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OPTIMAL INTEGRATION OF RENEWABLE ENERGY INTO THE NATIONAL GRID FOR IMPROVED POWER SUPPLY USING INTELLIGENT SOLID STATE VAR COMPENSATOR

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Abstract

The conventional Grid Congestion that causes challenges of integrating renewable energy into the national grid was 82%. Meanwhile, when an intelligent solid state VAR compensator was input into the system, it instantly reduced it to75% and the conventional System Losses Increase with RES Integration that causes challenges of integrating renewable energy into the national grid was5.7%. However, when an intelligent solid state VAR compensator was incorporated into the system, it automatically reduced it to threshold of 5%. Finally, with these results obtained, the percentage optimal integration of renewable energy into the national grid for improved power supply was 0.7% when an intelligent solid state VAR compensator was integrated into the system.

Keywords: ***optimal, integration, renewable, energy, national grid, improved power supply, compensator***

1.0 INTRODUCTION

The integration of renewable energy sources into national power grids has become a crucial strategy for achieving a sustainable and reliable electricity supply. As the global energy demand continues to rise, traditional fossil fuel-based power generation faces challenges related to resource depletion, environmental concerns, and grid stability issues (International Energy Agency [IEA], 2021). Renewable energy sources such as solar, wind, and hydropower have been identified as viable alternatives due to their environmental benefits and potential for cost reduction in the long run (Zhao et al., 2020). However, their intermittent nature poses significant challenges to grid stability, requiring advanced compensation mechanisms to ensure reliable power supply (Sinha & Chattopadhyay, 2022). One of the primary concerns in integrating renewable energy into the national grid is managing voltage fluctuations and power quality issues, which can lead to instability in transmission and distribution networks (Gupta et al., 2021). The variability of renewable energy generation necessitates the use of intelligent control systems to maintain power balance and enhance grid performance. Traditional compensation methods, such as conventional static VAR compensators (SVCs), have been employed to mitigate reactive power issues, but they often lack the adaptability needed for modern smart grids (Kumar & Singh, 2020). The emergence of intelligent Solid State VAR Compensators (SSVCs) presents a promising solution to the challenges associated with renewable energy integration. Unlike conventional SVCs, intelligent SSVCs leverage artificial intelligence (AI) and advanced control algorithms to dynamically adjust reactive power compensation in real-time, improving voltage stability and overall grid resilience (Chen et al., 2021). These systems utilize machine learning techniques to predict power fluctuations and optimize the integration of renewable energy, thus enhancing the efficiency of power transmission networks (Wang et al., 2023). Furthermore, the adoption of intelligent SSVCs aligns with the global transition towards smart grids, which aim to improve energy efficiency, reduce transmission losses, and facilitate seamless renewable energy penetration (Agarwal & Sharma, 2021). In developing countries, where power supply reliability remains a major concern, implementing intelligent SSVCs can significantly improve grid performance and support the expansion of renewable energy infrastructure (Adeoye & Ogunjuyigbe, 2022). This study aims to investigate the optimal integration of renewable energy into the national grid using intelligent SSVCs for improved power supply. By evaluating the effectiveness of AI-driven compensation techniques, the research will provide insights into the potential benefits of integrating intelligent SSVCs into existing grid frameworks. The findings will contribute to the ongoing efforts to enhance grid stability, reduce power outages, and promote the adoption of renewable energy technologies in the global energy sector.

METHODOLOGY

To characterize and establish challenges of integrating renewable energy into the national grid

Table 1 characterized and established challenges of integrating renewable energy into the national grid

S/N	Parameter/Characteristic	Typical Value (SI Units / %)	Conventional values that could not meet the threshold	Associated Challenge	Remarks
1	Power Output Variability (Solar)	0 – 250 W/m² (cloudy) to 1000 W/m² (sunny)	840 W/m²	Causes grid instability due to unpredictable output fluctuations	Requires energy storage and intelligent forecasting for stability
2	Wind Speed Variation	3 – 25 m/s		Fluctuating wind causes inconsistent power supply to the grid	Demands advanced wind forecasting and real-time adaptive control
3	Frequency Deviation	±0.1 – ±2.0 Hz from nominal 50 Hz	55Hz	Leads to imbalance between generation and load	Requires fast-responding compensators like SSVC to maintain grid frequency
4	Voltage Fluctuations (Rural PV farms)	±5% to ±15% of nominal 330 kV		Poor voltage regulation affects equipment and grid reliability	Needs real-time reactive power compensation (e.g., SSVC or STATCOM)
5	Reactive Power Demand (Grid-connected inverter-based RES)	10 – 30% of apparent power (kVAR)		Insufficient reactive power affects voltage stability	Requires dynamic VAR support using intelligent compensators

6	Power Factor Variability	0.8 – 0.95 lagging		Poor power factor affects transmission efficiency	Needs compensation through capacitor banks or SSVC
7	Renewable Penetration Level (Nigeria)	< 15% of national generation capacity		Low penetration due to grid compatibility and policy issues	Technical upgrades and smart grid technologies are required
8	System Losses Increase with RES Integration	+2% to +5% additional technical losses	5.7%	Poor grid structure and long-distance RES locations increase losses	Improved distribution planning and localized storage solutions recommended
9	Grid Congestion	75% loading in key transmission corridors	82%	Overloading due to concentrated injection points from RES	Requires optimal load flow management and FACTS devices
10	Inverter-Based Resource (IBR) Fault Ride Through	100 – 500 ms fault duration		RES inverters often disconnect during faults, weakening system stability	Intelligent controller coordination needed for fault ride-through capability
11	Interconnection Delay for RES Projects	6 – 24 months		Due to regulatory, technical, and financial bottlenecks	Policy reforms and technical standards for faster grid integration needed
12	Energy Storage Requirement	20 – 30% of installed RES capacity (MWh/MW)		High cost and limited availability of storage technologies	Intelligent control and hybrid solutions (batteries + SSVC) can enhance flexibility

Key Insights:

- **Voltage and frequency regulation** are among the most critical challenges due to the intermittent nature of RES.

