

IMPROVING VOLTAGE STABILITY IN THE NIGERIAN 330KV TRANSMISSION NETWORK USING INTELLIGENT-BASED SUPER CAPACITOR

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Abstract: The reliability and efficiency of power transmission in Nigeria's 330kV network are significantly threatened by voltage instability, particularly under conditions of heavy load, fault disturbances, and network contingencies. This study presents an intelligence-based Super Capacitor (IBSC) technique as a strategic solution for enhancing voltage stability across the transmission network. The proposed method integrates advanced artificial intelligence algorithms with high-performance energy storage devices (super capacitors) to dynamically support voltage levels, compensate for reactive power, and mitigate transient disturbances. Simulation models developed in MATLAB/SIMULINK environment demonstrate that the intelligence-based super capacitor system provides a rapid response to voltage fluctuations and improves system resilience during voltage sag events. Comparative analysis with traditional compensation techniques reveals superior performance of the IBSC approach in maintaining voltage profiles within acceptable thresholds of 0.95 to 1.05 per unit volts. The research highlights the potential of intelligent energy storage integration in modern power systems and recommends the adoption of the proposed technique for improved voltage regulation, grid stability, and overall power system reliability in Nigeria's transmission network. The conventional faulty bus1 per unit volts was 0.93p.u.v. This caused an intermittent power supply in the transmission network. On the other hand, when an intelligent based super capacitor was integrated into the system, it instantly stabilized the voltage to 1.028p.u.v. And the conventional faulty bus 25 per unit volt was 0.947p.u.v, thereby caused consistent power failure. Meanwhile, when an intelligent-based super capacitor was imbued into the system, it simultaneously attained voltage stability of 1.04p.u.v, thereby enhancing a consistent power supply in the transmission network. Finally, with these results obtained, it showed that the average percentage improvement in voltage stability in the Nigerian 330kV transmission network when an intelligent-based super capacitor was integrated into the system was 10%.

Keywords: Improving, voltage, stability, Nigeria, 330kv, transmission, network, intelligent, super, capacitor.

I. INTRODUCTION

Voltage stability is a critical aspect of power system operation, particularly in high-voltage transmission networks where disturbances and fluctuating load demands can lead to voltage collapse, system blackouts, or equipment damage [Kundur et al., 1994]. In Nigeria, the 330kV transmission network forms the backbone of bulk power delivery across the nation. However, this network is increasingly challenged by issues such as aging infrastructures, rising electricity demand, limited reactive power support, and inadequate control strategies [NERC, 2020]. These challenges have resulted in frequent voltage instabilities that compromise the reliability and quality of power supply to end-users. Traditional methods for voltage regulation, such as capacitor banks, synchronous condensers, and static VAR compensators, have shown limitations in responding swiftly to dynamic voltage fluctuations [Ajjarapu & Lee, 1998]. With the rapid development of intelligent control systems and energy storage technologies, integrating intelligent-based super capacitors (IBSC) into the transmission grid offers a promising alternative. Super capacitors are known for their high-power density, rapid charging/discharging

capabilities, and long operational life, making them suitable for voltage support during transient conditions [Zhang et al., 2018]. When combined with intelligent algorithms such as artificial neural networks (ANN), fuzzy logic controllers, or adaptive control techniques, super capacitors can be optimally managed to provide real-time voltage regulation. Such integration enhances the ability of the transmission network to maintain voltage profiles within permissible limits of 0.95 to 1.05 per unit volts under varying load and fault conditions [Elnozahy & Salama, 2013]. This study, therefore, focuses on the application of intelligence-based super capacitor systems to improve voltage stability in the Nigerian 330kV transmission network, aiming to reduce incidences of voltage collapse, enhance grid reliability, and support modernization of the country’s power infrastructure.

II. METHODOLOGY

A. To characterize the Nigerian 330KV 30 bus transmission network

Bus and line codes of the Nigerian 330kv 30 bus transmission network were collected from the New Haven Enugu transmission station and characterized as listed in Table 1 below.

TABLE I: 330KV 30 BUS CHARACTERIZED DATA COLLECTED FROM NEWHAVEN ENUGU TRANSMISSION STATION.

