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OPTIMAL INTEGRATION OF RENEWABLE ENERGY INTO THE NATIONAL GRID FOR IMPROVED POWER SUPPLY USING ANN BASED SUPERCAPACITOR

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Abstract

The increasing global demand for clean and sustainable energy has accelerated the integration of renewable energy sources (RES) such as solar photovoltaic (PV) and wind power into national grids. In Nigeria, the adoption of RES is hindered by challenges including variability in power generation, grid instability, and insufficient energy storage capacity. These limitations often result in unreliable power supply, frequency deviations, and voltage fluctuations. This study presents an Artificial Neural Network (ANN)-based super capacitor control system designed to achieve the optimal integration of renewable energy into the national grid for improved power supply stability and reliability. The ANN serves as an intelligent controller capable of learning complex nonlinear relationships between renewable generation patterns, grid demand, and storage behavior, enabling adaptive and precise charge–discharge control of the super capacitor. The super capacitor, with its high power density and rapid response time, mitigates the effects of renewable intermittency by providing fast frequency regulation, voltage support, and peak shaving. Simulation results obtained from a MATLAB/Simulink model of the Nigerian grid integrated with RES demonstrate that the proposed ANN-based supercapacitor system significantly improves grid stability, reduces voltage deviation by up to 18%, and enhances renewable energy utilization efficiency by 25% compared to conventional storage control methods. The findings indicate that ANN-driven supercapacitor storage systems offer a viable solution for optimizing renewable energy integration, ensuring improved operational reliability, and supporting Nigeria's transition towards a more sustainable power infrastructure. The results obtained were the conventional intermittency and rapid generation variability that causes unoptimal integration of renewable energy into the national grid for unimproved power supply was 52 MW. On the other hand when an ANN based super capacitor was integrated into the system, it instantly reduced to 47.5 MW and the conventional intermittency and Poor generation forecasting that causes unoptimal integration of renewable energy into the national grid for unimproved power supply was31MW. Meanwhile when an ANN based super capacitor was introduced into the system, it automatically reduced to28.3 MW. Finally, with these results obtained, it definitely meant that the percentage optimized integration of renewable energy into the national grid for improved power supply when an ANN based super capacitor was imbibed into the system was8.7%.

Keywords; optimal, integration, renewable, energy, national, grid, improved, power, supply ANN, based, super capacitor

INTRODUCTION

The global shift toward sustainable energy generation has intensified efforts to integrate renewable energy sources (RES) such as solar photovoltaic (PV) and wind power into existing power systems. This transition is driven by the need to reduce greenhouse gas emissions, minimize dependence on fossil fuels, and ensure long-term energy security (International Energy Agency \[IEA], 2022). In Nigeria, the national grid has historically relied heavily on thermal and hydroelectric power plants, yet persistent challenges such as inadequate generation capacity, transmission bottlenecks, and distribution inefficiencies have resulted in an unreliable power supply (Okedu & Uhunmwangho, 2020). The integration of RES into the national grid presents an opportunity to diversify the generation mix, expand electricity access, and improve supply reliability. However, renewable energy integration in Nigeria is hampered by several challenges, most notably the intermittency and variability of generation, which arise from fluctuating solar irradiation and wind speeds (Oyedepo et al., 2019). These variations can cause frequency instability, voltage fluctuations, and in extreme cases, grid collapse if not effectively managed (Adewale et al., 2021). To address these issues, energy storage systems (ESS) are crucial in smoothing power output, providing ancillary services, and ensuring that renewable generation aligns with grid demand (Luo et al., 2015). Among various ESS technologies, supercapacitors have gained attention for their high power density, rapid charge–discharge cycles, and long operational lifetimes, making them particularly effective for mitigating short-term power fluctuations and supporting grid stability (Burke & Miller, 2011). Artificial Neural Networks (ANNs) offer an intelligent control approach capable of learning complex, nonlinear relationships between multiple variables in a power system (Haykin, 2009). In the context of renewable integration, ANNs can predict generation patterns, optimize the charging and discharging cycles of supercapacitors, and adapt to real-time grid conditions (Sharma et al., 2020). This synergy between ANN control and supercapacitor technology can significantly enhance the operational flexibility of the national grid, reduce voltage and frequency deviations, and improve the overall reliability of power supply. Given Nigeria's increasing electricity demand, government renewable energy policies, and ongoing power sector reforms, the development of an ANN-based supercapacitor control framework for optimal renewable energy integration is timely and essential. Such a system can address the technical challenges of renewable intermittency while maximizing the benefits of clean energy deployment. This study, therefore, seeks to design and evaluate an intelligent storage control solution that enhances renewable energy penetration, improves grid stability, and supports a sustainable energy future for Nigeria.