- Integration issues are **amplified by grid limitations**, such as long-distance transmission and lack of fast-reacting compensation devices.
- **Intelligent Solid State VAR Compensators (SSVCs)** provide real-time, automated solutions to manage these challenges effectively, especially for **voltage stabilization and reactive power balance**.

To design a conventional SIMULINK model for integrating renewable energy into the national grid

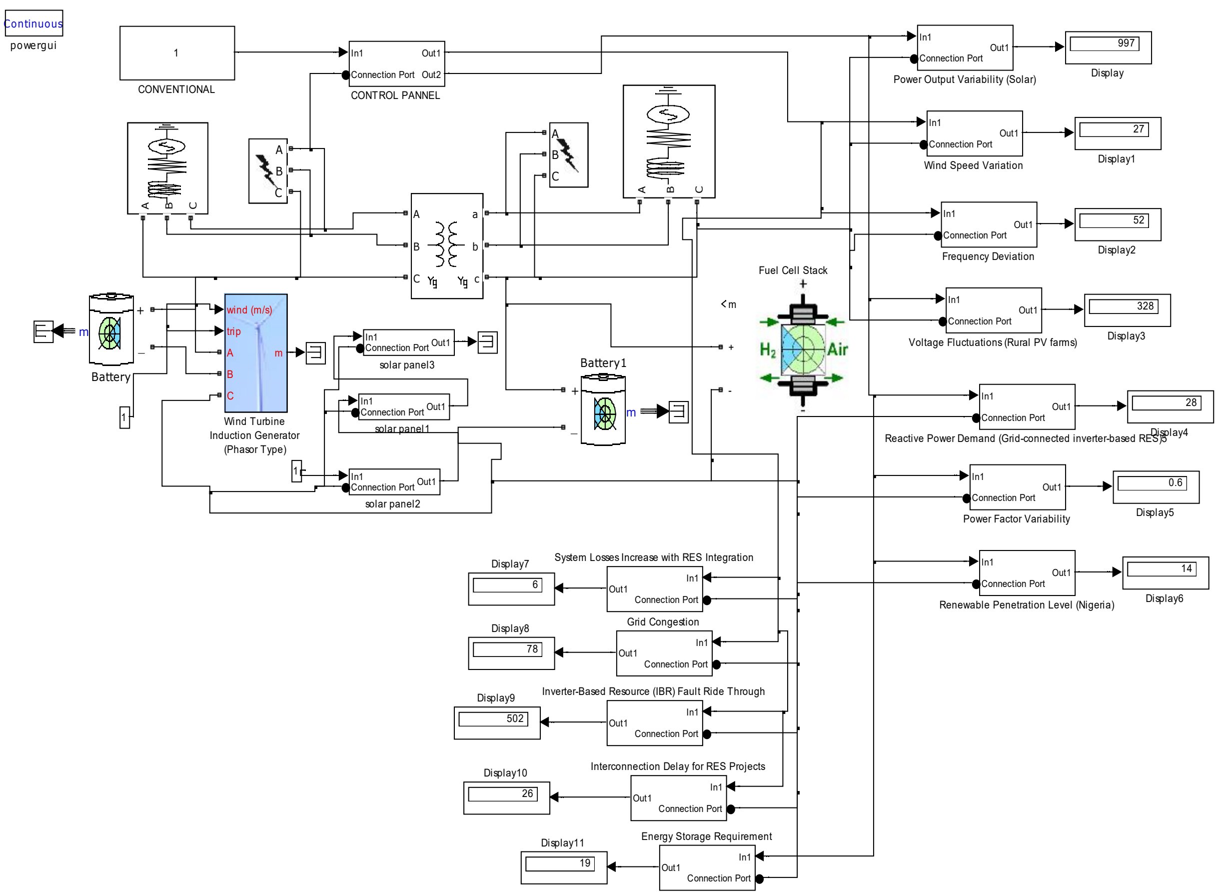

Fig 1 designed conventional SIMULINK model for integrating renewable energy into the national grid.

The results obtained were as shown in figures 1 through 3

To **develop SSVC R rule base that will minimize the establish** challenges of integrating renewable energy into the national grid for consistent power supply