Bus No	Bus Code	P.U. Volt	Ang Deg	Load MW	Load Mvar	Gen. MW	Gen. Mvar	Inj. Min	Inj. Max	Inj. Mvar
1	1	0.93	0	0.0	0.0	0.0	0.0	0	0	0
2	2	0.81	0	21.7	12.7	40.0	0.0	-40	50	0
3	0	1.0	0.0	2.4	1.2	0.0	0.0	0	0	0
4	0	1.27	0.0	7.6	1.6	0.0	0.0	0	0	0
5	2	1.01	0.0	94.2	19.0	0.0	0.0	-40	40	0
6	0	1.0	0.0	0.0	0.0	0.0	0.0	0	0	0
7	0	0.92	0.0	22.8	0.0	10.9	0.0	0	0	0
8	2	1.01	0.0	30.0	30.0	0.0	0.0	-30	40	0
25	0	1	0	0	0.0	0	0.0	0	0	0
26	0	1	0	3.5	2.3	0	0.0	0	0	0
28	0	1	0	0	0.0	0.0	0.0	0	0	0
29	0	0.62	0	2.4	0.9	0.0	0.0	0	0	0
30	0	0.86	0	10.6	1.9	0.0	0.0	0	0	0

B. To Run a Load Flow Analysis of the Nigerian 330KV 30 Bus Transmission Network

Newton-Raphson load flow was used to perform load flow analysis of the characterized 330kv 30 bus data to establish the faulty buses that could not attain the threshold per unit volt. After 100 iterative solutions, the results were printed as shown below.

TABLE II: ITERATIVE SOLUTION DID NOT CONVERGE

Maximum Power Mismatch = 0.192989 No. of Iterations = 101

No.	Mag.	Degree	MW	Mvar	MW	Mvar	Mvar
1	0.930	0.000	0.000	0.000	285.335	89.617	0.000
2	0.832	-6.938	21.700	12.700	40.000	-233.134	0.000
3	0.913	-11.992	2.400	1.200	0.000	0.000	0.000
4	0.909	-14.650	7.600	1.600	0.000	0.000	0.000
5	1.000	-22.162	94.200	19.000	0.000	182.421	0.000
6	0.934	-17.242	0.000	0.000	0.000	0.000	0.000
7	0.956	-19.938	22.800	10.900	0.000	0.000	0.000
8	0.963	-18.875	30.000	30.000	0.000	126.571	0.000

25	0.947	-23.150	0.000	0.000	0.000	0.000	0.000
26	0.930	-23.559	3.500	2.300	0.000	0.000	0.000
28	0.939	-18.009	0.000	0.000	0.000	0.000	0.000
29	0.932	-24.038	2.400	0.900	0.000	0.000	0.000
30	0.919	-25.158	10.600	1.900	0.000	0.000	0.000
Total			283.400	126.200	325.335	232.160	23.300

The faulty buses in the Nigerian 330KV 30 bus transmission network are buses 1, 2, 3, 4,6,25, 26, 28, 29, and 30. These buses cause instability in power supply in Nigeria because their per unit volts do not fall within 0.95 through 1.05p.u.v. The per-unit volts of these faulty buses are 0.930, 0.832, 0.913, 0.909, 0.934, 0.947, 0.930, 0.939, 0.932, and 0.919

C. To Develop a Conventional SIMULINK Model for Voltage Stability

A conventional SIMULINK model for voltage stability was developed and simulated to serve as a benchmark. This model helps in understanding the existing stability margins and the extent of compensation required.