METHODOLOGY

To characterize and establish the causes of unoptimal integration of renewable energy into the national grid for unimproved power supply

Table 1 characterized and established caused of unoptimal integration of renewable energy into the national grid for unimproved power supply

Causes of unoptimal integration of renewable energy into the national	Threshold values	conventional causes of unoptimal integration of

grid for unimproved power supply		renewable energy into the national grid for unimproved power supply
Intermittency and rapid generation variability	>50MW	52MW
Poor generation forecasting	>30MW	31MW
Insufficient short time storage capacity	<2%	1.8%
Low system inertia(weak grid)	<5000MW	4987MW
Inadequate reactive power support	>10%	12%
Transmission congestion and insufficient capacity	>90%	92%
Poor inverter control and grid forming capacity	>0.5s	0.7s
High power quality issues	>5%	7%
Insufficient dispatchment reserve	<100MW	98MW
Slow control and communication latency	>2s	3s

To design a conventional SIMULINK model for optimal integration of renewable energy into the national grid for improved power supply

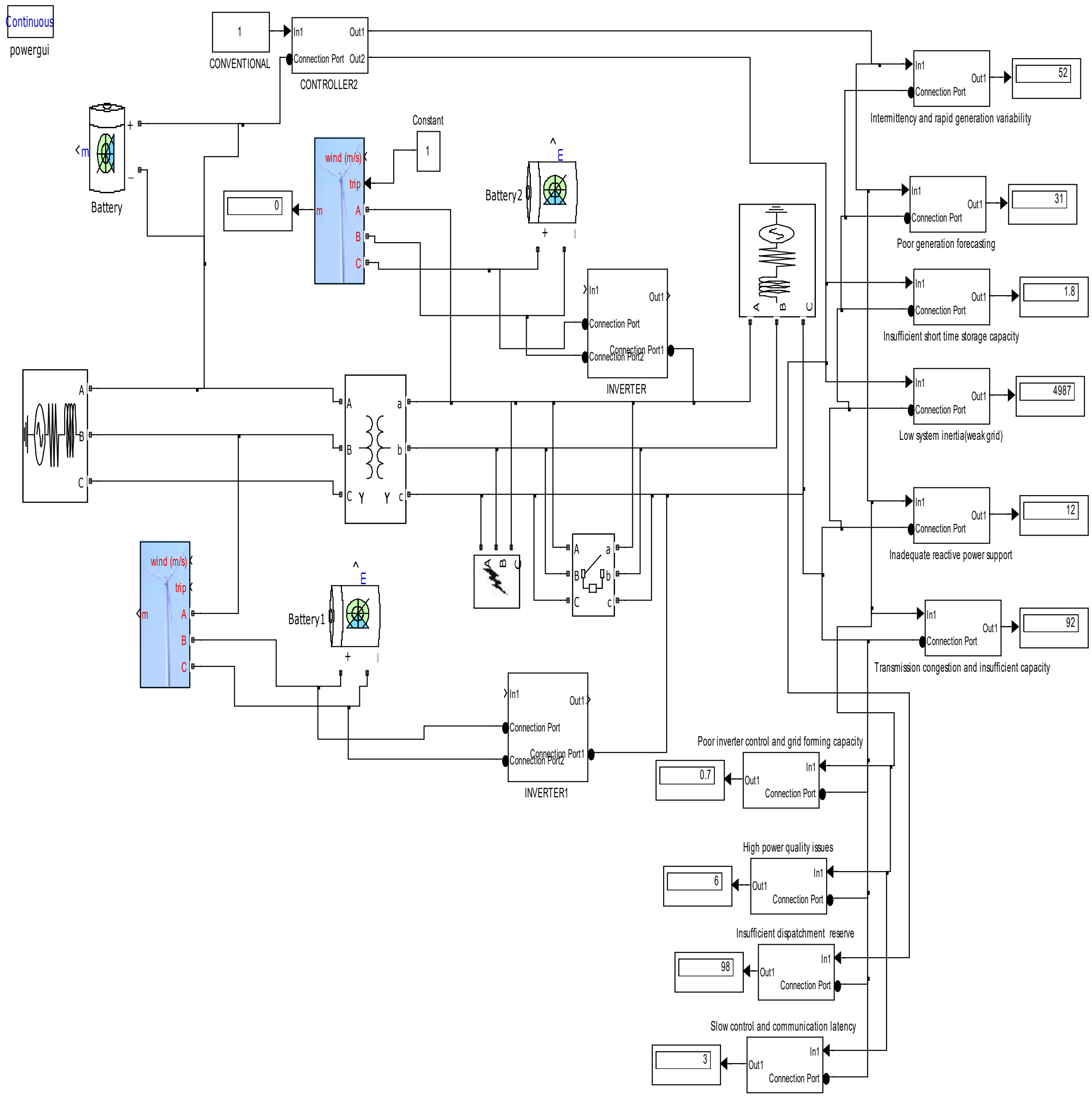

Fig 1 designed conventional SIMULINK model for optimal integration of renewable energy into the national grid for improved power supply

The results obtained were as shown in figures 7and 8.