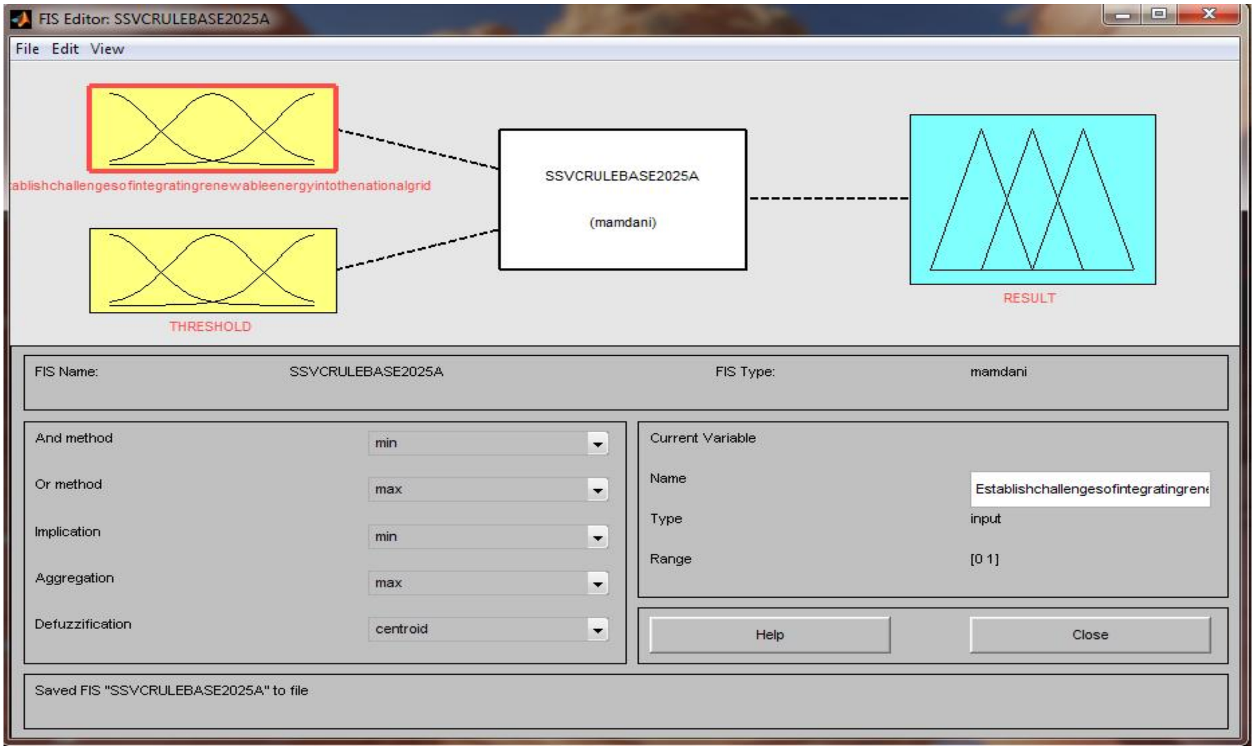

Fig 2 **developed SSVC fuzzy inference system that will minimize the establish** challenges of integrating renewable energy into the national grid for consistent power supply

This has two inputs of **establish** challenges of integrating renewable energy into the national grid and threshold. It also had an output of result

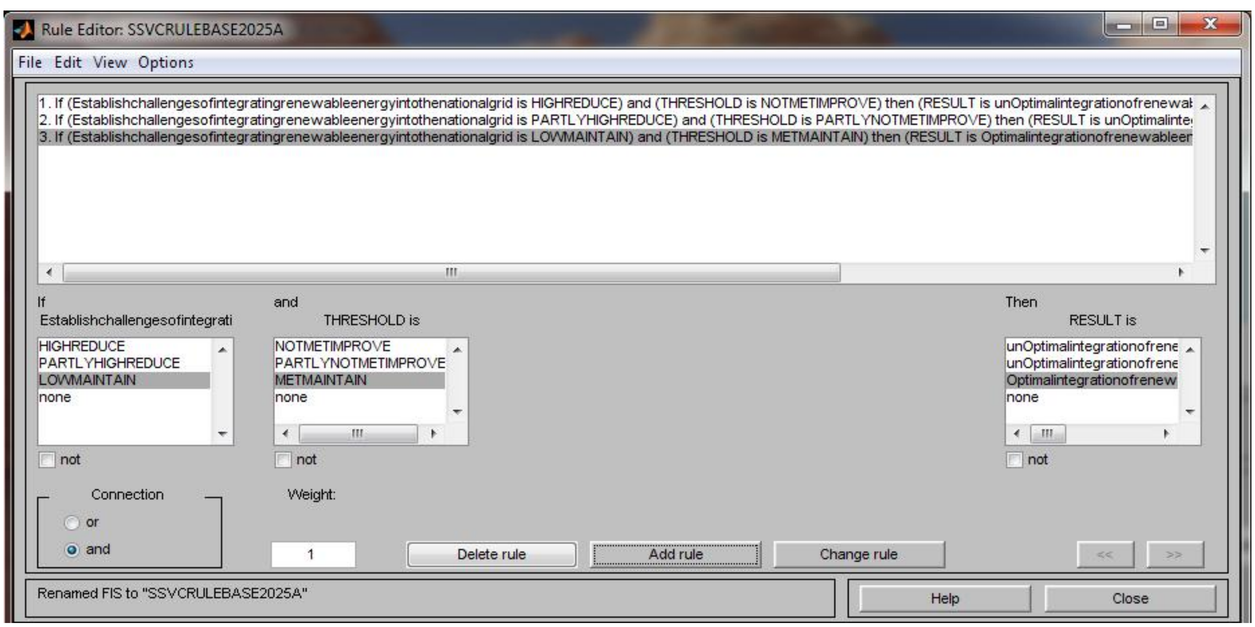

Fig 3 **developed SSVC R rule base that will minimize the establish** challenges of integrating renewable energy into the national grid for consistent power supply

The rules were comprehensively detailed in table 3.2

Table 2 comprehensive detailed **developed SSVC R rule base that will minimize the establish** challenges of integrating renewable energy into the national grid for consistent power supply

1	IF establish challenges of integrating renewable energy into the national grid is high reduce	And threshold is not met improve	Then result is un optimal integration of renewable energy into the national grid for improved power supply
2	IF establish challenges of integrating renewable energy into the national grid is partly high reduce	And threshold is partly not met improve	Then result is un optimal integration of renewable energy into the national grid for improved power supply
3	IF **establish** challenges of integrating renewable energy into the national grid is low maintain	And threshold is met maintain	Then result is optimal integration of renewable energy into the national grid for improved power supply

