Improving Load Frequency Control in Renewable Rich Grid Using ANN Based ULTRACAPACITOR

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ABSTRACT

The persistent power failure that had crippled business activities were caused by the following factors that could not attain their respective thresholds. System Frequency Deviation, Rate of Change of Frequency Steady-State Frequency Error, Area Control Error Tie-Line Power Deviation, Frequency Recovery Time, Inertia Constant, Primary Frequency Reserve Margin, Secondary Reserve Availability that did not attain threshold, Renewable Power Forecast Error, Automatic Generation Control Delay, Governor Dead Band and Damping Ratio of Frequency Oscillations. This constant power failure in the country was subdued by introducing improving load frequency control in renewable rich grid using ANN based ULTRACAPACITOR. To perfectly achieve this, it was done in this manner, load frequency control in renewable rich grid was characterized and causes of poor load frequency control in renewable rich grid were established and a conventional SIMULINK model for load frequency control in renewable rich grid was designed. Then, ANN was trained in the causes of poor load frequency control in renewable rich grid for effective reduction of causes of poor load frequency control in renewable rich grid was designed, ANN was trained in the causes of poor load frequency control in renewable rich grid for effective reduction of causes of poor load frequency control in renewable rich grid and a SIMULINK model for ULTRACAPACITOR was designed. Later, algorithm that would implement the process was developed, a SIMULINK model for improving load frequency control in renewable rich grid using ANN based ULTRACAPACITOR was designed and the results were validated and justified. The results obtained were the conventional System Frequency Deviation that caused poor load frequency control in renewable rich grid was0.4 Hz. On the other hand, when an ANN based ULTRACAPACITOR was input into the system, it instantly reduced it to 0.2 Hz and the conventional Renewable Power Forecast Error that that caused poor load frequency control in renewable rich grid was18%. meanwhile, when an ANN based ULTRACAPACITOR was integrated into the system, it instantly reduced to13%. With these results obtained, the percentage improvement in load frequency control in renewable rich grid when an ann based ULTRACAPACITOR was input into the system was 5%.

Keywords, Improving, load, frequency, control, renewable, rich, grid, ANN, based, ULTRACAPACITOR

INTRODUCTION

The modern electric power system is undergoing a significant transformation due to the increasing integration of renewable energy resources such as wind and solar photovoltaic (PV) systems. The global transition toward clean energy is driven by environmental concerns, the need to reduce greenhouse gas emissions, and the depletion of fossil fuel reserves. While renewable energy sources offer substantial environmental and economic benefits, their intermittent and stochastic nature poses considerable challenges to power system stability, particularly in maintaining system frequency within acceptable limits (Kundur et al., 2004). Load Frequency Control (LFC) is an essential ancillary service in power systems that maintains the balance between power generation and load demand while ensuring that system frequency remains close to its nominal value. In conventional power systems dominated by thermal and hydroelectric plants, frequency regulation is achieved through governor action and automatic generation control (AGC). However, the increasing penetration of