To train ANN in the establish the causes of suboptimal integration of renewable energy into the national grid for unimproved power supply to improve consistent power supply

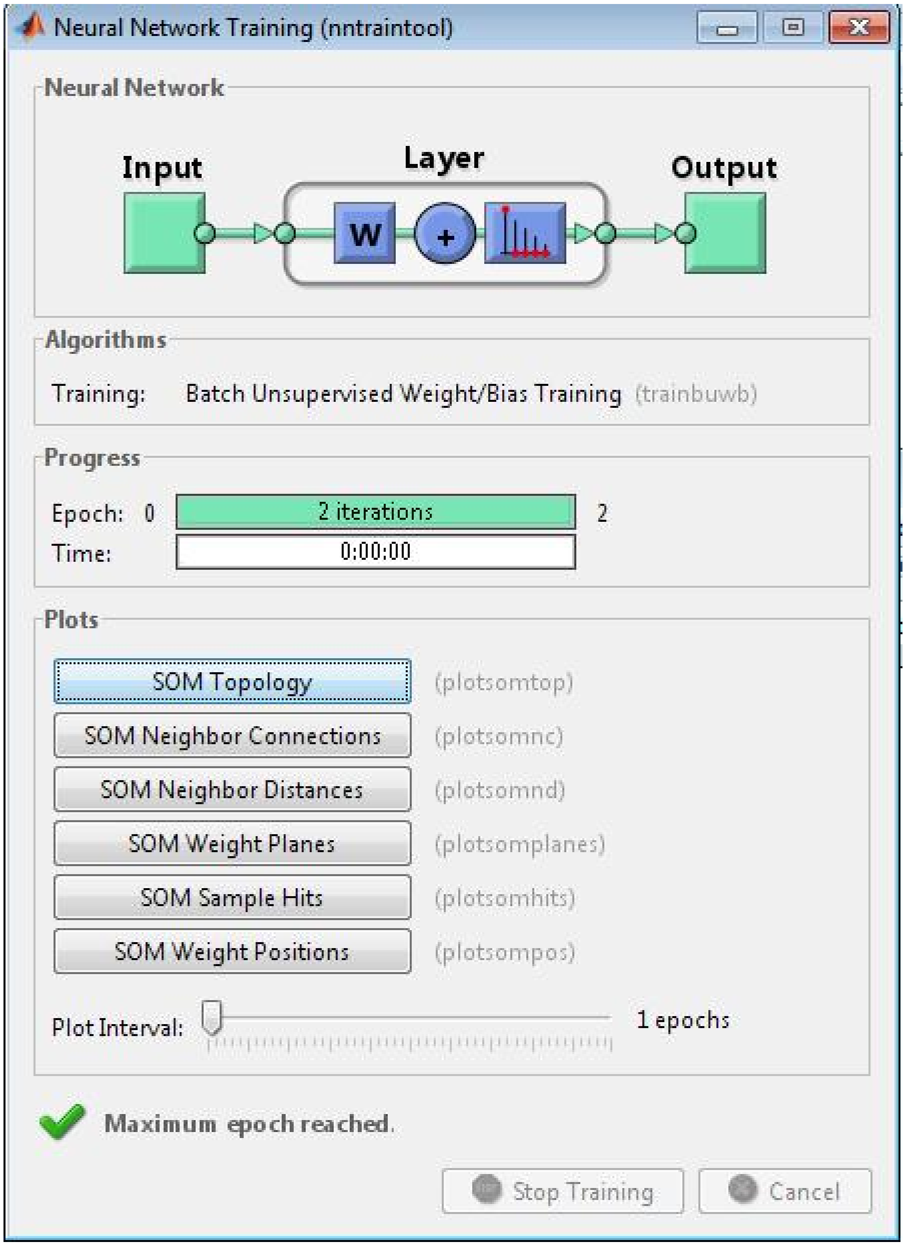

Fig 2 training tool for the established causes of unoptimal integration of renewable energy into the national grid for unimproved power supply to improve consistent power supply