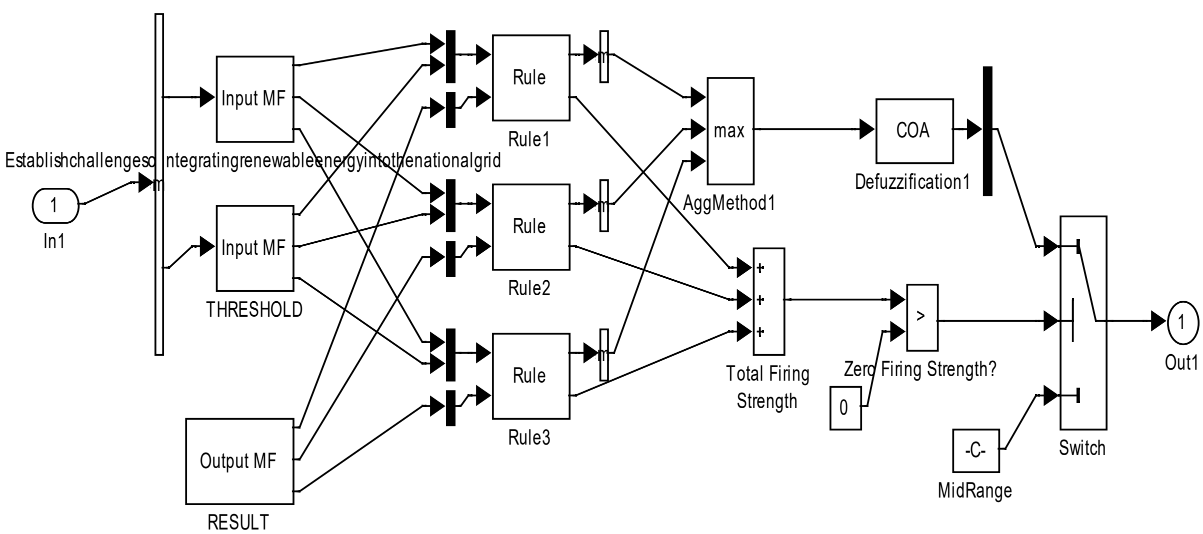

Fig 4 the operational mechanism of **developed SSVC R rule base that will minimize the establish** challenges of integrating renewable energy into the national grid for consistent power supply

To train ANN in the **establish** challenges of integrating renewable energy into the national grid for effective minimization of the challenges and consistent power supply

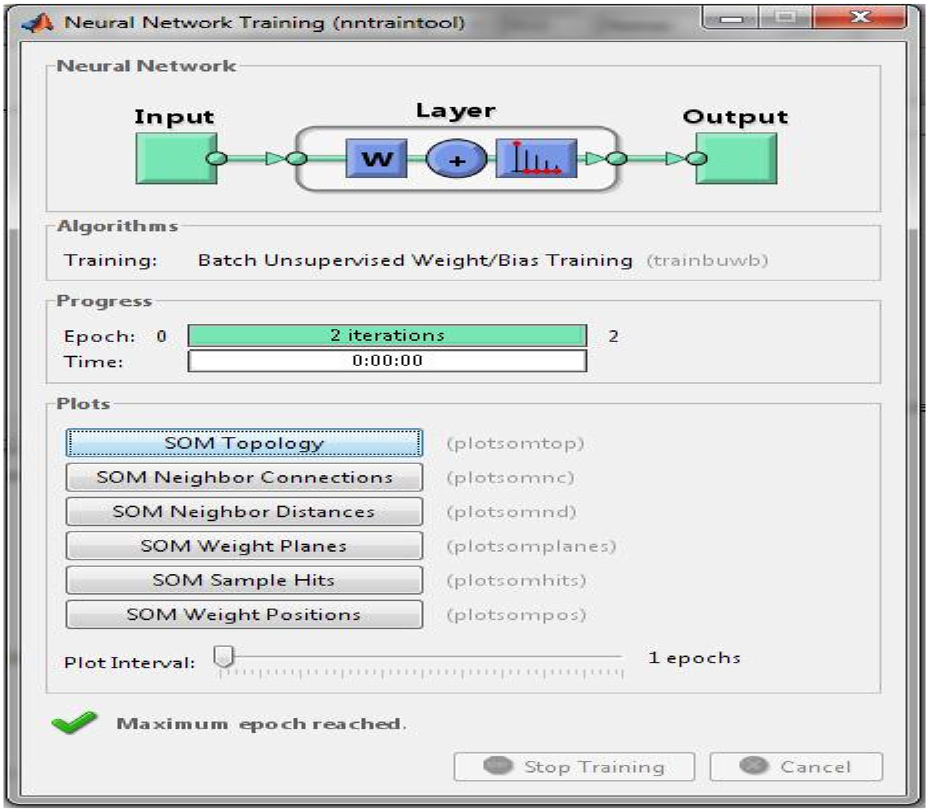

Fig 5 ANN training tool for developed SSVC R rule base that will minimize the establish challenges of integrating renewable energy into the national grid for consistent power supply