renewable energy sources introduces fluctuations in power generation, leading to frequent imbalances between supply and demand, thereby affecting system frequency stability (Bevrani, 2014). Renewable-rich grids are characterized by reduced system inertia because many renewable energy generators are connected through power electronic converters rather than synchronous machines. This reduction in inertia causes the grid frequency to respond more rapidly to disturbances, making traditional LFC strategies less effective. Consequently, advanced control techniques and fast-response energy storage systems have become necessary to enhance frequency regulation performance in modern power systems (Milano et al., 2018). Among various energy storage technologies, ultra capacitors, also known as super capacitors, have attracted considerable attention due to their high power density, rapid charge-discharge capability, long cycle life, and high efficiency. Unlike conventional batteries, ultra capacitors can respond almost instantaneously to frequency deviations, making them suitable for short-term energy balancing and frequency support applications. Their ability to absorb and inject power quickly enables them to mitigate the effects of renewable energy intermittency and improve the dynamic performance of LFC systems (Miller & Simon, 2008). In addition to energy storage solutions, Artificial Neural Networks (ANNs) have emerged as powerful tools for power system control and optimization. ANN-based controllers possess self-learning, adaptive, and nonlinear mapping capabilities, allowing them to effectively handle the uncertainties and nonlinearities associated with renewable energy integration. Compared with conventional Proportional-Integral (PI) and Proportional-Integral-Derivative (PID) controllers, ANN controllers can provide improved dynamic response, reduced overshoot, and faster settling times under varying operating conditions (Haykin, 2009). The integration of ANN-based control strategies with ultra capacitor energy storage systems presents a promising approach for enhancing load frequency control in renewable-rich power grids. By utilizing ANN algorithms to intelligently coordinate ultra capacitor charging and discharging operations, frequency deviations can be minimized, and overall system stability can be improved. Several studies have demonstrated that intelligent control techniques combined with fast-acting energy storage devices significantly outperform traditional control methods in maintaining frequency stability under renewable generation fluctuations and load disturbances (Bevrani et al., 2019). Despite the progress achieved in this area, challenges remain regarding the optimal design and implementation of ANN-based ultra capacitor control systems for large-scale renewable-rich grids. Variations in renewable energy output, changing load patterns, and system uncertainties necessitate the development of more robust and adaptive frequency control strategies. Therefore, this study focuses on improving load frequency control in renewable-rich grids using an ANN-based ultra capacitor system to enhance frequency regulation, system reliability, and grid stability under varying operating conditions. The findings of this study are expected to contribute to the advancement of intelligent energy management systems and support the reliable integration of renewable energy resources into modern power networks.

METHODOLOGY

To characterize and establish the causes of poor load frequency control in renewable rich grid

Table 1 characterized and established causes of poor load frequency control in renewable rich grid

LFC Performance Metric	**Symbol**	**Typical Acceptable Threshold**	**Poor LFC Condition**	**Conventional** causes of poor load frequency control in renewable rich grid	**SI Unit**	**Primary Causes in Renewable-Rich Grids**
System Frequency Deviation	Δf	$\|\Delta f\| \leq 0.05$ Hz (normal operation)	$\|\Delta f\| > 0.2$ Hz sustained	0.4 Hz	Hz	Renewable intermittency, insufficient reserves, forecasting errors
Rate of Change of Frequency	RoCoF (df/dt)	≤ 0.5 Hz/s	> 1 Hz/s	3 Hz/s	$Hz \cdot s^{-1}$	Low system inertia due to displacement of

						synchronous generators
Frequency Nadir After Disturbance	f_nadir	>49.5 Hz (50-Hz systems)	<49.0 Hz	47 Hz	Hz	Insufficient fast frequency response (FFR), low inertia
Steady-State Frequency Error	e_ss	<0.02 Hz	>0.05 Hz	0.07 Hz	Hz	Poor governor action, inadequate secondary control
Area Control Error	ACE	Near 0 MW	Persistent large ACE (>100 MW depending on area size)	102 MW	MW	Renewable forecast uncertainty, tie-line power fluctuations
Tie-Line Power Deviation	ΔP_tie	<1–2% of scheduled interchange	>5% deviation	7%	MW	Variable renewable generation across interconnected areas
Frequency Recovery Time	T_rec	<30 s	>60–120 s	122	s	Slow AGC response, communication delays
Inertia Constant	H	≥4–6 s (large interconnected systems)	<2 s	4s	s	High penetration of inverter-based resources
Primary Frequency Reserve Margin	PFR	≥3–5% of system load	<2%	4%	MW	Retirement of conventional units, inadequate reserve procurement
Secondary Reserve Availability	SR	≥5–10% of renewable penetration	Insufficient reserve deployment	12%	MW	Forecast errors, reserve scarcity
Renewable Power Forecast Error	ε_RE	<5% (day-ahead)	>10–15%	18%	% (dimensionless)	Weather uncertainty, poor forecasting tools
Automatic Generation Control Delay	τ_AGC	<2 s	>10 s	12s	s	Communication latency, cyber-physical limitations
Governor Dead Band	DB	≤0.036 Hz	>0.06 Hz	008Hz	Hz	Improper governor settings reducing frequency sensitivity
Damping Ratio of Frequency	ζ	>0.2	<0.1	0.3	Dimensionless	Weak system damping, inverter-control

Oscillations						interactions
Fast Frequency Response Availability	FFR	≥10–20% of renewable capacity	Insufficient FFR	22	MW	Lack of battery storage or synthetic inertia support