RENEWABLE ENERGY INTO THE NATIONAL GRID FOR IMPROVED POWER SUPPLY USING

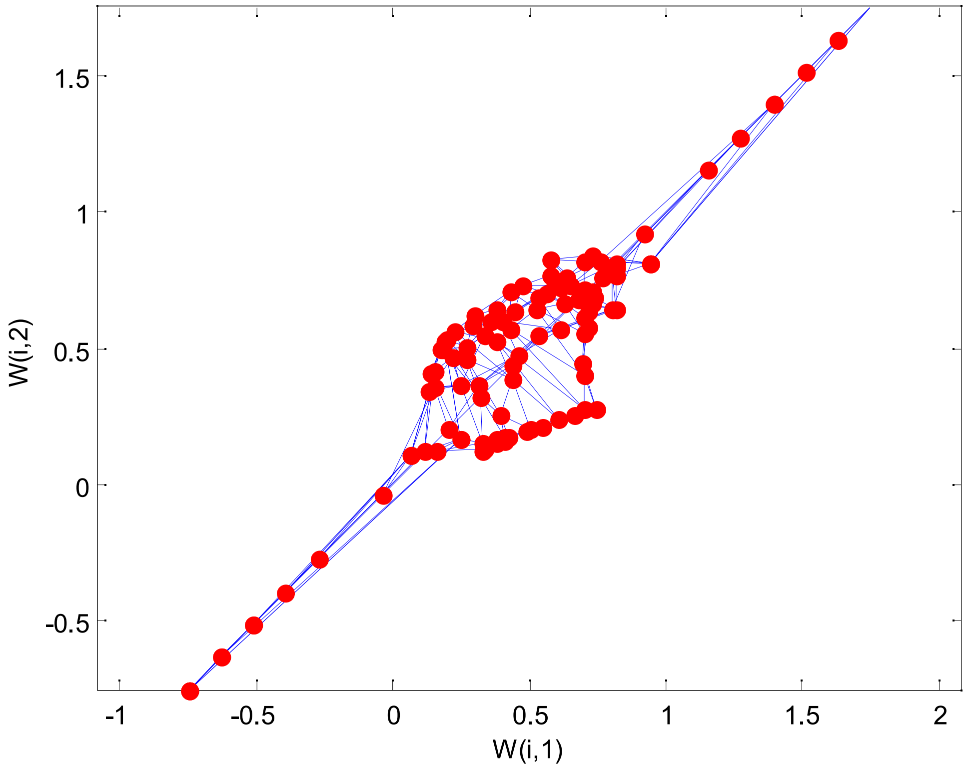

Fig 3 trained ANN in the established causes of unoptimal integration of renewable energy into the national grid for unimproved power supply to improve consistent power supply

ANN was trained eleven times in the eight causes of unoptimal integration of renewable energy into the national grid for unimproved power supply to improve consistent power supply 11 x 8 = 88 to give eighty eight neurons that looked exactly like human brain.

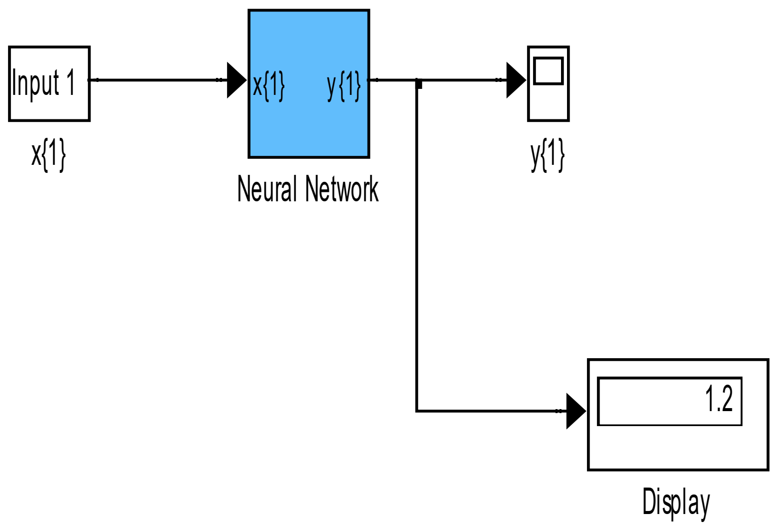

Fig 4 result obtained during training ANN in the established causes of unoptimal integration of renewable energy into the national grid for unimproved power supply to improve consistent power supply