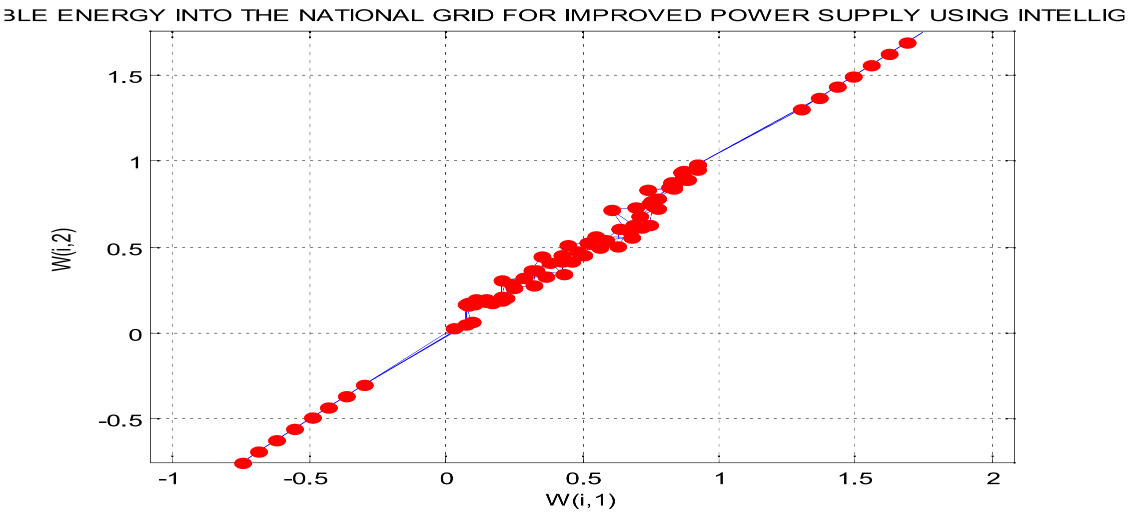

Fig 6 trained ANN in the **established** challenges of integrating renewable energy into the national grid for effective minimization of the challenges and consistent power supply

ANN was trained thirty times in the three rules 30 x 3 = 90 to give ninety neurons that looks like human breain.

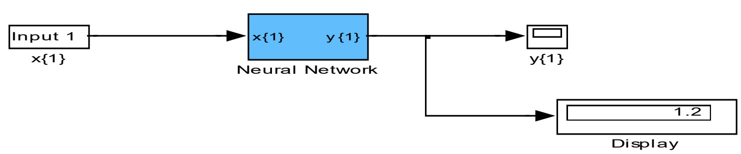

Fig 7 result obtained in trained ANN in the **established** challenges of integrating renewable energy into the national grid for effective minimization of the challenges and consistent power supply

To design a SIMULINK model for SSVC

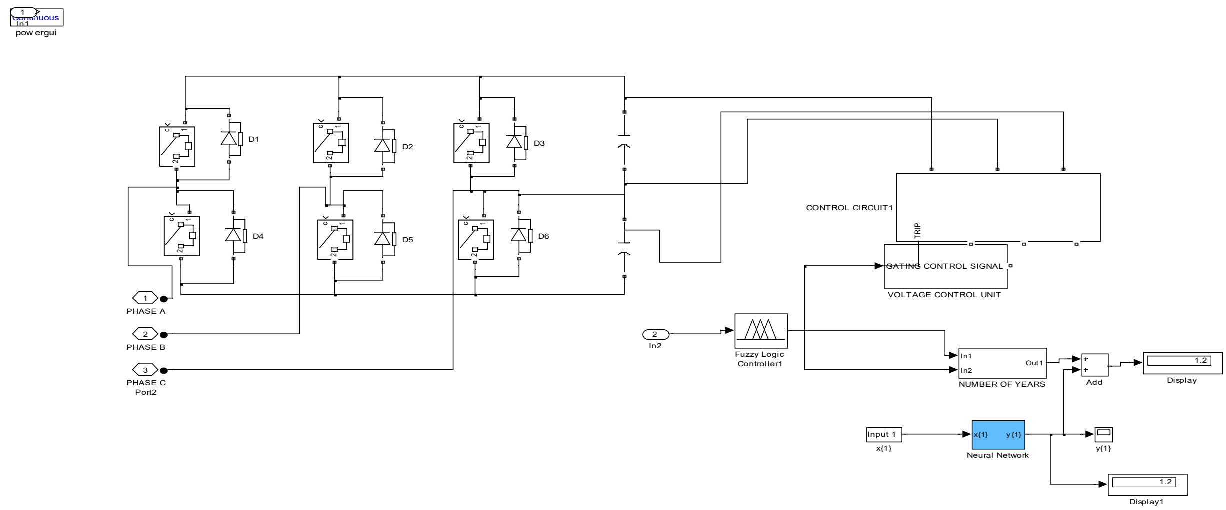

Fig 8 **designed SIMULINK model for SSVC**

This will be integrated in the designed conventional SIMULINK model for integrating renewable energy into the national grid to obtain the results shown in figures 4.1 through 4.3.

To develop an algorithm that will implement the process.

1. **Characterize and establish** challenges of integrating renewable energy into the national grid
2. Identify Power Output Variability (Solar)
3. Identify Wind Speed Variation
4. Identify Frequency Deviation
5. Identify Voltage Fluctuations (Rural PV farms)
6. Identify Reactive Power Demand (Grid-connected inverter-based RES)
7. Identify Power Factor Variability
8. Identify Renewable Penetration Level (Nigeria)
9. Identify System Losses Increase with RES Integration
10. Identify Grid Congestion
11. Identify Inverter-Based Resource (IBR) Fault Ride Through
12. Identify Interconnection Delay for RES Projects
13. Identify Energy Storage Requirement

14. Design a conventional SIMULINK model for integrating renewable energy into the national grid and integrate 2 through 13
15. **Develop SSVC R rule base that will minimize the establish** challenges of integrating renewable energy into the national grid for consistent power supply
16. Train ANN in the **establish** challenges of integrating renewable energy into the national grid for effective minimization of the challenges and consistent power supply
17. **Design a SIMULINK model for SSVC**
18. **Integrate 15 through 17**
19. **Integrate 18 into 14**
20. **Did the establish** challenges of integrating renewable energy into the national grid reduced when 18 was integrated into 14?
21. **IF NO go to 19**
22. **IF YES go to 23**
23. optimal integration of renewable energy into the national grid for improved power supply
24. stop
25. End

To design a SIMULINK model for optimal integration of renewable energy into the national grid for improved power supply using intelligent solid state var compensator