To design a conventional SIMULINK model for load frequency control in renewable rich grid

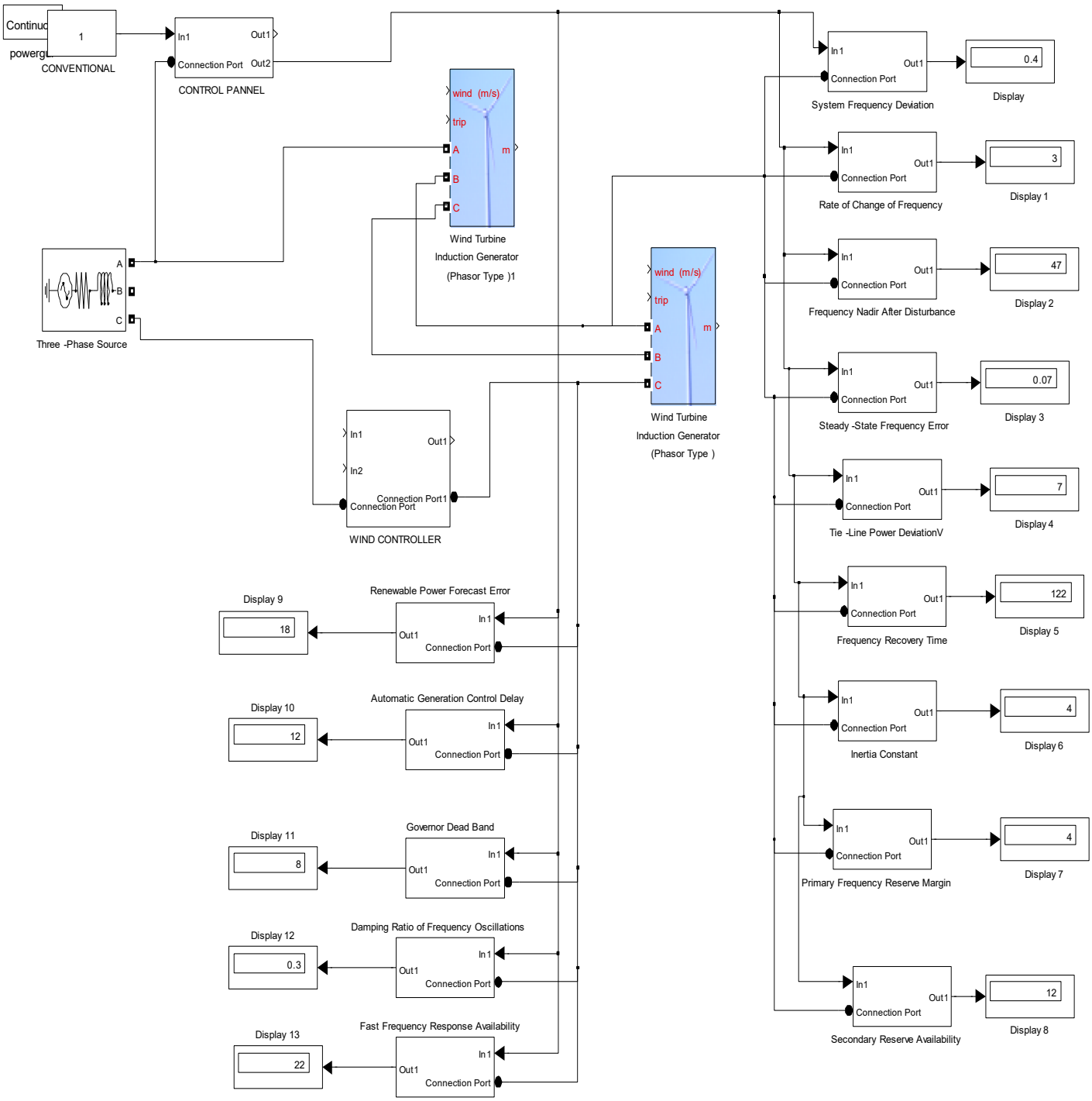


Fig 1 designed conventional SIMULINK model for load frequency control in renewable rich grid

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

To train ANN in the causes of poor load frequency control in renewable rich grid for effective reduction of causes of poor load frequency control in renewable rich grid