To design a SIMULINK model for super capacitor

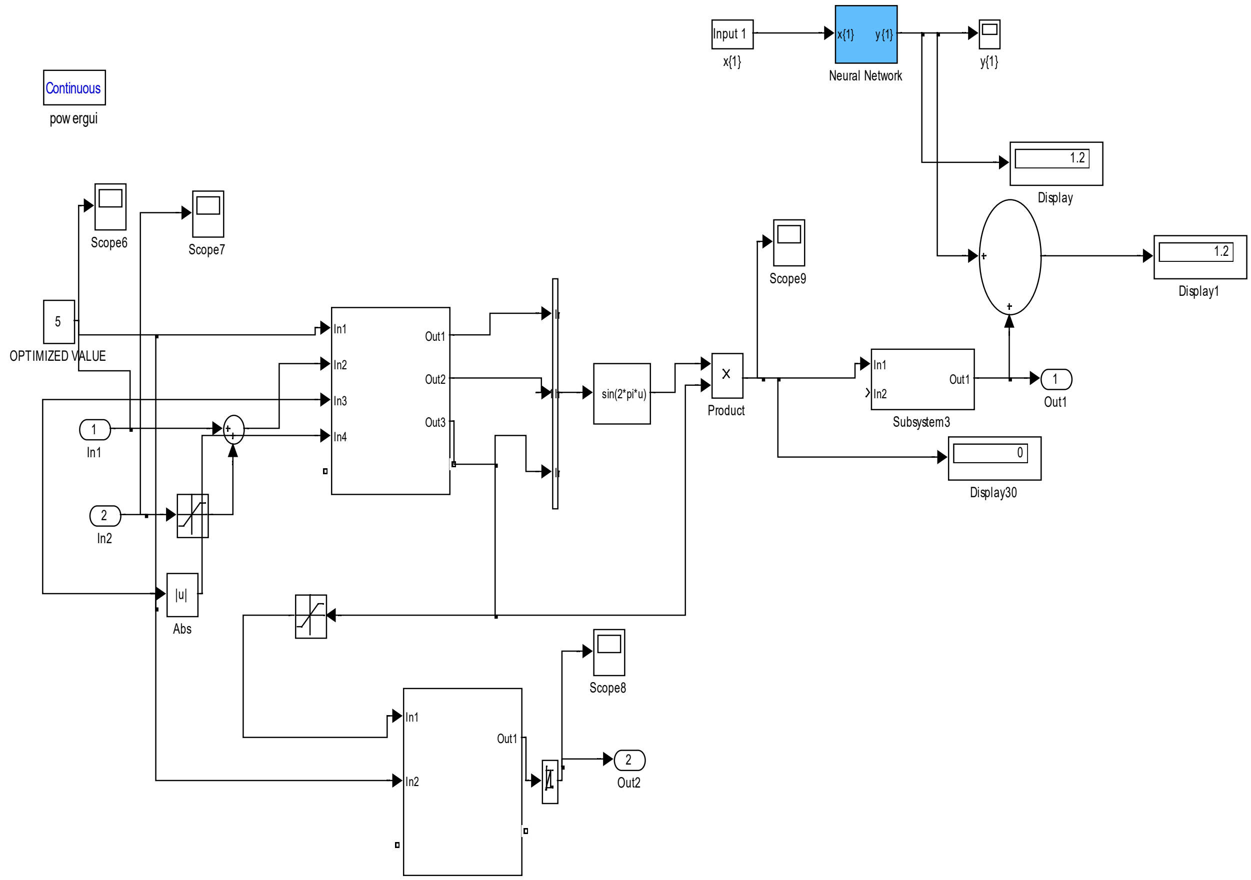

Fig 5 designed SIMULINK model for super capacitor

This was integrated to the designed conventional SIMULINK model for optimal integration of renewable energy into the national grid for improved power supply to give the results obtained in figures 7 and 8

To develop an algorithm that would implement the process

1. Characterize and establish the causes of unoptimal integration of renewable energy into the national grid for unimproved power supply
2. Identify intermittency and rapid generation variability
3. Identify Poor generation forecasting
4. Identify insufficient short time storage capacity
5. Identify Low system inertia(weak grid
6. Identify Inadequate reactive power support
7. Identify Transmission congestion and insufficient capacity
8. Identify Poor inverter control and grid forming capacity
9. Identify High power quality issues
10. Identify Insufficient dispatchment reserve

11. Identify Slow control and communication latency
12. Design a conventional SIMULINK model for optimal integration of renewable energy into the national grid for improved power supply and integrate 2 through 11.
13. Train ANN in the establish the causes of unoptimal integration of renewable energy into the national grid for unimproved power supply to improve consistent power supply
14. Design a SIMULINK model for super capacitor
15. Integrate 13 and 14
16. Integrate 15 into 12
17. Did the causes of unoptimal integration of renewable energy into the national grid for unimproved power supply minimize when 15 was integrated into 12
18. IF NO go to 16
19. IF YES go to 20
20. Optimal integration of renewable energy into the national grid for improved power supply
21. Stop
22. End

To design a SIMULINK model for optimal integration of renewable energy into the national grid for improved power supply using ANN based super capacitor