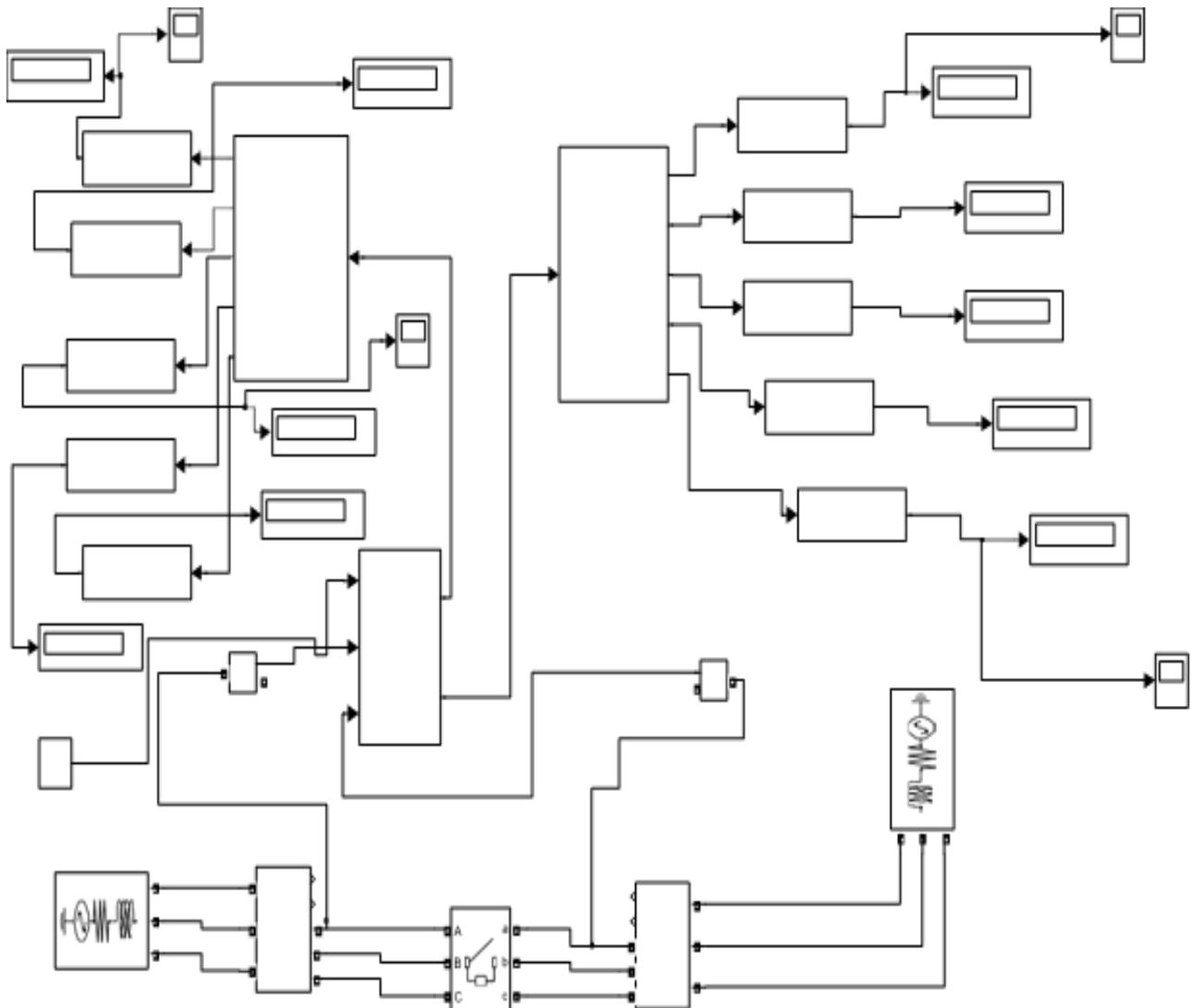


Fig. 1: Conventional SIMULINK model for voltage stability of the Nigerian 330KV transmission network.

The results obtained from the load flow analysis of the faulty buses were incorporated into the conventional network model controlled by a capacitor bank and simulated. The simulation results gave the exact faulty buses whose per-unit voltages could not attain stable voltages of 0.95 through 1.05 per unit volts. The comprehensive results obtained after simulations are shown in Tables 2, 3, and Figures. 6, 7.

D. To Train the ANN in the established faulty buses to attain stability

An artificial neural network was trained using data from the network operational conditions to create an intelligent controller for the super capacitor. This training was done using the ANN toolbox.

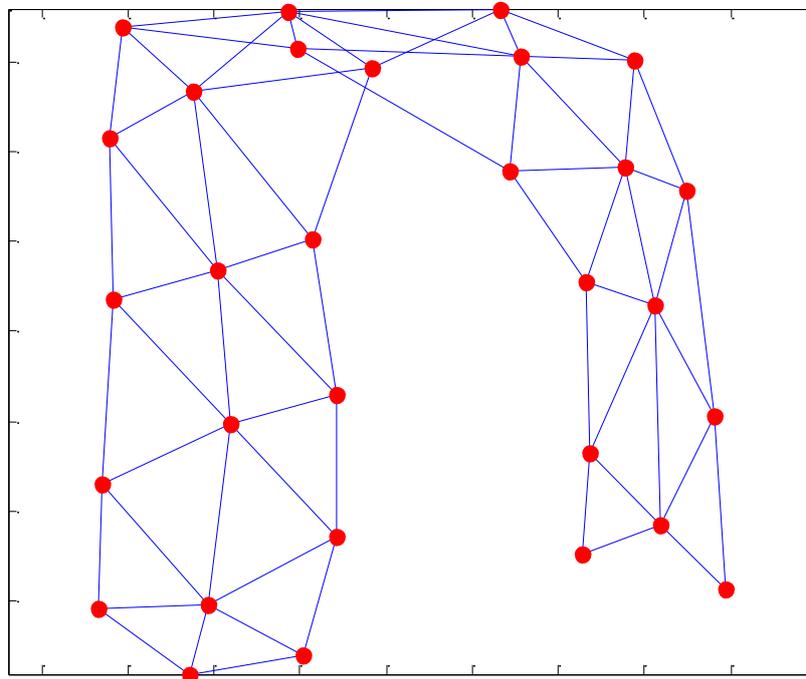


Fig.2: Trained ANN on the established faulty buses to attain stability.