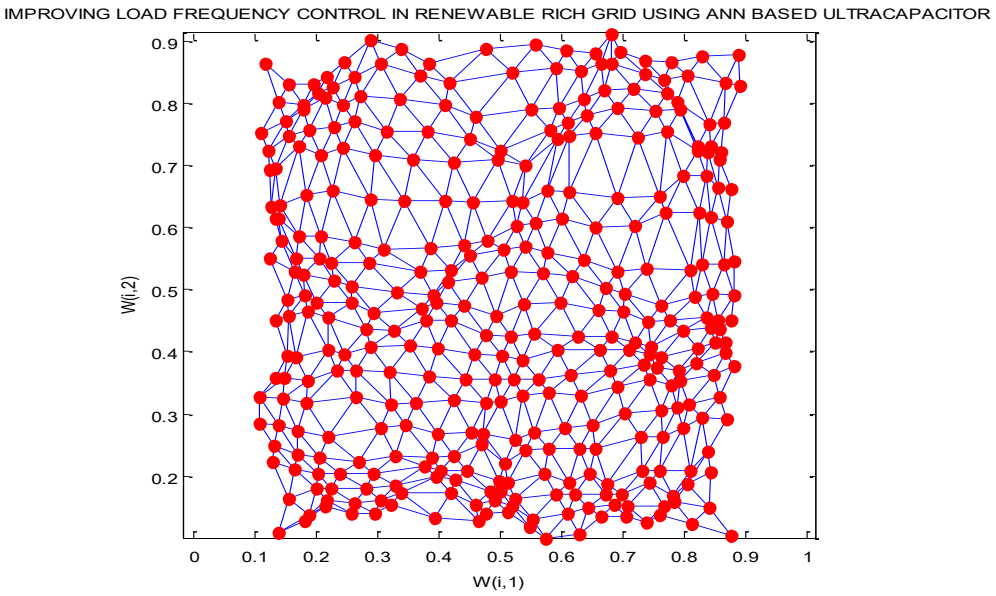


Fig 2 trained ANN in the causes of poor load frequency control in renewable rich grid for effective reduction of causes of poor load frequency control in renewable rich grid

In fig 2 ANN was trained twenty times in seventeen caused poor load frequency control in renewable rich grid 20 x 17 = 340 to give three hundred and forty neurons that looked identical to human brain.

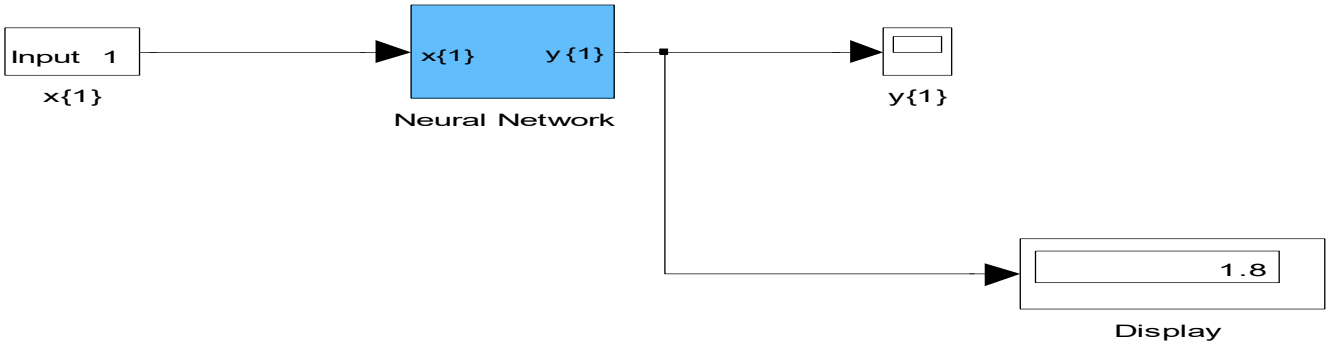


Fig 3 result obtained when trained ANN in the causes of poor load frequency control in renewable rich grid for effective reduction of causes of poor load frequency control in renewable rich grid.

