SSRG International Journal of Electrical and Electronics Engineering
ISSN: 2348-8379/ https://doi.org/10.14445/23488379/IJEEE-V11I11P107

Volume 11 Issue 11, 65-76, November 2024

Original Article

ANN Hybridized FACTS Controller for Wind Energy Conversion System

Vaishali Chavhan[1], Mukesh Kumar[2], Santosh Kumar Singh[3], Sweta Suman[4]

[1,2]*Department of Electrical Engineering, G H Raisoni University, Maharashtra, India.*
[3]*REDX Innovation, WE School, Maharashtra, India.*
[4]*Government College of Engineering, Vaishali, Bihar, India.*

[1]*Corresponding Autor : vaishalichavhan88@gmail.com*

Received: 05 September 2024 Revised: 06 October 2024 Accepted: 04 November 2024 Published: 30 November 2024

***Abstract** - Demand for power is rising, highlighting the need for renewable energy sources as long-term energy sources. Wind power is a prominent renewable energy source. Dually Fed Induction Generator (DFIG) wind energy system has become increasingly popular because of its many advantages, which include independent control of reactive and active power And variable speed operation. Energy system experts now have serious concerns about integrating wind farms with DFIG into the electrical grid. When there are grid disruptions, voltage stability is essential to keep DFIG-based wind farms operational. The total voltage stability of the system may start to be impacted by wind turbines during grid faults large, wind farm tripping due to the wind power's rapid growth in penetration into power systems. Unbalanced loads, disturbances, shifting system conditions, and rising load demand are some of the causes of voltage instability. The Artificial Neural Network (ANN) controlled the Proportional Integral (PI)-controlled STATCOM, which is examined in this paper. Within the MATLAB environment, simulation is performed. Furthermore, the simulation findings demonstrated that in comparison to PI-controlled STATCOM and STATCOM devices with artificial neural networks mitigate consequences of grid disruptions and failures, such as L-G failures, L-L faults, and voltage stability problems. Research acquired simulated results of bus voltages, reactive power, and real power. These graphs depict the results before and after a fault in the term of voltage is 228 kV, reactive power is 23.37 MVAR and 185.67 kV, reactive power is 28.95 MVAR, which are enhanced by STATCOM voltage is 226 kV, reactive power is 25.7 MVAR, and further refined for greater accuracy using ANN voltage is 229.9 kV and reactive power is 23.307 MVAR. The proposed and implemented system outperforms the state-of-the-art approaches the evaluation centers on assessing their capability to regulate voltage profiles and reactive energy compensation margins of the system. Additionally, the research scrutinizes the best placement of both devices connected to the load side to maximize their efficiency in improving voltage profiles.*

***Keywords** - ANN, DFIG, 9 bus IEEE, Static Synchronous Compensator (STATCOM), Static compensator, 12 pulse, Voltage stability, Wind Energy Conversion System (WECS).*

1. Introduction

Nowadays, Electric utilities cannot fulfil the electricity requirement for modern society due to growing living standards and urbanization to meet load demands and resolve power issues [1]. Renewable energy sources have been a viable alternative to conventional energy sources throughout the past 30 years. From a technical and economic perspective, wind power is among the numerous sustainable energy resources available [2].

The devices Static Synchronous Compensator (STATCOM), 12 pulse STATCOM, Dual-Feed Induction Generator (DFIG), Artificial Neural Network (ANN) and 9 bus IEEE systems are used in this study. This work suggests an innovative approach to enhance stability by connecting a Flexible AC Transmission System (FACTS) controller on the load side of the system. A number of researchers have integrated the FACTS device into a transmission line in the literature; however, these studies have a load-side focus. An integration of STATCOM at the appropriate location of the load side is crucial to enhancing voltage stability throughout the system. The system’s voltage profile and flexible power flow can both be improved by the STATCOM integrated system [3].

A notable endeavor has been produced recently to explore unique and non-traditional control strategies, which can frequently enhance or supplant traditional approaches. Artificial Neural Network (ANN) techniques have emerged as highly beneficial in power electronics, particularly for ensuring system stability across a broad operational spectrum. ANN controllers possess the ability to learn, retain information, and make decisions autonomously [4]. The input consists of real data or signals. The following phase involves summarizing. A final decision is made based on the summation. Activation functions, either linear or non-linear, can be used to make any kind of decision. This research consists of

- Based on these neurons, an ANN might now include neural feed-forward perceptrons in a single layer. It is called a single-layer neuron because the input layer of this study's source nodes projects onto the output layer of neurons. The feed-forward propagation method gets its name from the fact that this network always moves ahead, indicating that it is processed forward and lacks a feedback loop or connection.
- Perceptron feed-forward multi-layer neural network Several hidden layers or multilayers are utilized when a single layer is unable to provide an accurate result or output. In this study, error correction learning is employed. The learning back-propagation method is the most widely used algorithm for error correction.

An effective method for training Artificial Neural Networks (ANNs) is the Back-Propagation (BP) methodology, predicated on the gradient descent method. Employing the Levenberg Marquardt (LM) Back Propagation (BP) algorithm as its training method within this neural network controller [5]. When a delicate load is attached, the control Artificial Neural Network (ANN) method seeks to maintain a steady voltage magnitude despite system disruptions. Compared to the Fundamental Frequency Switching (FFS) techniques preferred in Flexible Alternating Current Transmission Systems (FACTS) applications, PWM techniques provide a more adaptable choice.

An error signal derived from the reference voltage and the observed terminal voltage's root mean square value serves as the controller's input. An ANN controller processes this error and outputs the angle δ, which is then sent to the PWM signal generator. The wind energy system with DFIG-based variables is an advantageous alternative for the current situation of the energy market. Energy derived from wind is known as wind energy. The purpose of a wind turbine is to extract kinetic energy from the wind and convert it to mechanical and, finally, electrical energy with the DGIG [6].

The turbine blade and wound rotor induction generator couple through the gearbox of the wind energy system, utilizing the DFIG. Both reactive and active powers are autonomously managed here. To maintain grid voltages, the generator can also supply reactive power [7].

Voltage stability is one of the system's important priorities and one of the most difficult studies. It relates to the capacity of the system's ability to keep the voltage on all its buses within acceptable bounds after being disrupted. Significant occurrences (blackouts) have been brought on by voltage swings throughout the world [8, 9]. As a result, it is imperative to consistently meet the need for reactive energy. Voltage instability can result from Numerous elements, such as heightened demand for load, unbalanced load, disruption, and evolving system conditions [10, 11].

This study aims to assess how well the FACTS controller can recover system voltage in the load side of a metropolitan area by implementing a reactive power compensation approach, and the execution of the FACTS device is improved by ANN [12]. For various reasons, voltage imbalance and collapse have emerged as universal problems. System stability problems are managed with FACTS devices. This study examines the importance and use of STATCOMs for improving the power system voltage profile on the load side. The research utilizes MATLAB 2020 software for analysis and simulation purposes.

MATLAB 2020 has a smooth integration with Simulink, an excellent instrument for modeling and simulation. From algorithm research to system simulation and implementation, a smooth workflow is made possible by combining MATLAB and Simulink. In the current scenario of power systems using DFIG, STATCOM is utilized to increase voltage stability [13]. This article's main advantages include;

1. The study examines FACTS devices such as ANN and STATCOMCS, outlining their benefits, limits, and ways to mitigate power stability problems in contemporary power systems.
2. The paper discusses the ideal position for FACTs devices using a case study overview of IEEE standard networks developed from a literature review. The FACTS controller in this study is linked to the system's load side.
3. Literature has observed that a number of researchers work on transmission lines, but in this study, we focus on load buses.
4. Different occurrences are considered in this area to validate the offered option, including different types of faults (symmetrical and unsymmetrical).
5. To ensure the voltage stability improvement and reactive power consumptions experienced across by evaluating the wind speed profiles and faults.
6. In the study implementing the FACTS Controller to overcome all these circumstances obtained the result in normal condition faulty conditions and mitigated by STATCOM. The fulfillment of the FACTS device is improved by ANN and improves the voltage stability and reactive power compensation [14].
7. The article describes the new challenges that power systems face because of integrating variable renewable energy sources like wind. The difficulties include power flow control problems, frequency instability, and voltage variations.