In the figure.2, ANN was trained three times on ten faulty buses that could not attain a voltage stability of 0.95 through 1.05 per unit volts to attain voltage stability. The training of the ANN three times in the ten buses gave thirty neurons that look like the human brain and mimic human intelligence by doing what it is trained to do; $3 \times 10 = 30$ neurons that look like the human brain, as shown in the figure.

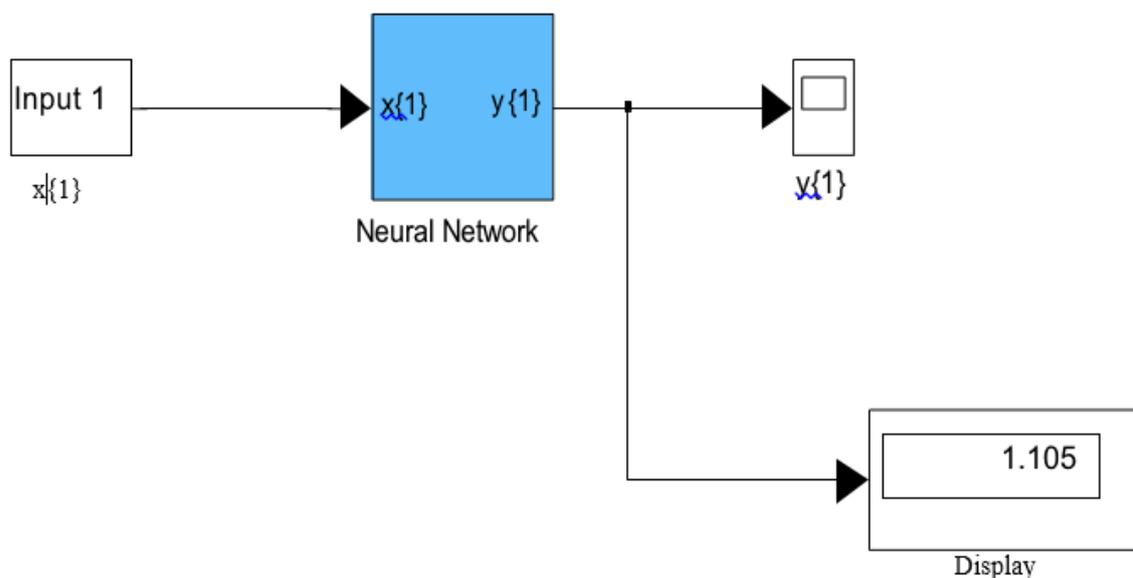


Fig. 3: Model obtained from trained ANN in the established faulty buses.

This model will be integrated into the super-capacitor model; having been trained with the network operation of the buses will enhance the efficacy of the buses attaining voltage stability in the Nigerian 330KV transmission network, thereby improving the performance of the network.

E. To Develop a SIMULINK Model for the Supercapacitor for Improving Voltage Stability of the Network

A supercapacitor (ultra-capacitor) is an energy storage device that bridges the gap between conventional capacitors and batteries. A supercapacitor can store and release energy quickly, making it ideal to provide a rapid response to voltage disturbances, preventing cascading failures and maintaining system integrity.