To design a SIMULINK model for ULTRACAPACITOR

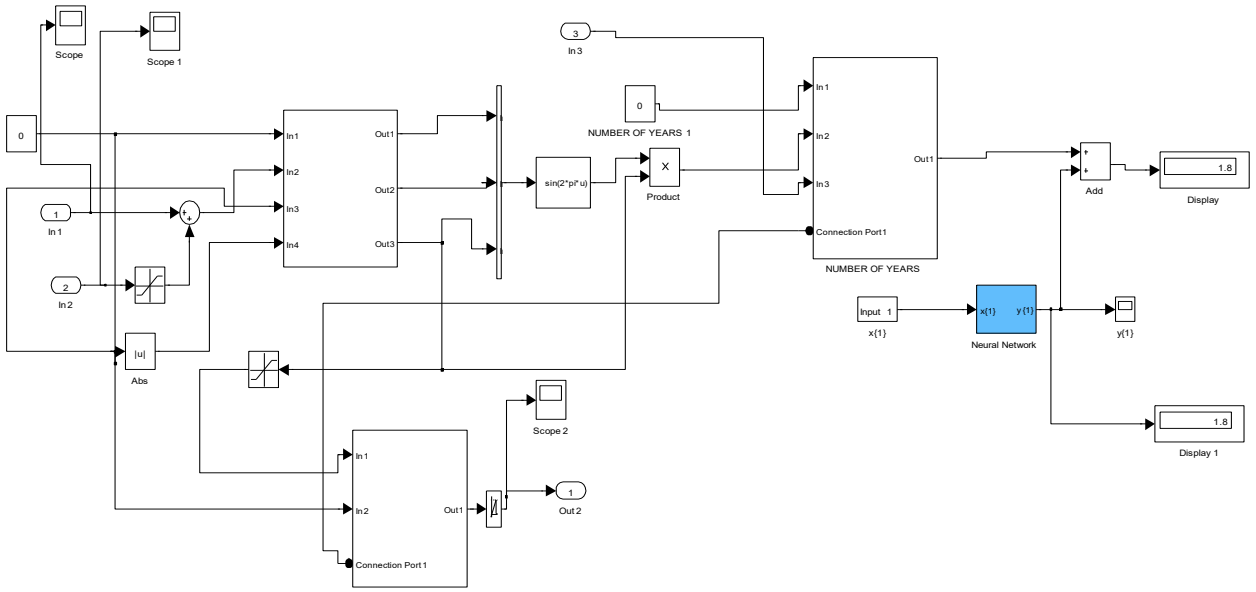


Fig 4 designed SIMULINK model for ULTRACAPACITOR

The results obtained after the integration to the conventional SIMULINK model for load frequency control in renewable rich grid were as shown in figures 7 and 8

To develop an algorithm that would implement the process

1.Characterize and establish the causes of poor load frequency control in renewable rich grid

2. Identify System Frequency Deviation that did not attain threshold.

3.Identify Rate of Change of Frequency that did not attain threshold.

4. Identify Steady-State Frequency Error that did not attain threshold.

5.Identify Area Control Error that did not attain threshold.

6. Identify Tie-Line Power Deviation that did not attain threshold.

7. Identify Frequency Recovery Time that did not attain threshold

8.Identify Inertia Constant that did not attain threshold

9. Identify Primary Frequency Reserve Margin that did not attain threshold

10.Identify Secondary Reserve Availability that did not attain threshold

11. Identify Renewable Power Forecast Error that did not attain threshold

12.Identify Automatic Generation Control Delay that did not attain threshold

13. Identify Governor Dead Band that did not attain threshold

14.Identify Damping Ratio of Frequency Oscillations that did not attain threshold

15.Identify Fast Frequency Response Availability that did not attain threshold

16. Design a conventional SIMULINK model for load frequency control in renewable rich grid and integrate 2 through 15.

17. Train ANN in the causes of poor load frequency control in renewable rich grid for effective reduction of causes of poor load frequency control in renewable rich grid

18. Design a SIMULINK model for ULTRACAPACITOR

19. Integrate 17 and 18

20. Integrate 19 into 16.

21. Did the causes of poor load frequency control in renewable rich grid reduce and attain threshold?

22. IF NO go to 20.

23. IF YES go to 24.

24. Improved load frequency control in renewable rich grid

25. Stop.

26. End

To design a SIMULINK model for improving load frequency control in renewable rich grid using ANN based ULTRACAPACITOR