1.1. Novelty and Application

- This research gives power system operators, planners, and researchers crucial information to ensure the stability and reliability of modern electrical grids. It also aids in their decision-making about integrating and applying STATCOM technology.
- Creating a new self-correcting Static synchronous reactive compensator for wind turbines that enhances the stability of the system voltage in both steady-state and transient modes under challenging circumstances, including various fault types.
- While addressing the issue in FACTS devices, the components or parameters that ought to be regarded as the best execution in terms of the precision of the resolution, the rate of convergence and efficacy, and the highest accomplishment percentage are investigated.
- This focus also discusses the advantages and disadvantages of several advanced techniques that have been applied to the resolution of voltage stability problems.
- Results obtained provide an overview of each amended document's useful objectives, test systems used, methodologies used, and kinds of FACTS devices studied.
- The wind energy system has been evaluated and implemented with STATCOM-based ANN and PI to improve overall performance and stability. The performances of the two newly released controllers have been thoroughly compared and displayed.

2. Methodology

2.1. DFIG-Based Wind Turbine System

Future wind farms will feature DFIGs, which offer many benefits over fixed-speed generators. These benefits, such as speed control, minimum flickering and Active (P) and Reactive (Q) power capabilities in four quadrants which, are mostly achieved through Rotor Side Converter (RSC) control.

This is ordinarily rated at somewhere between 30% and 35% of the generator rating for a certain rotor speed variation range of percentage (%). Figure 3 represents details about the system. Wound rotor IG uses DFIG-based wind turbines, which are coupled in Figure 3 via a gearbox; the modelling of DFIG is done by using the parameter shown in Table 1 [12]. The rotor and direct grid-connected stator of this generator are powered by a two-way power converter.

It also has a grid-connected system, RS and GS controllers and converters with DFIG. While the RS of DFIG is linked to the power grid via bidirectional power electronics converters, the stator side is directly connected to the source by a transformer. With these converter's control capabilities, the DFIG system is more adaptable and stable. It is possible to regulate the current and power transfer through the DFIG system. DC link voltage and the speed of the generator are controlled by the two power converters, the RS Controller and the GS Controller, as shown in Figure 3.

The voltage at the RS and converter voltage at GS are adjusted separately to control the RS and GS controllers. Sensors of many kinds are employed for the proposed control techniques to evaluate the total state variable values and feed those values back to minimize deviations in both the situation and the output of the examined system.

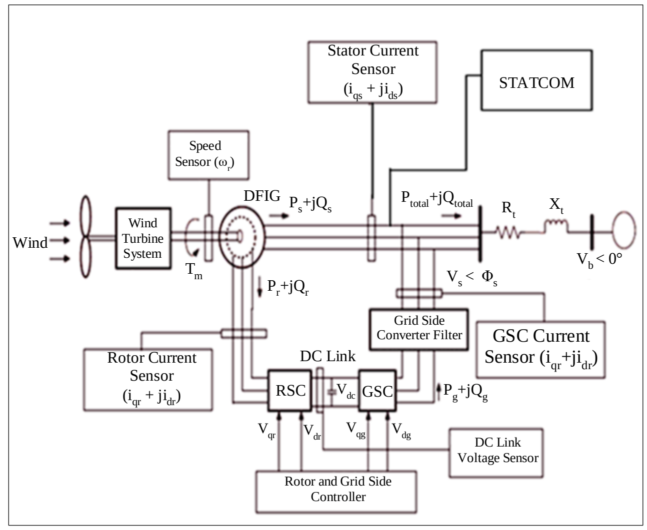

Fig. 1 Reference block diagram of a DFIG equipped WT

Table 1. DFIG parameter

Sr. No.	DFIG Parameter	Values
1	Nominal Power, L-L Voltage, and Frequency	(100e6 11.66e3 11e3 50)
2	Stator Side	(Rs, Lls) (0.0231 0.182)
3	Rotor Side (Rr', Llr')	(0.0161, 0.162)
4	Magnetizing inductance of IG Lm (p.u.)	2.91
5	Inertia Constant (k), the Friction Factor of the Generator, and Pairs of Poles	(0.685, 0.01 3)

As a prominent member of the FACTS family extensively deployed in contemporary power systems, the static compensator operates on the fundamental principle of being linked in parallel to the system, as illustrated in Figure 1 [15]. The modulation of output voltage (V_{out}) of VSC enables the supply of reactive power in between the system and static compensator; if the voltage output from the VSC is more than the system voltage, then STATCOMs produce capacitive reactive power; however, if it's lower, the STATCOMs absorbs inductive reactive power [16].

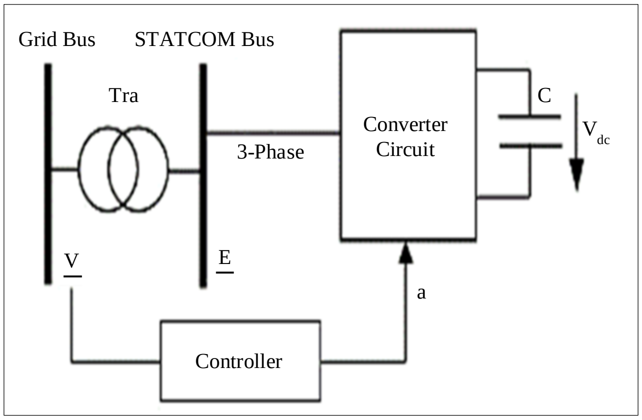

Fig. 2 STATCOM in power system

The connection between the fundamental component of the AC converter's V_{out} and the DC capacitor across voltage is articulated as [4].

$$V_{out} = k\ Vdc \tag{1}$$

Here, the coefficient k is contingent upon factors such as the quantity of electrical pulses, converter arrangement and the control implemented in the converter. The primary factor influencing the voltage output of the converter, V_{out}, is the direct current voltage, Vdc. The coupling transformer receives reactive power from the system and vice versa; it is determined by the variance. The connection between the V_{out} voltage output of the converter and the bus voltage of the AC system [17]. The exchanged reactive energy expressed below [4] .

$$Q=V_{ac2}-V_{out}\ V_{ac2} \cos X \tag{2}$$

It is possible to express the true power transfer between the VSC and the system as [4]:

$$P= V_{ac}\ V_{out}\ \mathrm{Sin}\alpha X \tag{3}$$

Here,

V_{out} - output voltage of converter,
Vac - the magnitude of the AC system is voltage,
X – the coupling transformer of leakage reactance.
Alpha (α) signifies the phase difference between the o/p Voltage of converter and the system voltage.

2.2. Sinusoidal Wave Pulse Width Modulation and Voltage Source Converter

The predominant SPWM method is sinusoidal Pulse Width Modulation (PWM). Here, a trigonal waveform is overlaid with a sinusoidal waveform at the suitable frequency, and the comparison between their levels regulates the actuation of components within each ph branch of the inverter. The characteristics of the inverter o/p voltage are as follows:

1. The frequency of SPWM matches the frequency of the triangular waveform, V trip.
2. The highest value of V voltage Control determines the amplitude.
3. The frequency (fr) of voltage control sets the fundamental frequency.

