; Hossain, A.; Ullah, A.; Rahman, S.M. Solar and wind energy integrated system frequency control: A critical review on recent developments. *Energies* **2023**, *16*, 812. [CrossRef]
12. Boubii, C.; El Kafazi, I.; Bannari, R.; El Bhiri, B.; Bossoufi, B.; Kotb, H.; AboRas, K.M.; Emara, A.; Nasiri, B. Synergizing Wind and Solar Power: An Advanced Control System for Grid Stability. *Sustainability* **2024**, *16*, 815. [CrossRef]
13. Meegahapola, L.; Sguarezi, A.; Bryant, J.S.; Gu, M.; Conde, D.E.R.; Cunha, R.B.A. Power system stability with power-electronic converter interfaced renewable power generation: Present issues and future trends. *Energies* **2020**, *13*, 3441. [CrossRef]
14. Shair, J.; Li, H.; Hu, J.; Xie, X. Power system stability issues, classifications and research prospects in the context of high-penetration of renewables and power electronics. *Renew. Sustain. Energy Rev.* **2021**, *145*, 111111. [CrossRef]
15. Machowski, J.; Lubosny, Z.; Bialek, J.W.; Bumby, J.R. *Power System Dynamics: Stability and Control*; John Wiley & Sons: Hoboken, NJ, USA, 2020.
16. Wu, Q.-H.; Bose, A.; Singh, C.; Chow, J.H.; Mu, G.; Sun, Y.; Liu, Z.; Li, Z.; Liu, Y. Control and stability of large-scale power system with highly distributed renewable energy generation: Viewpoints from six aspects. *CSEE J. Power Energy Syst.* **2023**, *9*, 8–14.
17. Ahmed, F.; Al Kez, D.; McLoone, S.; Best, R.J.; Cameron, C.; Foley, A. Dynamic grid stability in low carbon power systems with minimum inertia. *Renew. Energy* **2023**, *210*, 486–506. [CrossRef]
18. Gulzar, M.M. Designing of Robust Frequency Stabilization Using Optimized MPC-(1+PIDN) Controller for High Order Interconnected Renewable Energy Based Power Systems. *Prot. Control Mod. Power Syst.* **2023**, *8*, 1–14. [CrossRef]
19. Taher, A.M.; Hasanien, H.M.; Aleem, S.H.A.; Tostado-Véliz, M.; Ćalasan, M.; Turky, R.A.; Jurado, F. Optimal model predictive control of energy storage devices for frequency stability of modern power systems. *J. Energy Storage* **2023**, *57*, 106310. [CrossRef]
20. Caire, R. Management and Strategies for Driving Decentralized Production. Ph.D. Thesis, INP Grenoble, Saint-Martin-d'Hères, France, April 2004.
21. Richardot, O. Coordinated Voltage Adjustment in Distribution Networks Using Decentralized Generation. Ph.D. Thesis, Institut National Polytechnique de Grenoble-INPG, Saint-Martin-d'Hères, France, October 2006.
22. Yahya, A.O.M.; Mahmoud, A.O.; Youm, I. Study and modeling of a photovoltaic generator. *Renew. Energy Rev.* **2008**, *11*, 473–483.
23. Yuan, Z.; Zhao, C.; Cortés, J. Reinforcement learning for distributed transient frequency control with stability and safety guarantees. *Syst. Control Lett.* **2024**, *185*, 105753. [CrossRef]
24. Odonkor, E.N.; Moses, P.M.; Akumu, A.O. Intelligent ANFIS-based distributed generators energy control and power dispatch of grid-connected microgrids integrated into distribution network. *Int. J. Electr. Electron. Eng. Telecommun.* **2024**, *13*, 112–124. [CrossRef]
25. Zakariya, M.; Teh, J. A systematic review on cascading failures models in renewable power systems with dynamics perspective and protections modeling. *Electr. Power Syst. Res.* **2023**, *214*, 108928. [CrossRef]