FACT Device Analysis for WEC Integrated with Week Grid Voltage Stability: An Analysis of a Particular Site

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Abstract

In the modern period, wind power is always employed to generate electricity. It is more environmentally friendly and clean than other sources like diesel and thermal power plants. The utilization of renewable energy sources is increasing daily in India. India has a lot of potential for wind power. The only issue with power is the unpredictable nature of wind, which has an impact on total power generation and necessitates reactive power management. These days, a number of wind power projects are run in tandem with the grid. Because wind power plants produce varying amounts of power, these energy sources require effective power regulation. During speed fluctuations, wind turbines must be able to recover from short-duration faults and voltage imbalances without cutting off from the grid. This article aims to address the voltage stability issue at an old site in Madhya Pradesh, India, where E-31 Ratedi Enercon India wind turbines are being evaluated. The voltage level of the grid-connected wind converter under consideration is analysed using its 1-year data under a variety of operating conditions where output power varies with speed is simulated. Additionally, short-duration faults are created on a prepared base model, and the fault intensity is of E-31 collected data via SCADA. MATLAB 2021a software has been used for all simulation work. Lastly, the FACT devices SSSC, STATCOM, SVC, and UPFC are used to replicate the base model. It is discovered that the STATCOM device performs best for Voltage Profile Imbalances for failures with shorter durations.

Keywords: *FACT Devices, Wind Energy Convertor, Grid Integration, Renewable Energy Sources*

Introduction

In terms of the attractiveness of renewable energy countries for 2021, India is ranked third and is the world's third-largest energy consumer. By the end of 2022, the country hopes to produce 175 GW of renewable energy, and by 2030, it hopes to reach 500 GW. As of July 31, 2022, the total installed wind power capacity was 40.893 GW, making it the fourth largest installed wind power capacity globally. However, the unpredictable nature of wind creates variable wind power, which leads to other related issues such voltage control, reactive power, fluctuation, harmonics, flickers, etc. that cause instability in the already-existing network. To satisfy the demands of the expanding usage of wind energy, a wind farm must be able to support the network and function similarly to a traditional power generating plant.

The potential of the wind power generated and the design of the wind turbine generator are the primary determinants of the active power supply. Conversely, the grid's recovered power quality and conversion devices have an impact on the demand for reactive power. Voltage breakdown, reactive power redistribution, and volatility are all caused by wind farms connected to the electrical grid. Voltage variance caused by varying wind generation and dynamic voltage stability presents a major challenge for distribution network operators.

Reactive power management is essential since wind farm technology varies in its capabilities [1-3]. Reactive electricity must be transmitted over great distances because wind farms are typically found in isolated locations, which causes power loss. For wind farms to react to voltage fluctuations, which are connected to grid characteristics, reactive power control is crucial. Impedance and network short circuit capacity determine the effects of reactive power injection at different voltage levels. Because uncompensated reactive power stresses the hosting grid and has casting effects, reactive power correction is essential for wind farm operation and grid contribution. When transferring electricity to the main grid, reactive power compensation seeks to maintain a wind farm's voltage profile at a suitable level and reduce power losses while adhering to the grid code's connection requirements for reactive power exchange [9].

Reactive power is primarily adjusted by the station transformer's Under Load Tap Changer (ULTC). If the ULTC action does not meet grid requirements, reactive power requirements can be controlled using other compensator devices, such as static capacitors [25] and FACTS devices, such as Static Var Compensators (SVC), Unified Power Flow Controller (UPFC), Unified Power Quality Conditioner (UPQC), and Distributed Static Synchronous Compensators (DSTATCOM). The feasibility analysis, which takes into the account both technical and financial constraints, determines if VAR compensation mechanisms should be used. These devices are currently recommended for regulating the reactive power requirements of wind generators and are acceptable for controlling voltage stabilization. This increases the likelihood that wind electricity will be accepted into the worldwide distribution network.

Due to a number of technical, financial, and environmental advantages, wind energy has been employed more and more to generate power throughout the world in recent years. High-voltage transmission lines (TLs) are used to incorporate the bulk power produced by offshore wind farms into electric power networks. Large wind power flows may need the construction of new TLs or the upgrade of existing ones. More and more people are thinking about using FACTS-based compensating devices to increase the power transfer capacity of current TLs that connect wind farms. The UPFC [26–30] is one of the most important FACTS instruments. It effectively controls the line voltage and line impedance to independently and simultaneously manage the line active and reactive power flow. However, the nonlinear power versus wind speed characteristics of wind farms and the unpredictable line impedance variation during various UPFC operation modes greatly affect the effectiveness of conventional distance relaying-based TL protection techniques. The current article's main objective is to create a better protection plan for TLs connected to wind farms that have been compensated by UPFC.