When a sensitive load is attached to a Sine-wave PWM scheme, the controller wants to keep the voltage magnitude constant no matter what disruptions the system experiences. The switching strategy of the voltage source converter relies on sinusoidal PWM, providing both simplicity and excellent response characteristics [18]. The Voltage Source Converter (VSC) is an electronics power device with the ability to generate a sinusoidal voltage characterized by a designated frequency amplitude and phase angle α. It transforms the DC voltage, using the energy stored in the capacitor, into 3-phase AC output voltages. The desired voltage can be obtained by controlling the switching of the solid-state electronics devices within the converter [19].

2.3. The Control Circuit of STATCOM

The primary purpose of the FACTS device STATCOMs control circuit is to autonomously regulate both real and reactive power delivered to the system while maintaining voltage control over the DC-link capacitor. Figure 2 illustrates the fundamental control technique utilized for the STATCOMs. The elements that make up the control strategy include the generator pulse, current regulator, Phase Locked Loop (PLL), measurement network, and the conversion from Abc to Dq0 [20].

A Phase Locked Loop (PLL) that latches on to the three-phase primary voltage V1's positive-phase portion. The components d-q-axis of the 3-phase voltage of AC is V, and current I shown on the schematic as (Vd, Vq, Id and Iq) are calculated using the PLL output (angle θ= ωt) measurement network is configured to assess the d-q-axis components of AC positive sequence voltages and currents to facilitate regulation, in addition to monitoring the DC voltage Vdc. With the controller of PI works in control mode of voltage and the current regulator uses Id-ref and Iq-ref reference currents for AC and DC voltage, respectively, to control the amplitude and phase voltage produced by the spwm converter (V2d, V2q) [21].

2.4. The PI Controller

A Controller of PI is necessary to regulate/activate the FACTS device STATCOM during system disturbances, such as a decrease in levels of voltage. At the moment of common coupling (PCC), the voltage is detected and then transmitted via an order of the examiner. The loop of control reactive power governs the q-axis coordinate, and the real power regulator loop governs the d-axis coordinate, each utilizing an individual PI controller. The PI controller's structure is visualized in Figure 3.

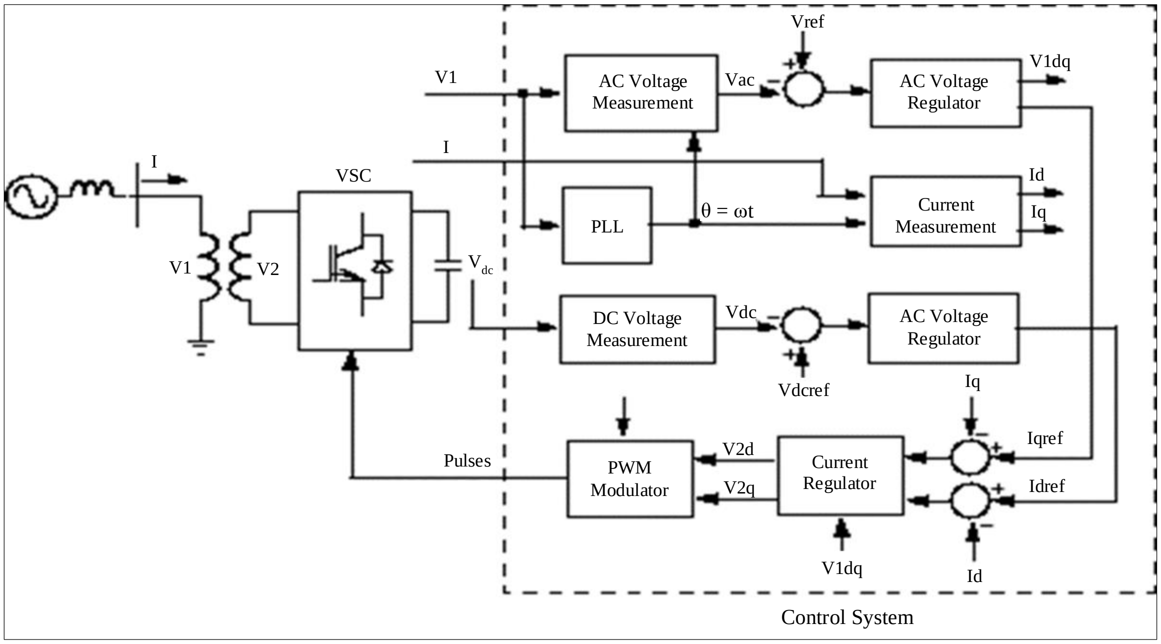

Fig. 3 Block representation of STATCOM

The voltage reference value in the q-coordinate control unit is set to one per unit (p.u). The integral gain Ki is under this control is 1000, while Kp, the proportional gain, is 5. In the d-coordinate control module, both Kp and Ki are 0.025. The PI controller's result gets transformed into a three-phase voltage, which is then used by the SPWM pulse generator to create pulses. These pulses are subsequently directed to the voltage source converter to activate the IGBT switches [21].

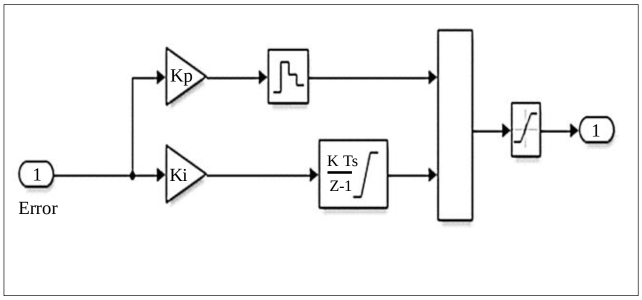

Fig. 4 Controller PI

2.5. Structure of 12 Pulses STATCOM Control Circuit

The VSC delivers rapid response, consistent voltage regulation, optimal efficiency, and reliable operation, ultimately achieving the primary goal of regulating the system's voltage and reducing transient disruptions. The VSC has the capability to operate using either PWM or multi-pulse methodologies. This paper presents a novel approach to STATCOM design, employing 2 sets of dual level twelve pulse VSC to keep the DC link active voltage steady. The reactive energy of the system is managed by adjusting the phase angle α difference between 2 sets of dual level twelve pulse VSCs. A comprehensive explanation of multilevel STATCOM based on cascading two-level inverters is given in [21].

2.6. Artificial Neural Network Controller

Network of neural, a densely interconnected network of many systems elements termed neurons design inspired by the human brain, has emerged as one of the emerging control technologies. Typically, the architecture of a neural network comprises multiple neuron layers, including an i/p layered, one or more concealed layers and an o/p layer, as shown in Figure 4.

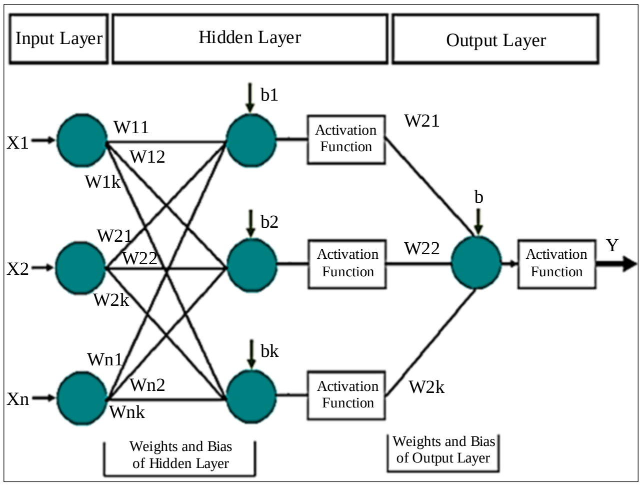

Fig. 5 The neural network structured

The artificial neural network underwent training utilizing the MATLAB tool, employing the Levenberg Marquardt (LM) Back Propagation (BP) algorithm as its training method within this neural network controller. The developed Artificial Neural Network (ANN) consists of two layers arranged in a feed-forward configuration: the concealed and the o/p layer. The training data for the ANN originates from the traditional controller PI. The Mean Square Error, the ANN controller performance metric, mirrors the disparity between the i/p and final values. The training of the ANN in the q-coordinate control module took 1000 epochs, with the optimal validation performance (0.00025303) attained at epoch 15. Once the offline training concludes, the subsequent phase involves replacing the traditional PI controller with the newly developed controller of ANN [21, 22].