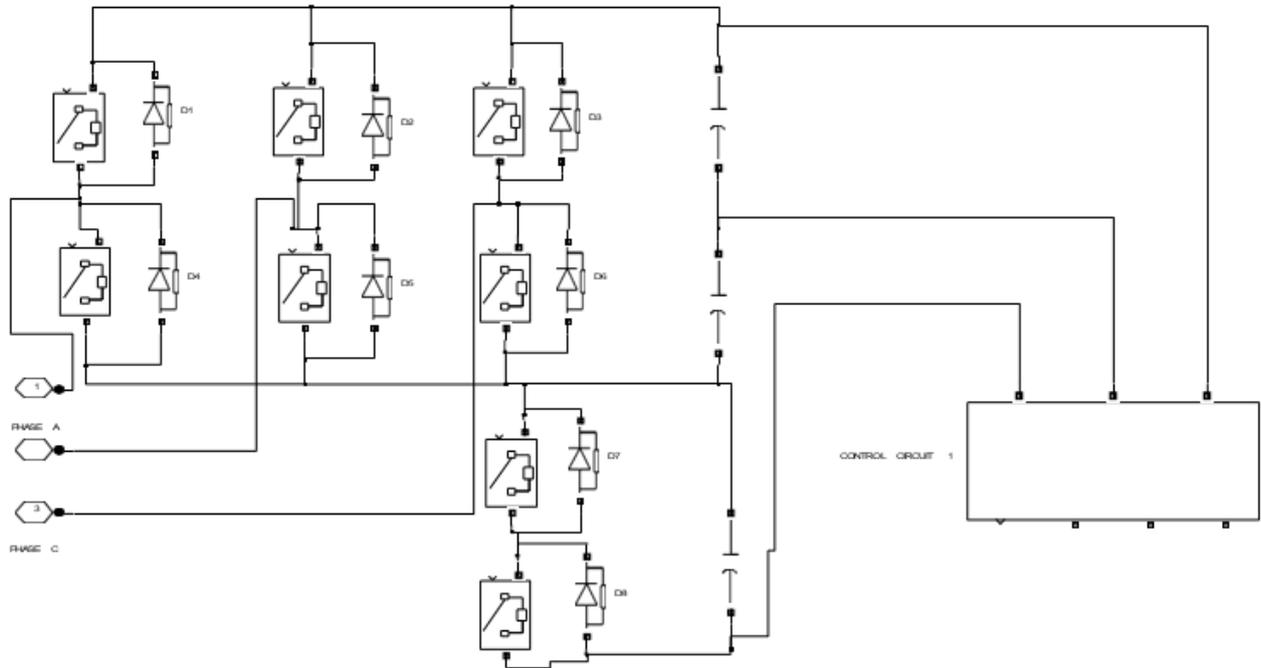


Fig.4: Developed SIMULINK model of the super-capacitor for improving voltage stability of the network.

This is designed in MATLAB/SIMULINK environment using ideal Simulink blocks for super-capacitor to boost the efficiency of faulty buses, attaining voltage stability in the Nigerian 330KV transmission network. Simulations were performed to attest to these claims.

F. To develop an algorithm that will implement the ‘Improvement of voltage stability in the Nigerian 330KV transmission network

1. Characterize voltage stability in the Nigerian 330kv transmission network.
2. Establish the faulty buses that their per unit volts could not attain voltage stability of 0.95 through 1.05 p.u. by running the load flow of the characterized data.
3. Identify bus1, 4. Identify bus2
5. Identify bus 3, 6. Identify bus4
7. Identify bus 6, 8. Identify bus25
9. Identify bus 26, 10. Identify bus28
11. Identify bus 29, 12. Identify bus30
13. Develop a conventional SIMULINK model for voltage stability in the Nigerian 330kv transmission network and integrate 3 through 12.
14. Train ANN in the established faulty buses so that their per unit volts could not attain voltage stability of 0.95 through 1.05
15. Design a SIMULINK model for Super-supercapacitor
16. Integrate 14 and 15
17. Integrate 16 into 13.

18. Did the identified faulty buses attain voltage stability of 0.95 through 1.05p.u.v when 16 was integrated to 13?
19. IF NO, go to 17.
20. IF YES, go to 21
21. Improved voltage stability in the Nigerian 330kv transmission network
22. Stop
23. End