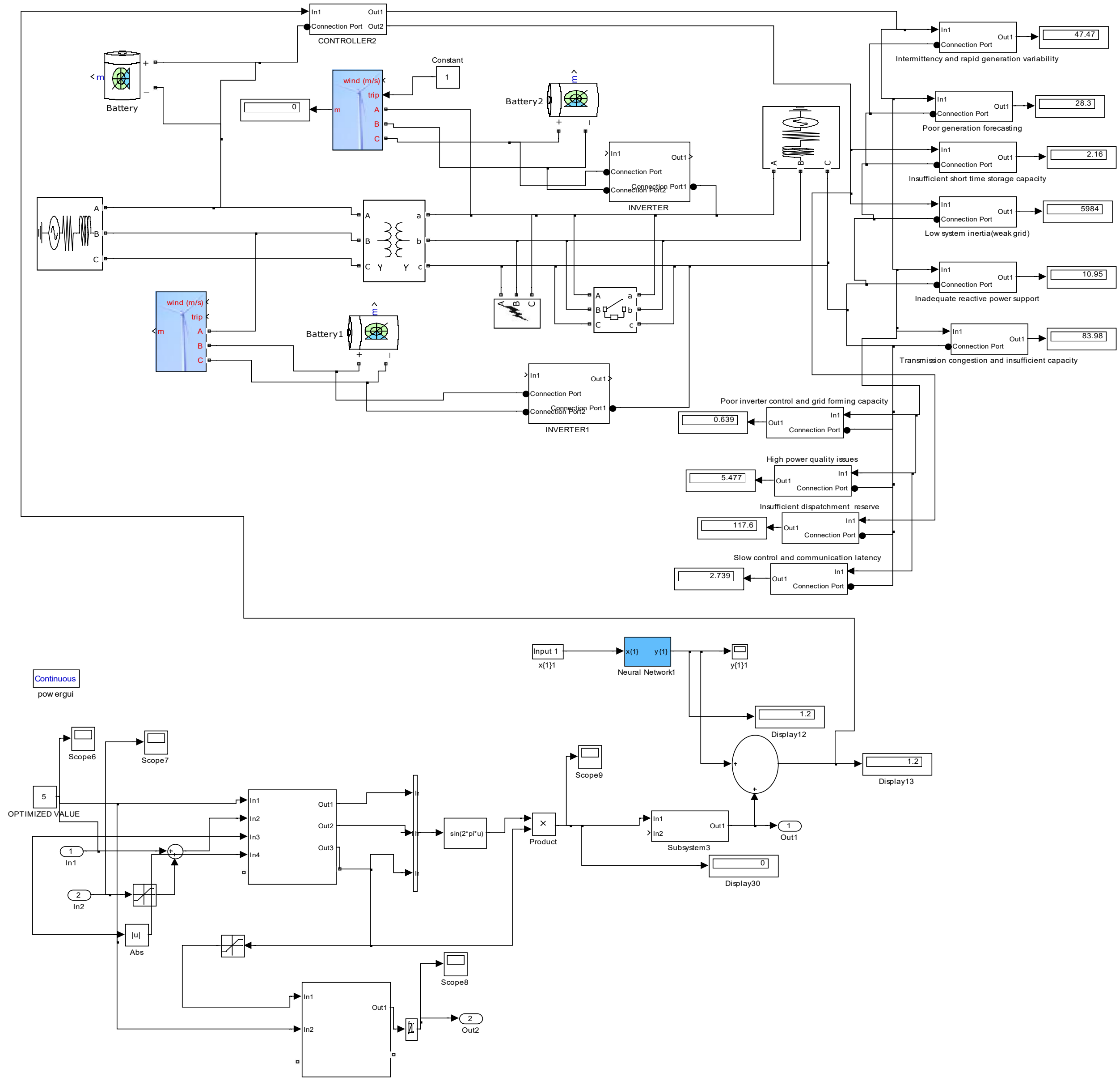

Fig 6 designed SIMULINK model for optimal integration of renewable energy into the national grid for improved power supply using ANN based super capacitor

The results obtained were conspicuously shown in figures 7 and 8

To validate and justify the percentage improvement in the reduction of causes of unoptimal integration of renewable energy into the national grid for unimproved power supply with and without ANN based super capacitor

To find percentage improvement in the reduction of intermittency and rapid generation variability causes of unoptimal integration of renewable energy into the national grid for unimproved power supply with ANN based super capacitor

Conventional intermittency and rapid generation variability =52MW

ANN based super capacitor intermittency and rapid generation variability= 47.5 MW

% improvement in the reduction of intermittency and rapid generation variability causes of unoptimal integration of renewable energy into the national grid for unimproved power supply with ANN based super capacitor=

Conventional intermittency and rapid generationV- ANN based super capacitor IRGV x 100%
Conventional intermittency and rapid generation variability 1

% improvement in the reduction of intermittency and rapid generation variability causes of unoptimal integration of renewable energy into the national grid for unimproved power supply with ANN based super capacitor=

52MW - 47.5 MW x !00%

52MW 1

% improvement in the reduction of intermittency and rapid generation variability causes of unoptimal integration of renewable energy into the national grid for unimproved power supply with ANN based super capacitor= 8.7%