2.7. System Modeling

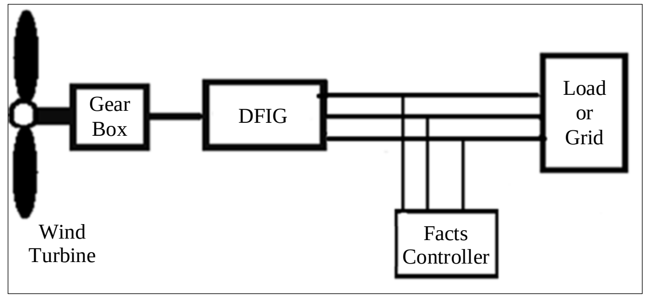

Fig. 6 Single line diagram WECS with FACTS controller

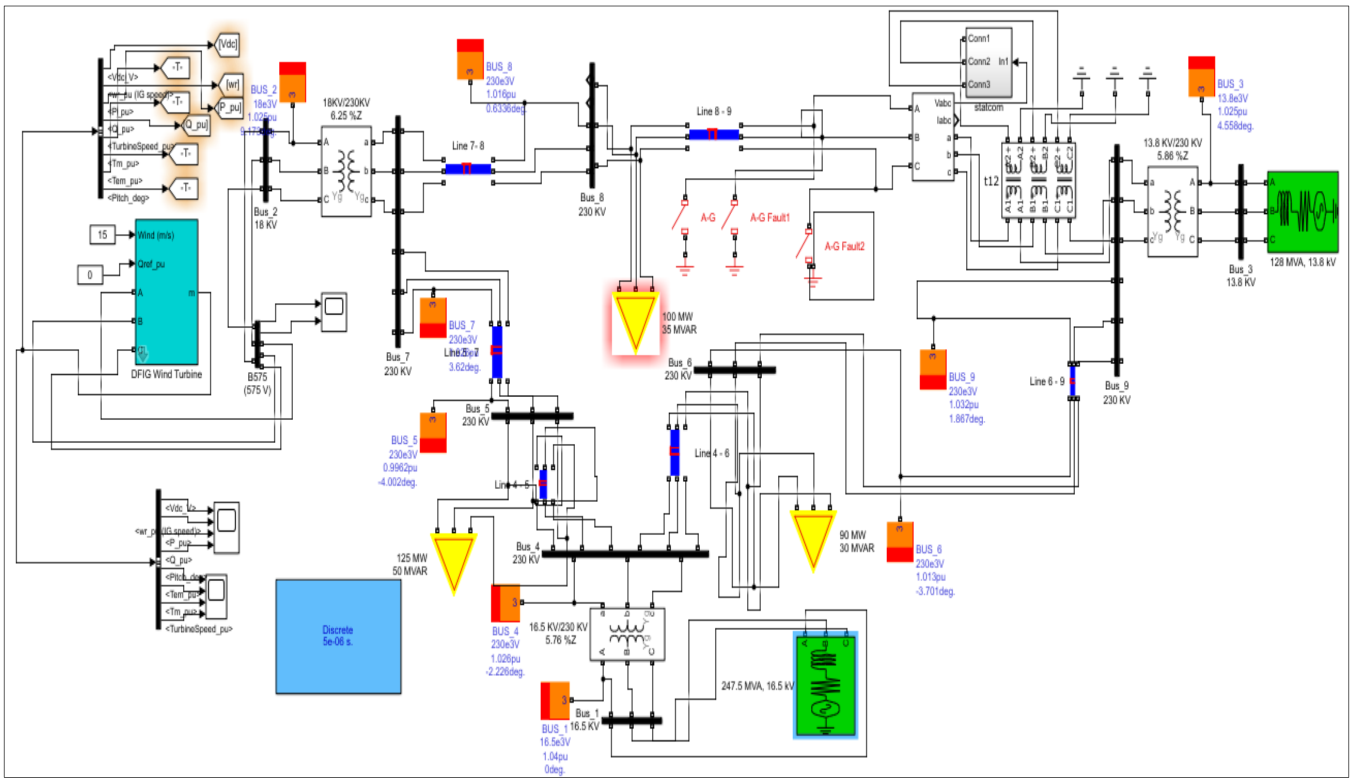

Fig. 7 Complete model IEEE 9 Bus with FACTS device and ANN [1]

The single line diagram represents the complete system of wind energy conversion system with a FACTS controller linked to the grid, which is a standard IEEE 9 bus. The IEEE 9-Bus system combined with the Doubly Fed Induction Generator (DFIG) is examined in this study for voltage stability. Studies were conducted using simulation to ascertain the system's pre-fault conditions.

Three-phase symmetrical and unsymmetrical faults were used to study the system's frequency, reactive power problems, imbalance, power angle fluctuations, and voltage instability. To overcome all the circumstances, integrating STATCOM at the appropriate location on the load side is crucial to enhancing voltage stability throughout the system.

The system's voltage profile and flexible power flow can both be improved by the STATCOM-integrated system. Artificial Neural Network is a crucial tool for nonlinear function mapping in artificial intelligence. Any function approximation can be modeled in real-time by a trained ANN. This research develops Artificial Neural Networks (ANNs) that provide the controller with settings for the lowest voltage variation in both normal and emergency conditions.

The designed ANN receives load data as input and outputs the reactive power to be supplied by the STATCOM, the tap position of the transformers, and the generator excitation. Using the traditional nonlinear optimization method, the data needed to train the ANN is acquired.

The study utilizes the 9-bus IEEE system, also known as the Coordinating Council Western System (WSCC) system, which comprises three 3-phase generators, three 3-phase transformers, and a 9-bus transmission line. It is divided into three load areas [19]. Table 2 illustrates the system configuration and parameters, along with adjustments made to the load and Simulink model using MATLAB, employing various techniques and design modifications we've implemented [23].

Table 2. The IEEE 9 bus system data

Units	Specification of parameters
Generators Rated in (kVA)	G1 equals 13.8, G2 equals 16.5, and G3 equals 18.
Transformer Rated in (kVA)	T1 is equivalent to 13.8 / 230, T2 equals 16.5/230, and T3 is 18 / 230.
BUS system	9 buses, 1st bus is the Slack Bus load at buses are 5,6 and 8

3. Result and Discussion

Tabulation results of DFIG-based wind generation with standard IEEE-9 Bus in the normal state, faulty, with STATCOM and ANN condition [23]. Table 3 represents a comparative analysis of the result of healthy, faulty, and compensated condition voltage stability improved by using STATCOM, 12-pulse STATCOM with ANN. This comparison considers bus 8 because this is a load bus. A steady-state wind energy conversion system connected to the IEEE 9 bus system obtained the result in terms of voltage (kV), current (amp), active (kW) and reactive power (MVAR) as per the actual system. When a fault occurs on the bus 8 system, unstable voltage drops by 19.57 %, the current is increased, and the reactive power is increased by 25%. This parameter is improved by STATCOM with ANN research, which obtained results upto to 95% with the given parameter and maintained the system in steady state condition. A system can be improved by up to 85% to 95% based on the comparative results shown in the table above. The bar diagram represents the tabulation result in bar form.