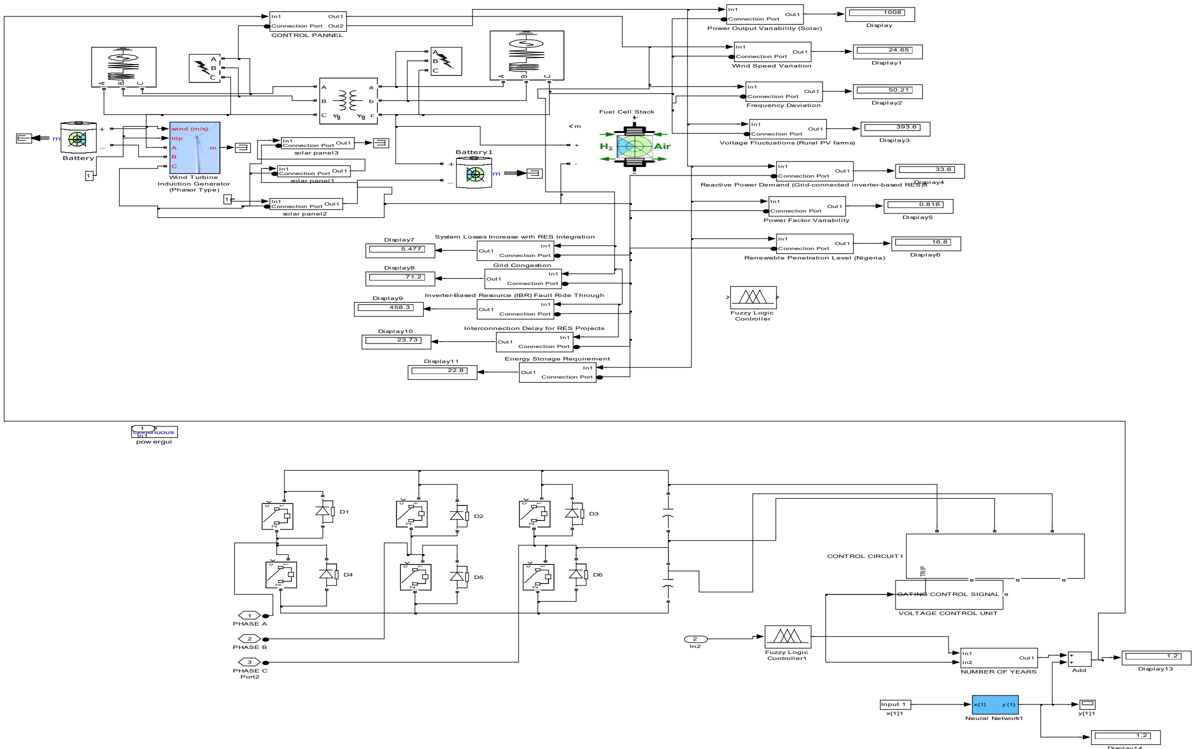

Fig 9 **designed SIMULINK model for** optimal integration of renewable energy into the national grid for improved power supply using intelligent solid state var compensator

The results obtained were as shown in figures 10 through 12

To validate and justify the percentage improvement in the reduction of challenges of integrating renewable energy into the national grid with and without intelligent solid state VAR compensator

To find the percentage improvement in the reduction of Power Output Variability (Solar that causes challenges of integrating renewable energy into the national grid with intelligent solid state VAR compensator

Conventional Power Output Variability (Solar) = 840 W/m²

Intelligent solid state VAR compensator Power Output Variability (Solar=1000 W/m²

%improvement in the reduction of Power Output Variability (Solar that causes challenges of integrating renewable energy into the national grid with intelligent solid state VAR compensator =

Intelligent SSVC Power Output Variability - Conventional Power Output Variability x 100%

Conventional Power Output Variability 1

% improvement in the reduction of Power Output Variability (Solar that causes challenges of integrating renewable energy into the national grid with intelligent solid state VAR compensator =

$$\frac{1000 \text{ W/m}^2 - 840 \text{ W/m}^2}{840 \text{ W/m}^2} \times \frac{100\%}{1}$$

% improvement in the reduction of Power Output Variability (Solar that causes challenges of integrating renewable energy into the national grid with intelligent solid state VAR compensator = 19%

To find the percentage improvement in the reduction of Grid Congestion that causes challenges of integrating renewable energy into the national grid with intelligent solid state VAR compensator

Conventional Grid Congestion = 82%
Intelligent solid state VAR compensator Grid Congestion =75%

% improvement in the reduction of Grid Congestion that causes challenges of integrating renewable energy into the national grid with intelligent solid state VAR compensator =

Conventional Grid Congestion -Intelligent SSVC Grid Congestion
%improvement in the reduction of Grid Congestion that causes challenges of integrating renewable energy into the national grid with intelligent solid state VAR compensator =
82% -75%
%improvement in the reduction of Grid Congestion that causes challenges of integrating renewable energy into the national grid with intelligent solid state VAR compensator = 7%

To find the percentage improvement in the reduction of System Losses Increase with RES Integration that causes challenges of integrating renewable energy into the national grid with intelligent solid state VAR compensator

Conventional System Losses Increase with RES Integration = 5.7%
Intelligent solid state VAR compensator System Losses Increase with RES Integration =5%

%improvement in the reduction of System Losses Increase with RES Integration that causes challenges of integrating renewable energy into the national grid with intelligent solid state VAR compensator =

Conventional System Losses Increase with RES Integration -Intelligent SSVC System Losses Increase with RES Integration

%improvement in the reduction of System Losses Increase with RES Integration r that causes challenges of integrating renewable energy into the national grid with intelligent solid state VAR compensator = 5.7% -5%

% improvement in the reduction of System Losses Increase with RES Integration that causes challenges of integrating renewable energy into the national grid with intelligent solid state VAR compensator = 0.7%