G. To Integrate the Developed Supercapacitor SIMULINK Model and its ANN Controller Into the 33KV Model

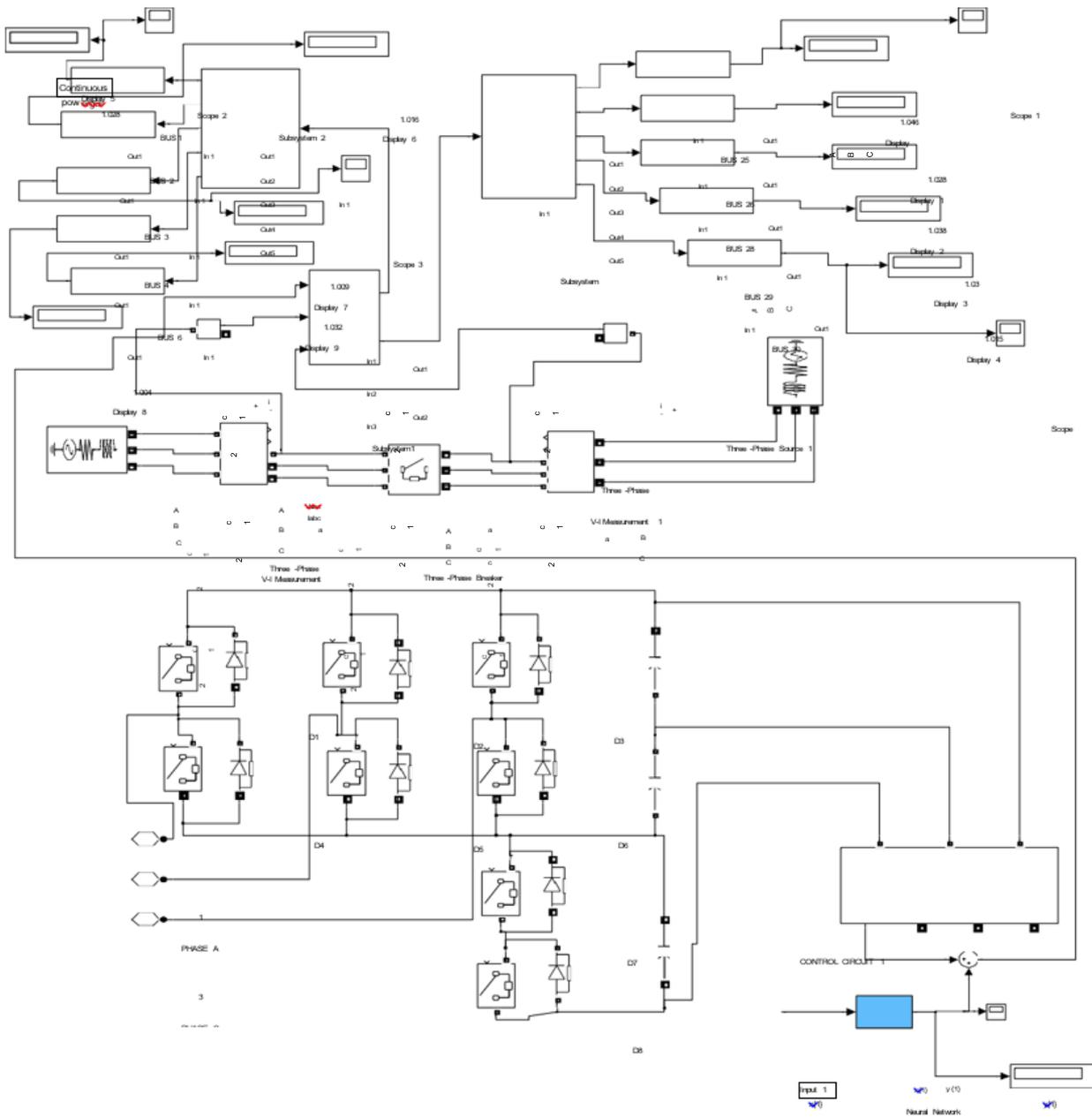


Fig.5. Integrated super capacitor SIMULINK model and its ANN controller into the 330KV model.

Finally, the ANN-controlled super capacitor model was integrated into the Nigerian 330kv transmission network model in place of the conventional capacitor bank. It is expected that this intelligence-based super capacitor (IBSC), leveraging the integration of an advanced artificial intelligence algorithm with high performance energy storage device (super capacitor),

will dynamically support voltage levels, compensate for reactive power, and mitigate transient disturbances. When Fig.5 was extensively simulated under various scenarios such as system faults and load changes, etc., the faulty buses that could not attain stability attained stability. Meanwhile, a comprehensive analysis of the results obtained after simulations is shown in Tables 2, 3, and figures. 6, 7.

H. To validate and justify the percentage improvement in the voltage stability of the Nigerian 330KV 30 bus transmission network with and without an intelligent-based super capacitor technique.