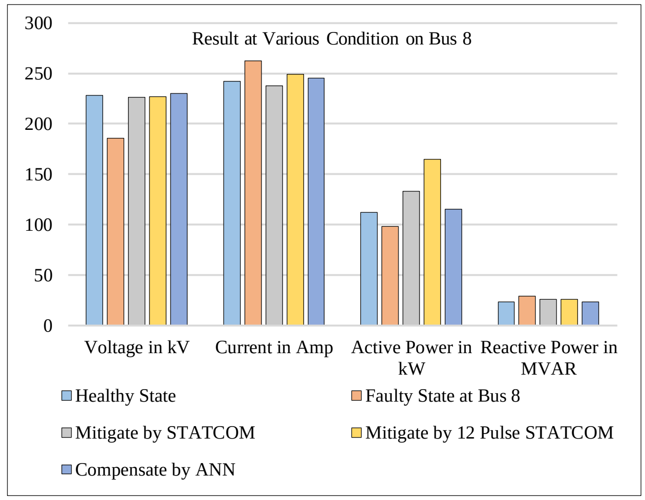

Fig. 8 Bar representation of different conditions

Table 3. IEEE 9 Bus in healthy state condition, faulty and with STATCOM condition, 12 pulse STATCOM with ANN

Bus 8	Healthy State	Faulty State at Bus 8	Mitigate by STATCOM	Mitigate by 12 Pulse STATCOM	Compensate by ANN
Voltage in kV	228	185.67	226	227	229.9
Current in Amp	242	262.1	237.5	249.1	245.45
Active Power in kW	112.1	98.21	132.7	165	115.36
Reactive Power in MVAR	23.37	28.95	25.7	26.02	23.302

3.1. Healthy Condition Standard IEEE 9 Bus System with Wind Generation

In Section 3.1, Figure 9 represents a healthy situation. In healthy condition, the System is in stable condition. The total generation is in stable condition, which is 350 MW of power and observed the voltage graph is 228 kV, real power (P) is 112.1 kW, and Reactive power (Q) is 23.37 MVAR in healthy condition. Looking at the literature, it seems that some papers don't generate as much power and don't produce as clear results when it comes to health situations.

3.2. Faulty Condition Standard IEEE-9 Bus System Connected Wind Generation

Section 3.2, Figure 10 represents a disturbance in this system when the fault occurs at Bus-8, the main bus connected to load 100 MW. The change arises from the occurrence of a three-phase LLL-G fault at Bus-8 due to this generated active power decreases and absorb reactive power increases at faulty state current increases.

When a fault occurs on Bus 8, It impacts the wind generation system; then, at the time of fault duration, the voltage of the main Bus 8 is reduced to 187.67 kV. To rephrase, the overall exported active power (P) from Bus-8 experiences a reduction upto 98.21 kW, and reactive power increases 28.95 MVAR. Looking at the literature, it seems that some papers don't reflect after the fault occurs and don't produce as clear results when it comes to faulty situations.