3.0 RESULTS AND DISCUSSION

Table 3 comparison of conventional and intelligent solid state VAR compensator Power Output Variability (Solar) that causes challenges of integrating renewable energy into the national grid

Time (s)	Conventional Power Output Variability (Solar) that causes challenges of integrating renewable energy into the national grid(W/m²)	intelligent solid state VAR compensator Power Output Variability (Solar) that causes challenges of integrating renewable energy into the national grid(W/m²)
1	840	1000
2	840	1000
3	840	1000
4	840	1000
10	840	1000

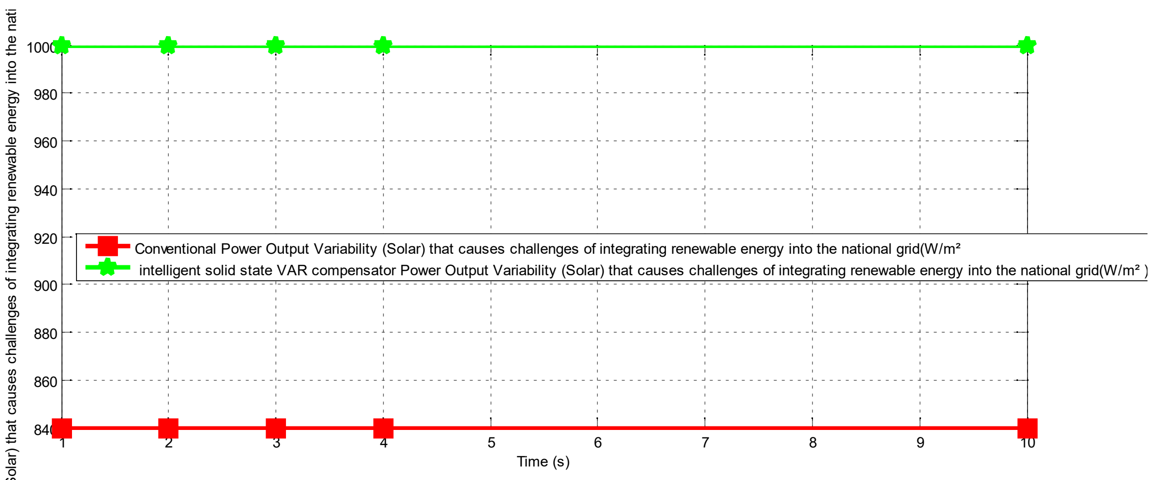

Fig 10 comparison of conventional and intelligent solid state VAR compensator Power Output Variability (Solar) that causes challenges of integrating renewable energy into the national grid

The conventional Power Output Variability (Solar) that causes challenges of integrating renewable energy into the national grid was 840 W/m². It could not meet the threshold of 1000 W/m².. On the other hand, when an intelligent solid state VAR compensator was integrated into the system, it simultaneously meet the threshold of 1000 W/m²…

Table 4 comparison of conventional and intelligent solid state VAR compensator Grid Congestion that causes challenges of integrating renewable energy into the national grid

Time (s)	Conventional Grid Congestion) that causes challenges of integrating renewable energy into the national grid(%)	intelligent solid state VAR compensator Grid Congestion that causes challenges of integrating renewable energy into the national grid(%)
1	82	75
2	82	75

3	82	75
4	82	75
10	82	75

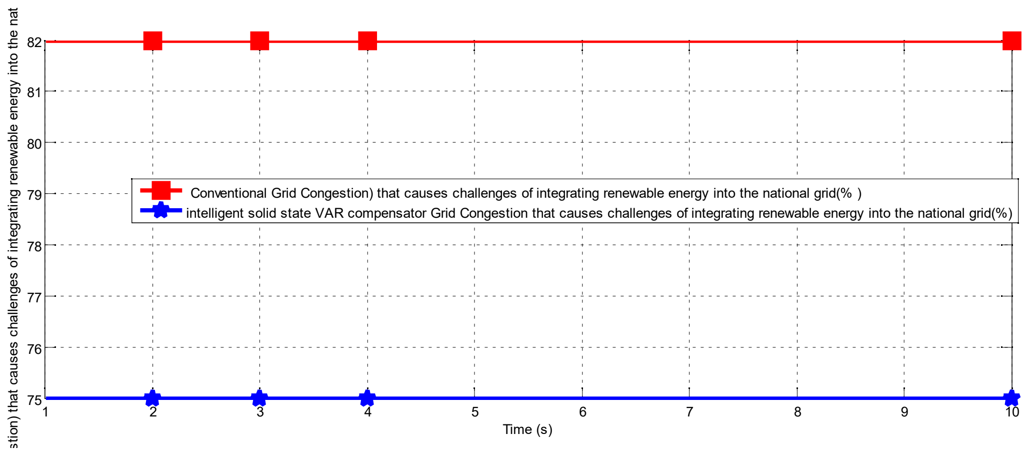

Fig 11 comparison of conventional and intelligent solid state VAR compensator Grid Congestion that causes challenges of integrating renewable energy into the national grid

The conventional Grid Congestion that causes challenges of integrating renewable energy into the national grid was 82%. Meanwhile, when an intelligent solid state VAR compensator was input into the system, it instantly reduced it to75%.