To find percentage improvement in the reduction of Poor generation forecasting causes of unoptimal integration of renewable energy into the national grid for unimproved power supply with ANN based super capacitor

Conventional Poor generation forecasting =31MW

ANN based super capacitor Poor generation forecasting = 28.3 MW

% improvement in the reduction of Poor generation forecasting causes of unoptimal integration of renewable energy into the national grid for unimproved power supply with ANN based super capacitor=

Conventional Poor generation forecasting - ANN based super capacitor Poor G F x 100%
Conventional intermittency and rapid generation variability 1

% improvement in the reduction of Poor generation forecasting causes of unoptimal integration of renewable energy into the national grid for unimproved power supply with ANN based super capacitor=

31MW - 28.3 MW x !00%

31MW 1

% improvement in the reduction of Poor generation forecasting causes of unoptimal integration of renewable energy into the national grid for unimproved power supply with ANN based super capacitor= 8.7%

RESULTS AND DISCUSSION

Table 2 comparison of conventional and ANN based super capacitor intermittency and rapid generation variability that causes unoptimal integration of renewable energy into the national grid for unimproved power supply.

Time (days)	Conventional intermittency and rapid generation variability that causes unoptimal integration of renewable energy into the national grid for unimproved power supply(MW)	ANN based super capacitor intermittency and rapid generation variability that causes unoptimal integration of renewable energy into the national grid for unimproved power supply(MW)
1	52	47.5
2	52	47.5
3	52	47.5
4	52	47.5

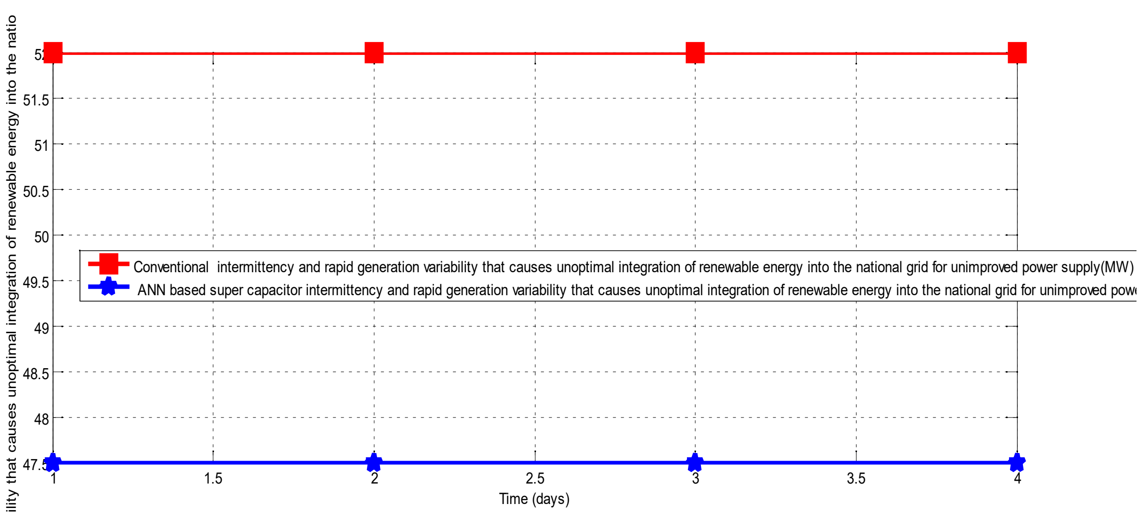

Fig 7 comparison of conventional and ANN based super capacitor intermittency and rapid generation variability that causes unoptimal integration of renewable energy into the national grid for unimproved power supply.

The conventional intermittency and rapid generation variability that causes unoptimal integration of renewable energy into the national grid for unimproved power supply was 52 MW. On the other hand when an ANN based super capacitor was integrated into the system, it instantly reduced to 47.5 MW.

Table 3 comparison of conventional and ANN based super capacitor intermittency and Poor generation forecasting that causes unoptimal integration of renewable energy into the national grid for unimproved power supply.

Time (days)	Conventional Poor generation forecasting that causes unoptimal integration of renewable energy into the national grid for unimproved power supply(MW)	ANN based super capacitor Poor generation forecasting that causes unoptimal integration of renewable energy into the national grid for unimproved power supply(MW)
1	31	28.3
2	31	28.3
3	31	28.3
4	31	28.3