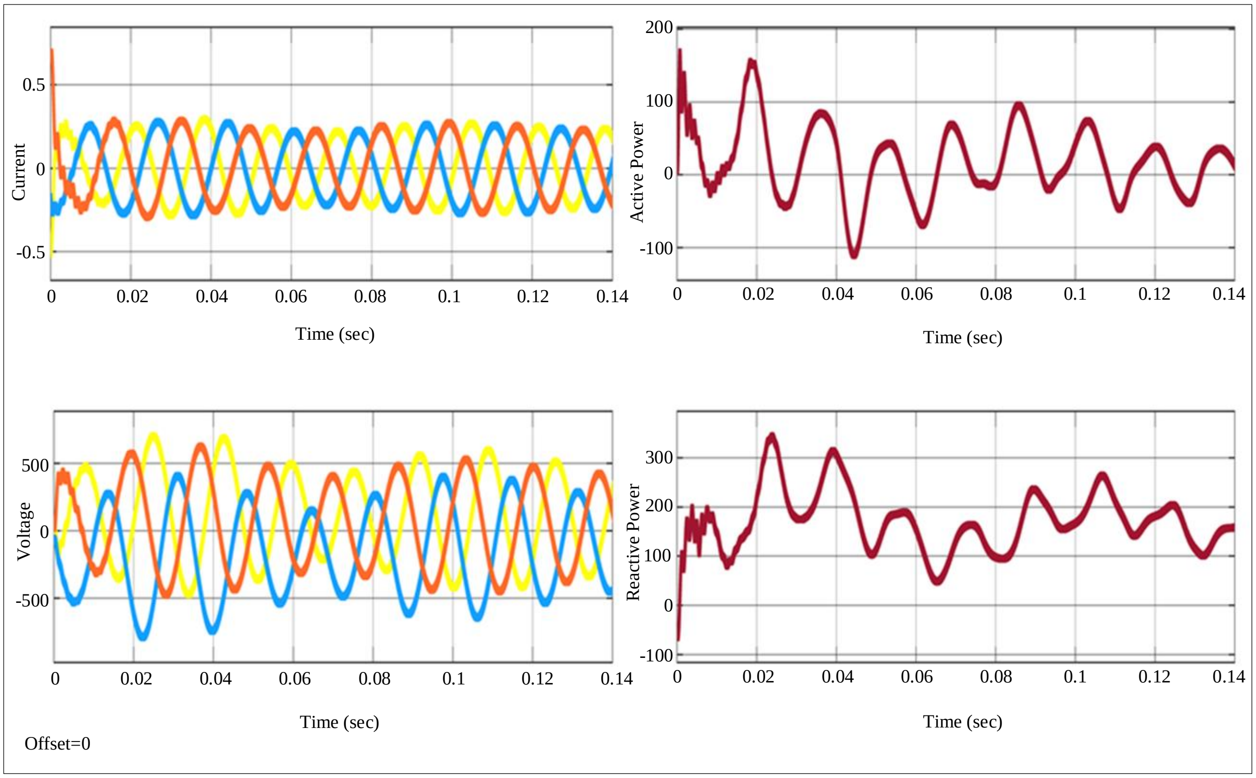

Fig. 9 Voltage current active and reactive power in a healthy state

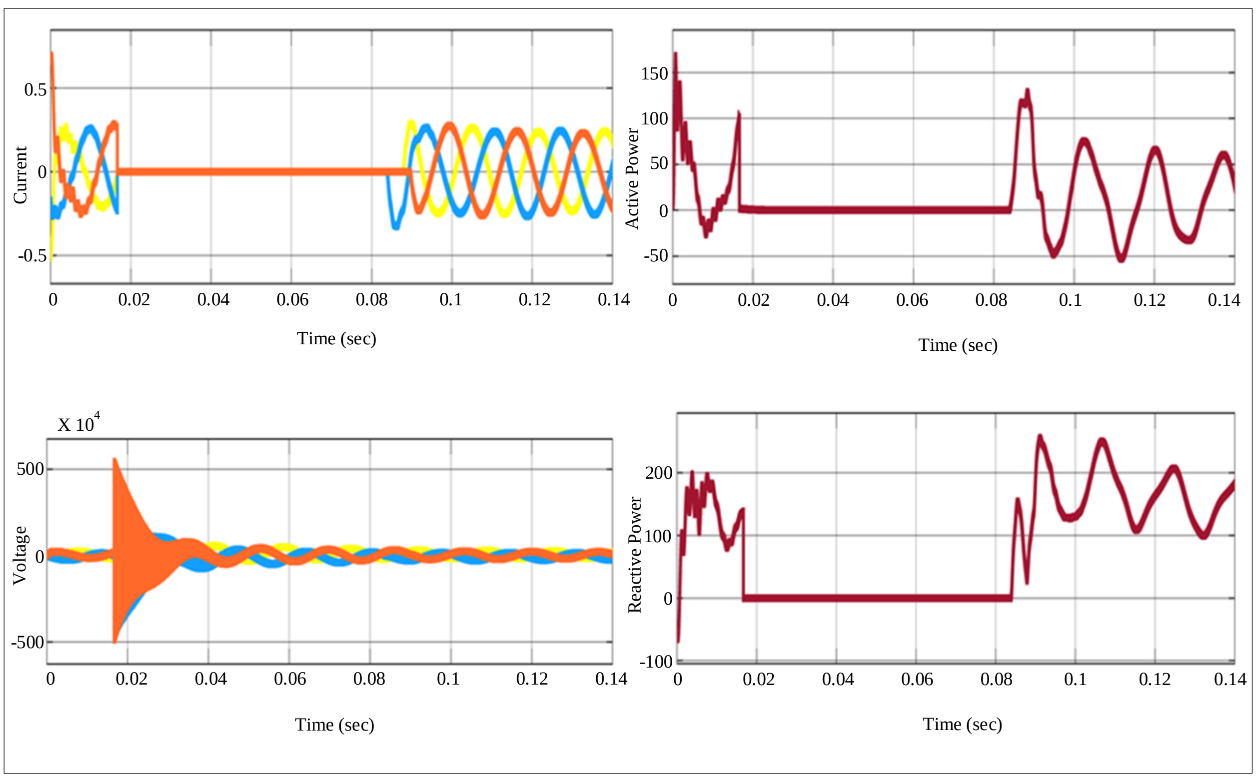

Fig. 10 Voltage current active and reactive power in faulty condition

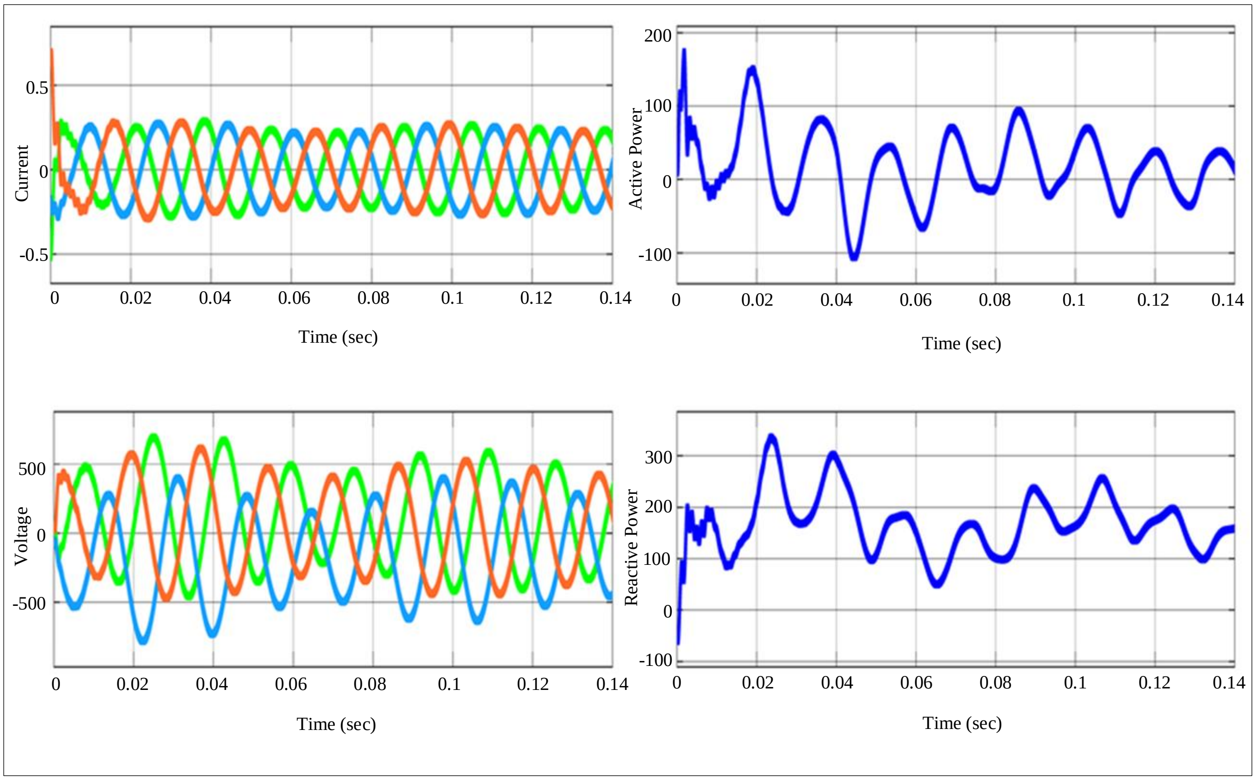

Fig. 11 Voltage, current, active and reactive power with STATCOM condition

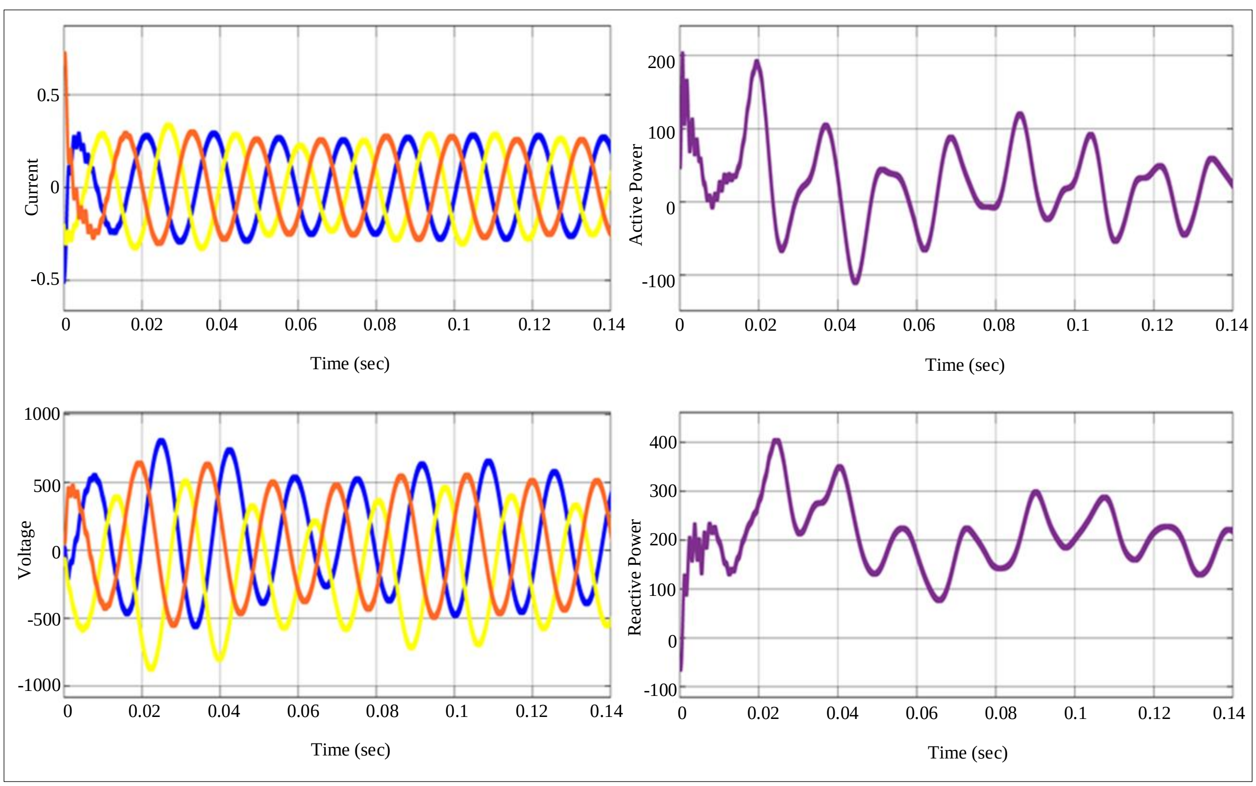

Fig. 12 Voltage, current, active and reactive power with 12 pulse STATCOM

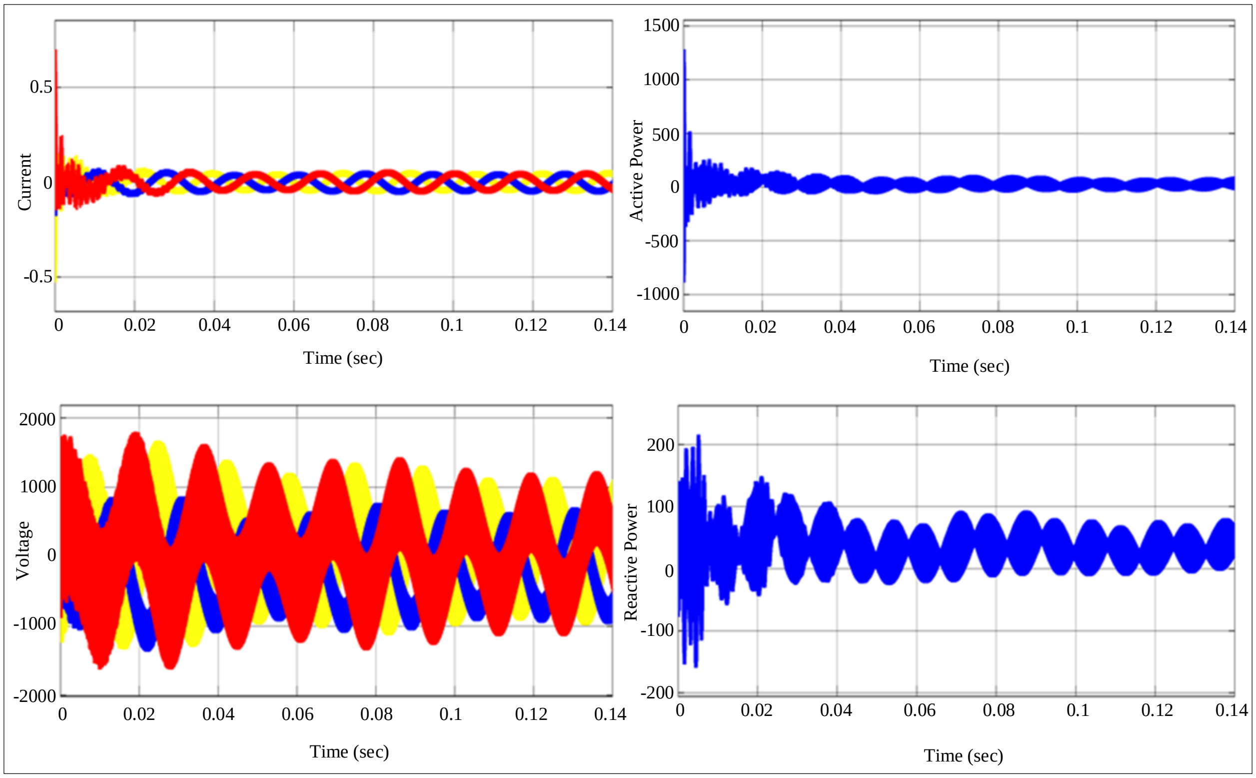

Fig. 13 Voltage, current, active and reactive power with 12 pulse STATCOM and ANN condition

3.3. WG Connected to IEEE 9 Bus System with Fault Compensated by STATCOM

Figure 11 in section 3.3 represents the connection of wind generation with the standard 9-Bus system with fault and STATCOM. When a fault occurs, this fault period voltage gets dropped and generated. Active power is decreased and absorbs reactive power which increases. In addition, STATCOM maintains the system voltage in steady state condition by getting a voltage of 226 kV, active power increases of 132.7 kW and reactive power of 25.7 MVAR. Once the issue is fixed, the generator speed returns to the normal state, and the mechanical and electromagnetic torques get balanced results, as mentioned in Table 2. After the fault clearance, reactive power (Q) is provided by the power system to recover the air-gap flux in case of an LLL-G fault, and the system resumes steady operation.

3.4. WG Connected to IEEE 9 Bus System with Fault Compensated by 12 Pulse STATCOM

Figure 12 represents the connection of WG with the standard 9-Bus system with fault and 12 pulse STATCOM. When a fault occurs, during this fault period, voltage is dropped and generated. Active power is decreased and absorbs reactive power, which increases with 12 pulse STATCOM, which improves harmonic distortion and maintains the system voltage in steady state condition. The result is obtained and mentioned in Table 2.

3.5. WG Connected to IEEE 9 Bus System with Fault Compensated by 12 Pulse STATCOM with ANN

Figure 13 represents the connection of wind generation with a standard 9-Bus system with fault and 12 pulse STATCOM with ANN. During this fault period, voltage is dropped and generated Active power is decreased and absorbed reactive power increases. With 12 pulse STATCOM and ANN for improving the performance of FACTS device and give exact accurate result and maintain the system voltage in steady state condition. The result is obtained and mentioned in Table 2.

4. Conclusion