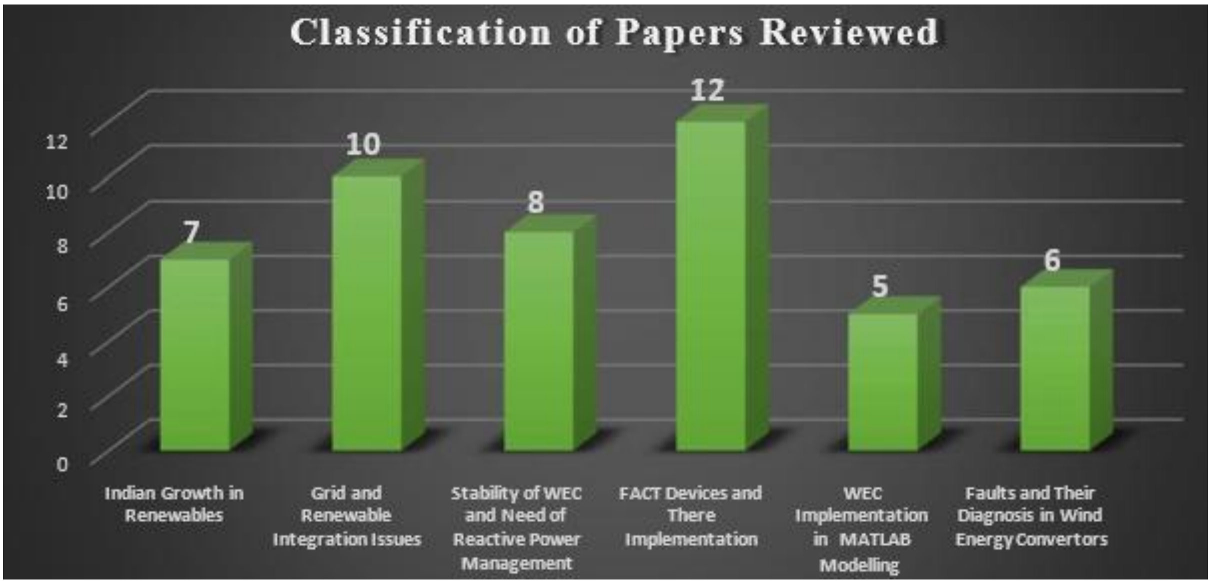


Figure 1: No of Papers Needed for MATLAB Implementation of WEC with Grid In MATLAB

The categorization of research papers related to this work to Model a Complete WEC (Wind Energy Convertor) of any site is displayed in Figure No. 1. Following this review study, a plan and technique are developed, the structure of which is depicted in Figure 2. The report is further categorized in several sections in accordance with this design and research objectives. Section II provides a brief explanation of relevant literature; Section III provides information about the Ratedi Site in Madhya Pradesh; Section IV examines the sources of voltage instability difficulties; and Section V examines the role of FACT devices. The 9 MW wind plant model is implemented in MATLAB, and various FACT devices are simulated both with and without fault conditions. The results are analyzed in the same section, and the article is concluded in section VI with a thank you to all the references taken into consideration.

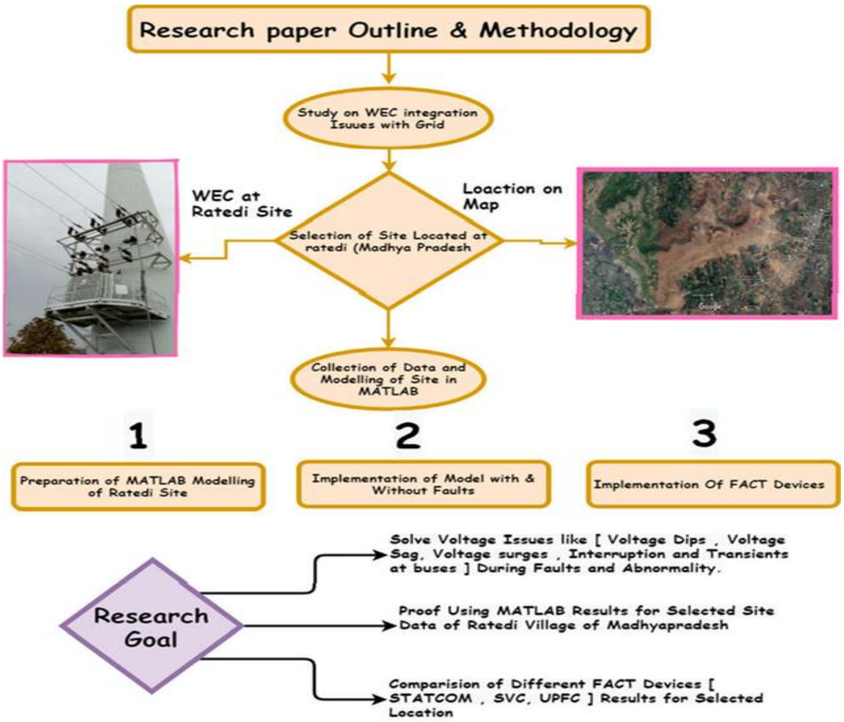


Figure 2: Proposed Plan and Research Goals for the Old site [Ratedi village Bhopal]