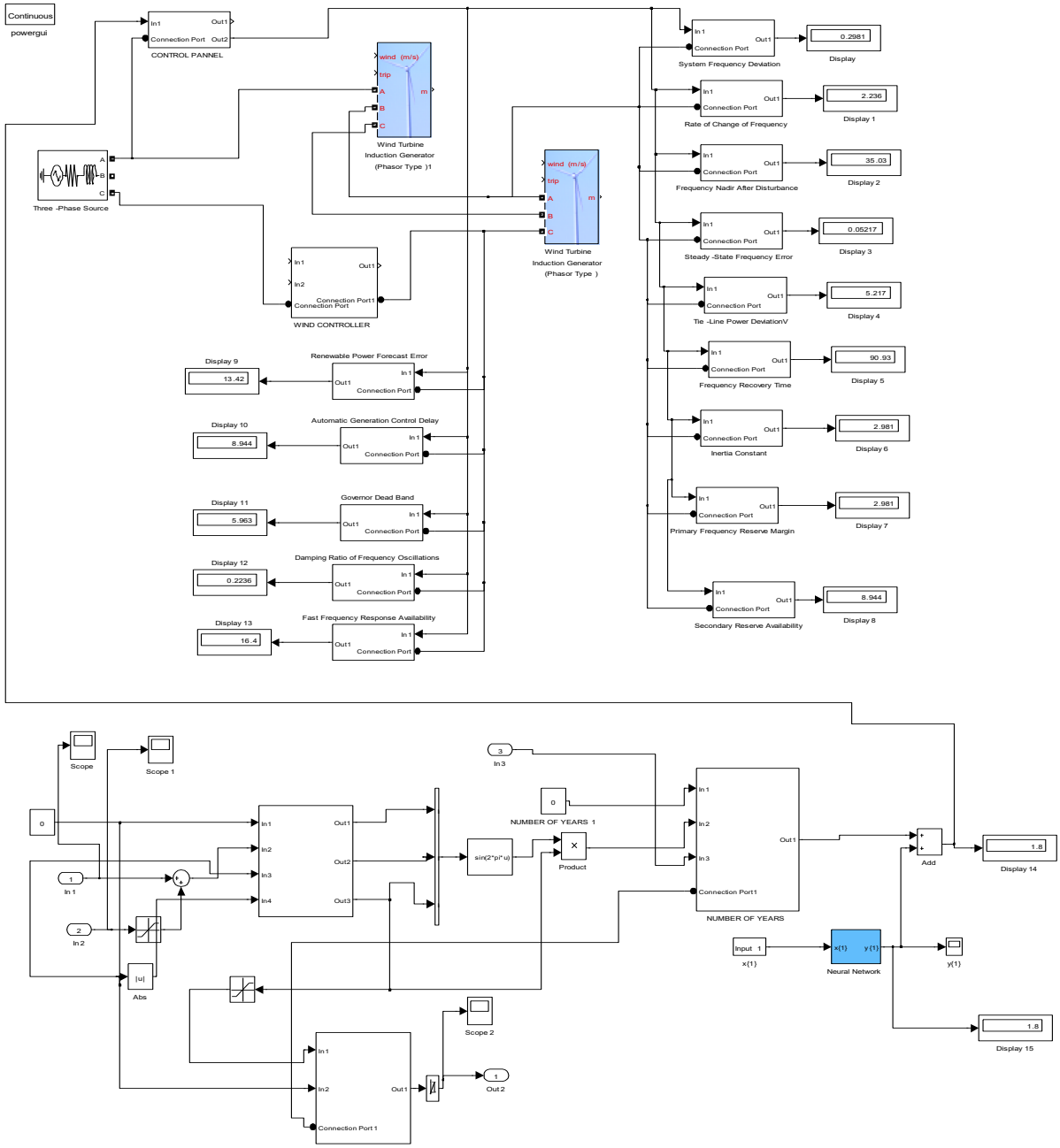


Fig 5 designed SIMULINK model for improving load frequency control in renewable rich grid using ANN based ULTRACAPACITOR

In figure 5 the results obtained were as shown in figures 6 and 7

To validate and justify the percentage improvement in the reduction of causes of poor load frequency control in renewable rich grid with and without ANN based ULTRACAPACITOR.