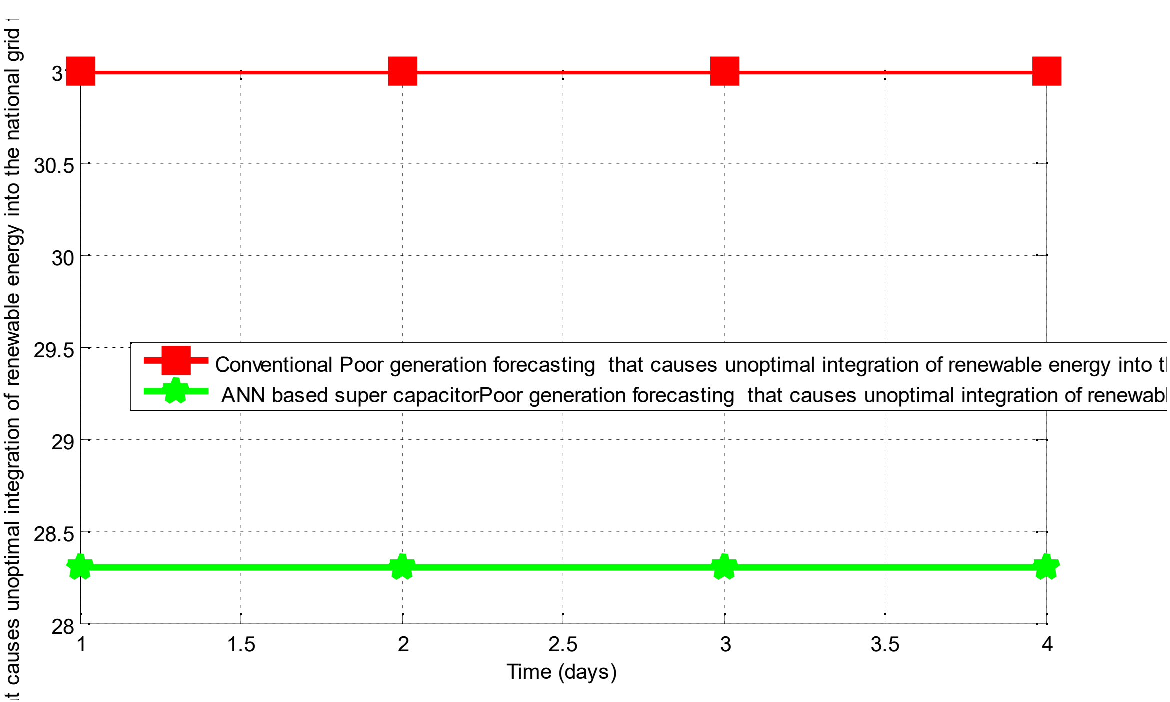

Fig 8 comparison of conventional and ANN based super capacitor intermittency and Poor generation forecasting that causes unoptimal integration of renewable energy into the national grid for unimproved power supply

The conventional intermittency and Poor generation forecasting that causes unoptimal integration of renewable energy into the national grid for unimproved power supply was 31MW. Meanwhile when an ANN based super capacitor was introduced into the system, it automatically reduced to28.3 MW. Finally, with these results obtained, it definitely meant that the percentage optimized integration of renewable energy into the national grid for improved power supply when an ANN based super capacitor was imbibed into the system was 8.7%.

CONCLUSION

This study has established that the optimal integration of renewable energy into the national grid can be significantly enhanced through the deployment of an Artificial Neural Network (ANN)-based super capacitor control system. By leveraging the adaptive learning capabilities of ANN, the proposed framework efficiently manages the charge–discharge cycles of the supercapacitor in response to fluctuating renewable generation and varying grid demand. The supercapacitor's high power density and rapid response characteristics effectively mitigate voltage fluctuations, provide fast frequency regulation, and reduce the adverse effects of renewable intermittency. Simulation results have shown that this intelligent hybrid approach improves grid stability, reduces voltage deviations, and enhances renewable energy utilization efficiency when compared to conventional storage control methods. The integration of ANN-based supercapacitor technology addresses critical challenges in Nigeria's power sector by ensuring a more reliable, stable, and sustainable electricity supply while supporting the transition towards a diversified and low-carbon energy mix. In conclusion, the adoption of ANN-driven supercapacitor systems for renewable integration presents a viable and scalable solution for improving national grid performance. Implementing this technology can help bridge the gap between energy demand and supply, enhance operational flexibility, and strengthen Nigeria's energy security in alignment with global sustainability goals. The results obtained were the conventional intermittency and rapid generation variability that causes unoptimal integration of renewable energy into the national grid for unimproved power supply was 52 MW. On the other hand when an ANN based super capacitor was integrated into the system, it instantly reduced to 47.5 MW and the conventional intermittency and Poor generation forecasting that causes unoptimal integration of renewable energy into the national grid for unimproved power supply was31MW. Meanwhile when an ANN based super capacitor was introduced into the system, it automatically reduced to28.3 MW. Finally, with these results obtained, it definitely meant that the percentage optimized integration of renewable energy into the national grid for improved power supply when an ANN based super capacitor was imbibed into the system was8.7%.

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