Related Previous Work

Research Gap: A crucial step in every research process is the literature review. A review of earlier research indicates that the effort and studies conducted by specific scholars and institutions contribute to further establishing the necessity of the study. Voltage stability is one of the most important grid integration concerns in wind-based distributed generation systems, according to a review of prior research and literature. A number of techniques were applied to improve voltage stability. The following table, Table No. 2, summarizes recent research publications from 2020 to 2022 on FACTS devices to improve stability of wind farms and WEC.

Table 1: Summary of Literature Review

Author	Year	Title	Findings
Mahmoud Ebadian *et al*. [4]	2014	Investigating the effect of high level of wind penetration on voltage stability by quasi-static time-domain simulation.	They use the Quasi Static Time Domain Simulations for Voltage stability analysis of Squirrel Cage induction generator.
J. Singh *et al*. [5]	2015	Voltage Stability of Wind Power by Using the FACTS Devices	They review several FACTS controllers for Voltage stability analysis (VSA) of the power system.
Luis Badesa *et al*. [6]	2016	Impact of Wind Generation on Dynamic Voltage Stability and Influence of the Point of Interconnection	They highlight the analysis of PCC for remotely located Wind Energy System.
Ramazan Bayindir *et al*. [7]	2016	Effects of renewable energy sources on the power system	They use Power Factory Software for Simulating RE Sources & comparative analysis between emergent changes to the bus voltage in the system before and after the interconnection of non-conventional energy sources is presented.
Z.D. Wu et al. [8]	2017	Influence on voltage stability of wind power connected to the grid	They used DFIG based WT's model and perform simulation in the PSCAD tool for capacity-based Voltage stability analysis of the system.
N. K. Rajalwal and P. Mishra. et al. [10]	2018	Impact of DFIG on voltage stability of a network in smart grid: An analysis	They use the Modal analysis method for voltage stability analysis of the Wind-based DG system.
Amirreza Gholizadeh et al. [11]	2018	A scenario-based voltage stability constrained planning model for integration of large-scale wind farms	They employed the 118 IEEE Test bus system to conduct a research on the Iranian grid for the interconnection of wind power. Additionally, describe the planning model with Voltage Stability constraints.
Sree Latha K et al. [12]	2018	Dynamic Voltage Stability Enhancement of a Wind Farm Connected to Grid Using Facts- A Comparison	They emphasized the use of FACTS for Voltage Stability Enhancement they use SVC & Statcom for Wind Interconnected Power System.
Sarika D. Patil et al. [1]	2012	Improvement of Power Quality Considering Voltage Stability in Grid Connected System by FACTS Devices	They recommend the Use of Statcom for improving both Steady State and the transient response of the entire system.
Y. Zhou et al. [2]	2013	Connecting Wind Power Plant with Weak Grid Challenges and Solutions	They discussed the issues in the integration of WEG's in the existing grid & highlights the issue of Voltage stability.

Author	Year	Title	Key Contribution / Findings	Limitations
Sheikh et al [32].	2021	Voltage Stability Enhancement of Grid-Connected Wind Farm Using Hybrid D-STATCOM	Hybrid D-STATCOM improves voltage stability, reduces voltage deviations and active power loss	Simulation-based study, no cost analysis
Nallagonda and Chandorkar [33]	2021	A Novel Voltage Control Strategy for a Hybrid Wind Energy Conversion System with STATCOM	STATCOM and hybrid voltage control strategy improves voltage stability, reduces THD and power loss	Simulation-based study, no comparison with other FACTS devices
Li et al [34].	2021	Voltage Stability Enhancement of Wind Farm Based on Hybrid SVC-STATCOM and Optimal Power Flow	Hybrid SVC-STATCOM improves voltage stability and reduces power loss, OPF used for optimal operation	Simulation-based study, no comparison with other FACTS devices

Guo et al. [35]	2021	Voltage Stability Enhancement of Grid-Connected Wind Farms Using a Hybrid UPFC	Hybrid UPFC improves voltage stability, reduces voltage deviations, and active power loss	Simulation-based study, no comparison with other FACTS devices
Fahmy et al. [36]	2022	Voltage Stability Improvement of Wind Farm Based on Hybrid UPQC-STATCOM	Hybrid UPQC-STATCOM improves voltage stability, reduces voltage deviations, and active power loss	Simulation-based study, no comparison with other FACTS devices
Dogramaci and Dursun [37]	2022	Power Quality Enhancement and Voltage Stability Improvement of a Wave Energy Converter System with a Hybrid D-STATCOM	Hybrid D-STATCOM improves voltage stability and reduces THD, active power loss	Simulation-based study, no comparison with other FACTS devices

Reviewing the Above literature, a real case study is considered in this paper of a site and Modelling is simulated in the later section of the paper using MATLAB.