To find percentage improvement in the reduction of System Frequency Deviation that caused poor load frequency control in renewable rich grid with ANN based ULTRACAPACITOR.

Conventional System Frequency Deviation = 0.4 Hz

ANN based ULTRACAPACITOR System Frequency Deviation= 0.2 Hz

%improvement in the reduction of System Frequency Deviation that caused poor load frequency control in renewable rich grid with ANN based ULTRACAPACITOR=

Conventional System Frequency Deviation - ANN based ULTRACAPACITOR S FD x 100%
Conventional System Frequency Deviation 1

%improvement in the reduction of System Frequency Deviation that caused poor load frequency control in renewable rich grid with ANN based ULTRACAPACITOR=

$$\frac{0.4\text{Hz} - 0.2\text{ Hz}}{0.4\text{Hz}} \times \frac{100\%}{1}$$

%improvement in the reduction of System Frequency Deviation that caused poor load frequency control in renewable rich grid with ANN based ULTRACAPACITOR= 50%

To find percentage improvement in the reduction of renewable power forecast error that caused poor load frequency control in renewable rich grid with ANN based ULTRACAPACITOR.

Conventional Renewable Power Forecast Error = 18%

ANN based ULTRACAPACITOR Renewable Power Forecast Error = 13%

%improvement in the reduction of Renewable Power Forecast Error that caused poor load frequency control in renewable rich grid with ANN based ULTRACAPACITOR=

Conventional Renewable Power Forecast Error - ANN based ULTRACAPACITOR RPFE

%improvement in the reduction of Renewable Power Forecast Error that caused poor load frequency control in renewable rich grid with ANN based ULTRACAPACITOR= 18 % - 13%

%improvement in the reduction of Renewable Power Forecast Error that caused poor load frequency control in renewable rich grid with ANN based ULTRACAPACITOR= 5%

RESULTS AND DISCUSSION

Table 3 comparison of conventional and ANN based ULTRACAPACITOR System Frequency Deviation that that caused poor load frequency control in renewable rich grid

Time (days)	Conventional System Frequency Deviation that that caused poor load frequency control in renewable rich grid(Hz)	ANN based ULTRACAPACITOR System Frequency Deviation that that caused poor load frequency control in renewable rich grid(Hz)
1	0.4	0.2
2	0.4	0.2
3	0.4	0.2
4	0.4	0.2

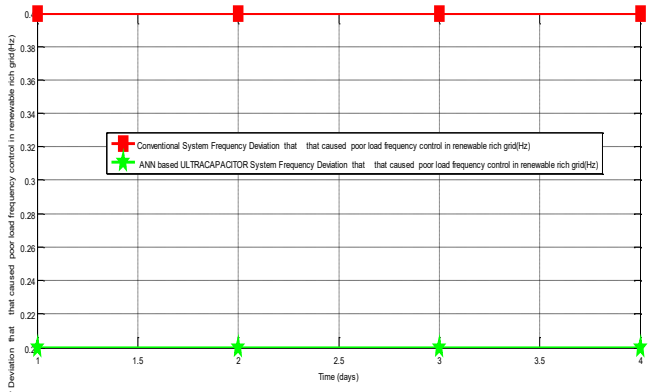


Fig 6 comparison of conventional and ANN based ULTRACAPACITOR System Frequency Deviation that that caused poor load frequency control in renewable rich grid

The conventional System Frequency Deviation that caused poor load frequency control in renewable rich grid was0.4 Hz. On the other hand, when an ANN based ULTRACAPACITOR was input into the system, it instantly reduced it to 0.2 Hz

Table 3 comparison of conventional and ANN based ULTRACAPACITOR Renewable Power Forecast Error that that caused poor load frequency control in renewable rich grid

Time (days)	Conventional Renewable Power Forecast Error that that caused poor load frequency control in renewable rich grid(%)	ANN based ULTRACAPACITOR Renewable Power Forecast Error that caused poor load frequency control in renewable rich grid(%)
1	18	13
2	18	13
3	18	13
4	18	13