To improve the electrical system's voltage stability, a disturbance mitigation device is needed between the power grid and the DFIG-based wind farm. To improve the distribution system's overall performance, The STATCOM has a link with the wind system at Bus 8 of the IEEE 9 system, which has 230 kV. Additionally, during grid failures, STATCOM can keep the wind system operational by preventing the mechanism for voltage protection from triggering the wind mechanism. With and without STATCOM, various fault scenarios have been simulated, including no-fault (normal condition), L-G, L-L, LLL-G, and a voltage drop of 25% at bus 8 is 230 kV. It is evident from the simulation and findings that using the PI controller in conjunction with STATCOM reduces voltage fluctuations while optimizing the system's stability.

Therefore preventing the preventing tripping and unplugging of generators and maintaining grid stability. When ANN is used in place of PI controllers, it has been found to improve performance over STACOM PI controllers by minimizing voltage variation and stabilizing generators. The obtained results are improved by the FACTS controller with ANN by up to 80%–90%. Finally, to provide suitable reactive control during faulty situations, the STATCOM is advised and mounted to the system at the load side of the load bus. The findings examined and assessed the numerous scenarios that can aid in the creation and management of the procedures for restoring the power system for the existing wind farms.

4.1. Future Scope

- This research has demonstrated a strong interest in creating reactive power coordinating techniques for improving voltage stability. In order to prevent system instability, reactive power coordination is essential. Proper collaboration between the wind sources and the STATCOM controller can overcome both transient and steady-state stability issues.
- Since STATCOMs are capable of displaying a brief transient overload capacity (usually between 150 and 200 percent) for two to three seconds. Therefore, using STATCOMs' overloading capacity can help with significant voltage stability problems.
- The integration of ANN and STATCOM holds potential for future advancements in research focused on improving load-side performance under various fault conditions across bus systems. Optimized Control Algorithms: Leveraging advanced optimization techniques with ANN to determine optimal STATCOM configurations and responses for various fault scenarios.
- Moreover, one efficient method for achieving grid code compliance for wind farms is to determine the best placement and rating of STATCOMs while considering various fault sites.
- Combining ANN with STATCOM provides a promising method to enhance power system reliability and stability under fault conditions. This integration could be essential for the future of intelligent power systems, potentially enabling fully autonomous grid management solutions.