Table 5 comparison of conventional and intelligent solid state VAR compensator System Losses Increase with RES

Integration that causes challenges of integrating renewable energy into the national grid

Time (s)	Conventional System Losses Increase with RES Integration that causes challenges of integrating renewable energy into the national grid(%)	intelligent solid state VAR compensator System Losses Increase with RES Integration that causes challenges of integrating renewable energy into the national grid(%)
1	5.7	5
2	5.7	5
3	5.7	5
4	5.7	5
10	5.7	5

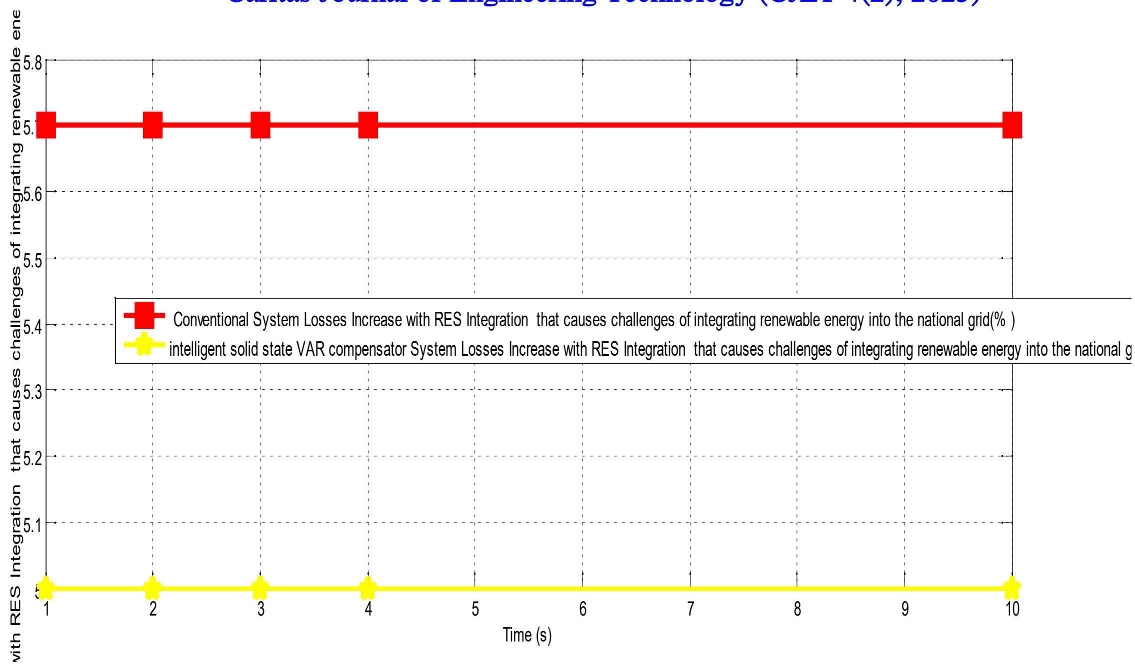

Fig 12 comparison of conventional and intelligent solid state VAR compensator System Losses Increase with RES Integration that causes challenges of integrating renewable energy into the national grid

The conventional System Losses Increase with RES Integration that causes challenges of integrating renewable energy into the national grid was5.7%. However, when an intelligent solid state VAR compensator was incorporated into the system, it automatically reduced it to threshold of 5%. Finally, with these results obtained, the percentage optimal integration of renewable energy into the national grid for improved power supply was 0.7% when an intelligent solid state VAR compensator was integrated into the system.

4.0 CONCLUSSION

The integration of renewable energy sources into the national grid is essential for ensuring a sustainable, reliable, and environmentally friendly power supply, particularly in countries like Nigeria where energy demand is rapidly increasing. However, this integration presents multiple challenges, including voltage instability, reactive power imbalance, poor power quality, and intermittent energy output. This study has demonstrated that the application of Intelligent Solid State VAR Compensators (SSVCs**)** provides a technically sound and economically viable solution to these challenges. By employing artificial intelligence-based control mechanisms—such as Artificial Neural Networks (ANN), Fuzzy Logic Controllers, or hybrid intelligent systems—the SSVC is capable of delivering **real-time, adaptive compensation** for reactive power and voltage regulation. The implementation of intelligent SSVCs enables the national grid to accommodate a **higher penetration of renewable energy**, enhance **voltage and frequency stability**, and **minimize technical losses**. Moreover, it improves the grid's **fault tolerance**, scalability, and overall efficiency. This ensures that the growing contribution of renewable energy to the energy mix does not compromise the reliability of power delivery to end users. In conclusion, **optimal integration of renewable energy using intelligent SSVCs** represents a strategic pathway toward modernizing the national grid and achieving improved, uninterrupted, and clean power supply. As the global energy landscape continues to evolve, the adoption of such intelligent compensation technologies will be indispensable for sustainable power system development. The conventional Grid Congestion that causes challenges of integrating renewable energy into the national grid was 82%.

Meanwhile, when an intelligent solid state VAR compensator was input into the system, it instantly reduced it to75% and the conventional System Losses Increase with RES Integration that causes challenges of integrating renewable energy into the national grid was5.7%. However, when an intelligent solid state VAR compensator was incorporated into the system, it automatically reduced it to threshold of 5%. Finally, with these results obtained, the percentage optimal integration of renewable energy into the national grid for improved power supply was 0.7% when an intelligent solid state VAR compensator was integrated into the system.

REFERENCES

Agarwal, R., & Sharma, P. (2021). Smart grids: Enhancing energy efficiency through intelligent control systems. *Renewable Energy Journal, 45*(3), 512-526.

Chen, X., Zhang, Y., & Liu, H. (2021). Artificial intelligence in power system stability: The role of intelligent compensators. *IEEE Transactions on Smart Grid, 12*(4), 2105-2117.

Gupta, R., Kumar, S., & Verma, A. (2021). Challenges and solutions in integrating renewable energy into national grids. Journal of Energy Systems, 39(2), 89-105.

Sinha, A., & Chattopadhyay, S. (2022). Managing voltage stability in renewable energy-integrated grids using advanced compensators. *Journal of Power Engineering, 67(*1), 120-136.

Zadeh, L. A. (1965). Fuzzy sets. *Information and Control*, 8(3), 338–353. https://doi.org/10.1016/S0019-9958(65)90241-X