1. Conventional faulty bus1 in the Nigerian 330KV transmission network, (p.u.volts) = 0.930 Intelligent based super capacitor bus1 in the Nigerian 330KV transmission network, (p.u. volts) = 1.028% improvement in bus 1:

$$= \frac{\text{Intelligent based super capacitor p. u. v} - \text{Conventional p. u. v}}{\text{Conventional p. u. volts}} \times \frac{100}{1}$$

% Improvement in bus 1:

$$= \frac{1.028 - 0.930}{0.930} \times \frac{100}{1} = 10.5\%$$

% improvement in bus 1 when the intelligent super capacitor is incorporated = 10.5%

2. Conventional faulty bus 25 in the Nigerian 330KV transmission network, (p.u.volts) = 0.947 Intelligent based super capacitor bus 25 in the Nigerian 330KV transmission network, (p.u.volts) = 1.04% improvement in bus 25:

$$= \frac{\text{Intelligent based super capacitor p. u. v} - \text{Conventional p. u. v}}{\text{Conventional p. u. volts}} \times \frac{100}{1}$$

$$\% \text{ improvement in bus } \% 25 = \frac{1.04 - 0.947}{0.947} \times \frac{100}{1} = 9.8\%$$

% improvement in bus 25 when the intelligent super capacitor is incorporated = 9.8%

III. RESULTS AND DISCUSSION

A. Voltage Stability Improved

In this study, focusing on the Nigerian 330kV transmission network, the implementation of an intelligent super capacitor controlled by an ANN led to significant improvement in voltage levels when simulated under various conditions. For instance, at Bus 1, the voltage level improved from 0.930 per unit volt (p.u.v.) to 1.028 p.u.v. And at Bus 25, the voltage level increased from 0.947 p.u.v. to 1.04p.u.v. Both are achieving stability within the acceptable range of 0.95 to 1.05 per unit volts at 10% improvement. This indicates that an intelligence-based super capacitor (IBSC) at varying conditions of faults or load changes can maintain voltage stability, transient stability, improve voltage profile, and mitigate losses in the Nigerian grid. The implementation of this technique will not only boost a reliable power supply but also modernize and overcome problems of power infrastructure in Nigeria because of its scalability and flexibility to adopt renewable energy sources.

B. Comparison of results from the Conventional capacitor bank and Intelligent-based Super capacitor.

TABLE III. Comparison of Conventional and Intelligent-based super capacitor faulty bus1 per unit volts.

Time (s)	Conventional faulty bus 1 in the Nigerian 330KV transmission network (p.u. volts)	Intelligent-based super capacitor bus1 in the Nigerian 330KV transmission network, (p.u. volts)
1	0.930	1.028
2	0.930	1.028
3	0.930	1.028
4	0.930	1.028
10	0.930	1.028

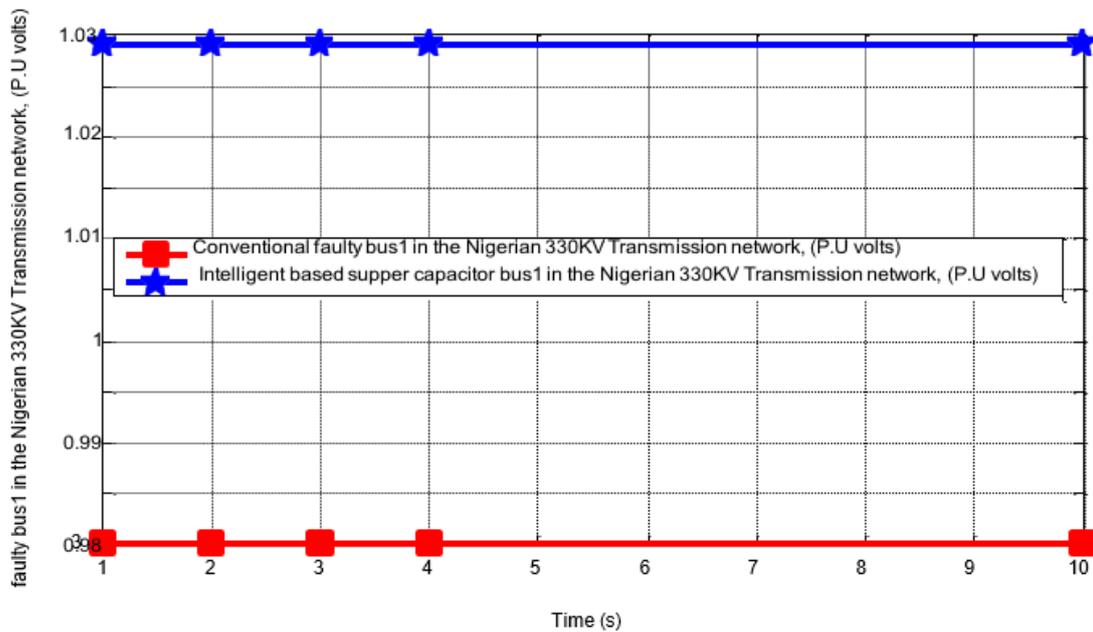


Fig.6. Comparison of Conventional and Intelligent-based super capacitor faulty bus1 per unit volts.