References

[1] Ban H. Alajrash et al., "A Comprehensive Review of FACTS Devices in Modern Power Systems: Addressing Power Quality, Optimal Placement, and Stability with Renewable Energy Penetration," *Energy Reports*, vol. 11, pp. 5350-5371, 2024. [CrossRef] [Google Scholar] [Publisher Link]

[2] Osama Majeed Butt, Muhammad Zulqarnain, and Tallal Majeed Butt, "Recent Advancement in Smart Grid Technology: Future Prospects in the Electrical Power Network," *Ain Shams Engineering Journal*, vol. 12, no. 1, pp. 687-695, 2021. [CrossRef] [Google Scholar] [Publisher Link]

[3] Tze-Zhang Ang et al., "A Comprehensive Study of Renewable Energy Sources: Classifications, Challenges and Suggestions," *Energy Strategy Reviews*, vol. 43, 2022. [CrossRef] [Google Scholar] [Publisher Link]

[4] Montaser Abdelsattar et al., "Voltage Stability Improvement of an Egyptian Power Grid Based Wind Energy System Using STATCOM," *Wind Energy*, vol. 25, no. 6, pp. 1077-1120, 2022. [CrossRef] [Google Scholar] [Publisher Link]

[5] Mohammed Salheen Alatshan et al., "Improvement of the Performance of STATCOM in Terms of Voltage Profile Using ANN Controller," *International Journal of Power Electronics and Drive System*, vol. 11, no. 4, pp. 1966-1978, 2020. [CrossRef] [Google Scholar] [Publisher Link]

[6] Badreddine Babes, Amar Boutaghane, and Noureddine Hamouda, "A Novel Nature-Inspired Maximum Power Point Tracking (MPPT) Controller Based on ACO-ANN Algorithm for Photovoltaic (PV) System Fed Arc Welding Machines," *Neural Computing and Applications*, vol. 34, pp. 299-317, 2021. [CrossRef] [Google Scholar] [Publisher Link]

[7] Hamidia Fethia, and Abbadi Amel, "DTC-DPC of Induction Machine Connected to Wind Generator," *International Conference in Artificial Intelligence and Renewables Towards an Energy Transition*, pp. 79-87, 2020. [CrossRef] [Google Scholar] [Publisher Link]

[8] Muhammad sarwar et al., "Stability Enhancement of Grid-Connected Wind Power Generation System Using PSS, SFCL and STATCOM," *IEEE Access*, vol. 11, pp. 30832-30844, 2023. [CrossRef] [Google Scholar] [Publisher Link]

[9] Hossam S. Salama, and István Vokony, "Voltage Stability Indices–A Comparison and A Review," *Computers & Electrical Engineering*, vol. 98, 2022. [CrossRef] [Google Scholar] [Publisher Link]

[10] Mohamed Metwally Mahmoud et al., "Integration of Wind Systems with SVC and STATCOM during Various Events to Achieve FRT Capability and Voltage Stability Towards the Reliability of Modern Power Systems," *International Journal of Energy Research*, vol. 2023, 2023. [CrossRef] [Google Scholar] [Publisher Link]

[11] Asma Meddeb et al., "Voltage Stability Enhancement Using FACTS Devices," *2020 4th International Conference on Advanced Systems and Emergent Technologies (IC_ASET)*, Hammamet, Tunisia, pp. 257-260, 2020. [CrossRef] [Google Scholar] [Publisher Link]

[12] Samson Ademola Adegoke, and Yanxia Sun, "Power System Optimization Approach to Mitigate Voltage Instability Issues: A Review," *Cogent Engineering*, vol. 10, no. 1, 2023. [CrossRef] [Google Scholar] [Publisher Link]

[13] Vinoda Patil, and Nandakumar, "Voltage Stability Improvement in Multi-Bus System Using Static Synchronous Series Compensator," vol. 10, no. 6, pp. 1052-1059, 2022. [CrossRef] [Publisher Link]

[14] Ibrahim M. Mehedi et al., "Reducing Fault Current by Using FACTS Devices to Improve Electrical Power Flow," *Mathematical Problems in Engineering*, 2021. [CrossRef] [Google Scholar] [Publisher Link]

[15] Ismail Marouani et al., "Optimized FACTS Devices for Power System Enhancement: Applications and Solving Methods," *Sustainability*, vol. 15, no. 12, 2023. [CrossRef] [Google Scholar] [Publisher Link]

[16] Seyed Reza Mosayyebi, Seyed Hamid Shahalami, and Hamed Mojallali, "Fault Ride-through Capability Improvement in a DFIG-Based Wind Turbine Using Modified ADRC," *Protection and Control of Modern Power Systems*, vol. 7, no. 4, pp. 1-37, 2022. [CrossRef] [Google Scholar] [Publisher Link]

[17] Mohamadreza Kholousi, Sajjad Tohidi, and Naghi Rostami, "Impact of Wind Turbines on Voltage Stability of Power Systems: Assessment and Improvement," *2021 12th Power Electronics, Drive Systems, and Technologies Conference (PEDSTC)*, Tabriz, Iran, pp. 1-7, 2021. [CrossRef] [Google Scholar] [Publisher Link]

[18] Ann Marie Ining et al., "A Study on Voltage Stability Improvement Using STATCOM and UPFC," *2021 IEEE 9th Conference on Systems, Process and Control (ICSPC 2021)*, Malacca, Malaysia, pp. 34-39, 2021. [CrossRef] [Google Scholar] [Publisher Link]

[19] L. Narayana Gadupudi, and Gudapati Sambasiva Rao, "Recent Advances of STATCOM in Power Transmission Lines-A Review," *Turkish Journal of Computer and Mathematics Education*, vol. 12, no. 3, pp. 4621-4626, 2021. [Google Scholar] [Publisher Link]

[20] Rehan Sadiq et al., "A Review of STATCOM Control for Stability Enhancement of Power Systems with Wind/PV Penetration: Existing Research and Future," *International Transactions on Electrical Energy Systems*, 2021. [CrossRef] [Google Scholar] [Publisher Link]

[21] Prashant Kumar Singh, and Anil Kumar Dahiya, "Analysis Modelling & Simulation of VSC Based D-Statcom for Reactive VAR Compensation," *2018 International Conference on Current Trends towards Converging Technologies (ICCTCT)*, Coimbatore, India, pp. 1-6, 2018. [CrossRef] [Google Scholar] [Publisher Link]

[22] G. Madhan Mohan Reddy, and K. Kalyan Kumar, "Two-Level Inverter Based STATCOM for High Power Applications with PQ Controller," *International Journal & Magazine of Engineering, Technology, Management and Research*, vol. 3, no. 7, pp. 63-67, 2016. [Google Scholar] [Publisher Link]

[23] Maha Saad Dawood Salman, Ahmed J. Sultan, and Mhdi F. Bonneya, "Assessment of Power System Voltage Stability Using ANN," *IEEE 3rd International Conference on Technology, Engineering, Management for Societal Impact Using Marketing, Entrepreneurship and Talent (TEMSMET)*, Mysuru, India, pp. 1-9, 2023. [CrossRef] [Google Scholar] [Publisher Link]