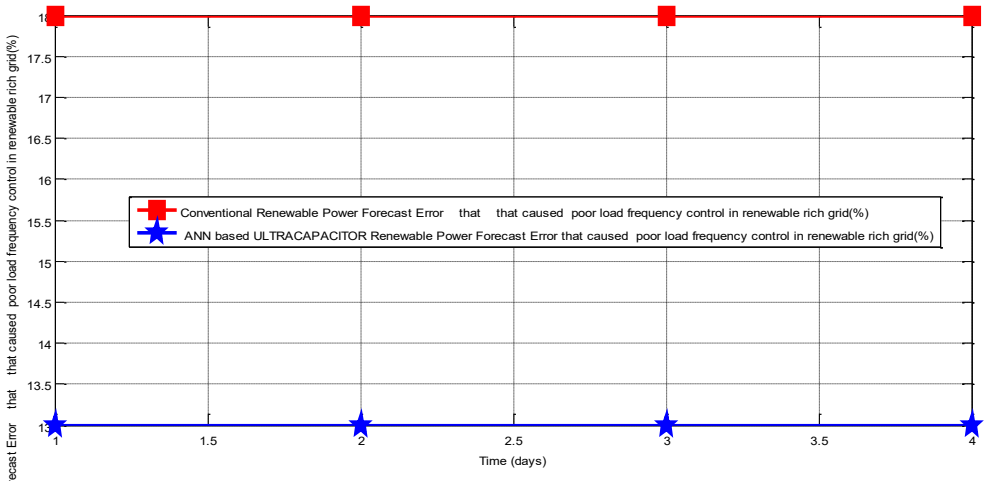


Fig 7 comparison of conventional and ANN based ULTRACAPACITOR Renewable Power Forecast Error that that caused poor load frequency control in renewable rich grid

The conventional Renewable Power Forecast Error that that caused poor load frequency control in renewable rich grid was18%. meanwhile, when an ANN based ULTRACAPACITOR was integrated into the system, it instantly reduced to13%. With these results obtained, the percentage improvement in load frequency control in renewable rich grid when an ann based ULTRACAPACITOR was input into the system was 5%.

CONCLUSION

The constant power failure in the country that had jeopardized business activities could be overcame by introducing improving load frequency control in renewable rich grid using ANN based ULTRACAPACITOR. To achieve this, it was done in this manner, load frequency control in renewable rich grid was characterized and causes of poor load frequency control in renewable rich grid were established and a conventional SIMULINK model for load frequency control in renewable rich grid was designed. Then, ANN was trained in the causes of poor load frequency control in renewable rich grid for effective reduction of causes of poor load frequency control in renewable rich grid was designed, ANN was trained in the causes of poor load frequency control in renewable rich grid for effective reduction of causes of poor load frequency control in renewable rich grid and a SIMULINK model for ULTRACAPACITOR was designed. Later, algorithm that would implement the process was developed, a SIMULINK model for improving load frequency control in renewable rich grid using ANN based ULTRACAPACITOR was designed and the results were validated and justified. The results obtained were the conventional System Frequency Deviation that caused poor load frequency control in renewable rich grid was0.4 Hz. On the other hand, when an ANN based ULTRACAPACITOR was input into the system, it instantly reduced it to 0.2 Hz and the conventional Renewable Power Forecast Error that that caused poor load frequency control in renewable rich grid

was18%. meanwhile, when an ANN based ULTRACAPACITOR was integrated into the system, it instantly reduced to13%. With these results obtained, the percentage improvement in load frequency control in renewable rich grid when an ann based ULTRACAPACITOR was input into the system was 5%.

REFERENCES

1. Bevrani, H. (2014). *Robust power system frequency control*. Springer.
2. Bevrani, H., Ghosh, A., & Ledwich, G. (2019). Renewable energy sources and frequency regulation: Survey and new perspectives. *IET Renewable Power Generation, 4*(5), 438–457.
3. Haykin, S. (2009). *Neural networks and learning machines* (3rd ed.). Pearson Education.
4. Kundur, P., Balu, N. J., & Lauby, M. G. (2004). *Power system stability and control*. McGraw-Hill Education.
5. Milano, F., Dörfler, F., Hug, G., Hill, D. J., & Verbič, G. (2018). Foundations and challenges of low-inertia systems. *Proceedings of the IEEE, 106*(9), 1634–1653.
6. Miller, J. R., & Simon, P. (2008). Electrochemical capacitors for energy management. *Science, 321*(5889), 651–652. https://doi.org/10.1126/science.1158736