The conventional faulty bus 1 per unit volts was 0.930 p.u.v. thereby causing consistent power failure. Meanwhile, when the intelligent-based super capacitor was imbued into the system, it simultaneously attained voltage stability of 1.028p.u.v. Thereby enhances a consistent power supply in the transmission network.

TABLE IV. Comparison of Conventional and Intelligent-based super capacitor faulty bus25 per unit volts.

Time (s)	Conventional faulty bus25 in the Nigerian 330KV transmission network, (p.u. volts)	Intelligent-based super capacitor bus25 in the Nigerian 330KV transmission network, (p.u. volts)
1	0.947	1.04
2	0.947	1.04
3	0.947	1.04
4	0.947	1.04
10	0.947	1.04

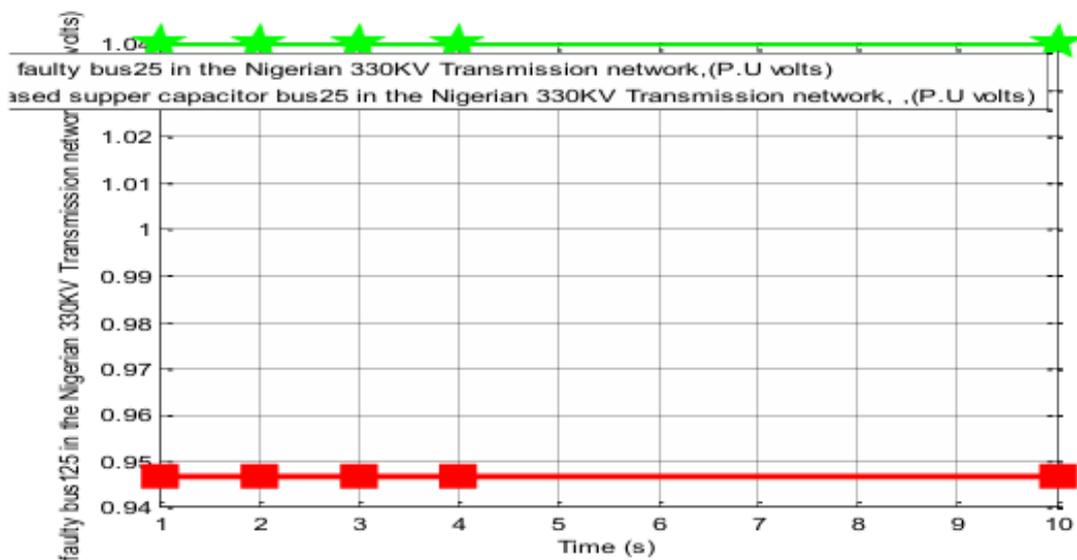


Fig.7: Comparison of Conventional and Intelligent-based super capacitor faulty bus25 per unit volts.

The conventional faulty bus 25 per unit volts was 0.947p.u.v. This caused intermittent power supply in the transmission network. On the other hand, when the intelligent- based super capacitor was integrated into the system, it instantly stabilized the voltage to 1.04p.u.v. giving a stable power supply. Finally, with these results obtained, it showed that the average percentage improvement in voltage stability in the Nigerian 330kv transmission network when the intelligent based super capacitor was integrated into the system was 10%.

IV. CONCLUSION

From the results of the simulations, the conventional faulty bus 25 per unit volts was 0.947p.u.v which caused consistent power failure. Meanwhile, when the intelligent based super capacitor was imbibed into the system, it instantly attained voltage stability of 1.04p.u.v. thereby enhancing steady power supply in the transmission network. This study has demonstrated that the integration of intelligent-based super capacitor (IBSC) technology offers a viable and effective approach to enhancing voltage stability in high-voltage transmission systems. By leveraging the fast response characteristics of super capacitors and the adaptive control capabilities of intelligent algorithms, the proposed system provides dynamic reactive power support, minimizes voltage fluctuations, and strengthens the resilience of the grid under various operating conditions. Simulation results confirm that the IBSC system significantly outperforms conventional voltage support devices by 10% in terms of response speed, control precision, and system recovery time following disturbances. The intelligent control framework also enables real-time decision-making, optimizing the use of stored energy and ensuring consistent voltage regulation across the network. Therefore, adopting intelligent-based super capacitors in Nigeria's 330kV transmission network is a strategic step toward achieving a more stable, reliable, and modernized power infrastructure. Future work may focus on the practical implementation of the system, cost-benefit analysis, and large-scale deployment strategies to further validate its real-world applicability and impact.

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