Details of 9 MW Ratedi Wind Power Plant

Madhya Pradesh, which is situated at 22.42º N and 72.54º, is the second largest state in terms of area. Chhattisgarh to the east, Uttar Pradesh to the northeast, Gujarat to the west, Rajasthan to the northwest, and Maharashtra to the south are its neighbours. Out of the ten states in India that produce the most wind power, it comes in at number seven. Table 2 shows the wind power generation capacity by district.

Table 2: District Wise Capacity of Wind Power Generation

S.No.	*District*	*Proposed Capacity [in MW]*	*Installed Capacity [in MW]*	*Mean Wind Power Density at 50m W/m^2*
1	Dewas	180.75	129.75	*287*
2	Ratlam	604.8	105.25	*255*
3	Mandsaur	159.5	4.80	*222*
4	Betul	236	Not Yet Installed	*215*
5	Badwani	167.50	Not Yet Installed	*255*
6	Shajapur	139.20	54.00	*217*

District Ratlam has the highest potential for wind power, as seen in the table above. Installations have currently been completed in the districts of Dewas, Ratlam, Mandsaur, and

Shajapur. There are 598 wind monitoring stations deployed nationwide, of which 225 are designated as wind power sites with a wind power density more than 200 W/m2. Table 2 shows the data of windy speed locations in Madhya Pradesh. The Government of India has built up dedicated wind speed monitoring sites in a number of districts, including Barwani, Betul, Dewas, Khargone, Ratlam, Shajapur, and others, which have good wind power potential. Barwani district has been shown to have a high wind speed. As of now many projects were in operation in District Dewas and in Ratlam.

This study takes into the account the Wind Power Plant in Ratedi Village, District Dewas, Madhya Pradesh, which is 165 km from Bhopal and 45.9 km from Indore. The Ratedi Wind Power Plant's geographic location is shown in Fig. 3.

Figure 3: (a) Geographical Location of Ratedi Wind Power Plant (b) Ratedi Wind Power Plant

Ratedi Wind Farm is depicted in the above figure. KS Oils Pvt. Ltd. is in charge of the 34 800 KW machines that are placed in this wind power plant. However, Manganese Ore (India) Limited, Nagpur, is in charge of 19 800 KW machines in another area of the plant. The Wind Asset Monitoring System, an online SCADA software system, is used to control all of the equipment. It programs and interfaces with a microcontroller-based system to identify any issues with the WEG's system. Measures are taken so that a remote-control system, such as a wind asset monitoring system, can perform several corrective actions. The appendix mentions the wind speed statistics.

Voltage Stability Problem and Roll of FACT devices

Voltage Stability of Wind Based DG System: The Voltage Stability is classified as;

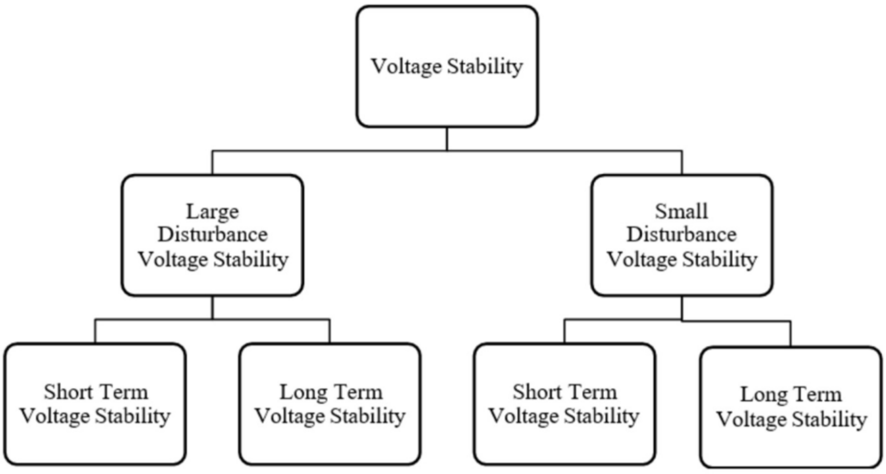


Figure 4: Classification of Voltage Stability

Following are major causes for voltage Instability:

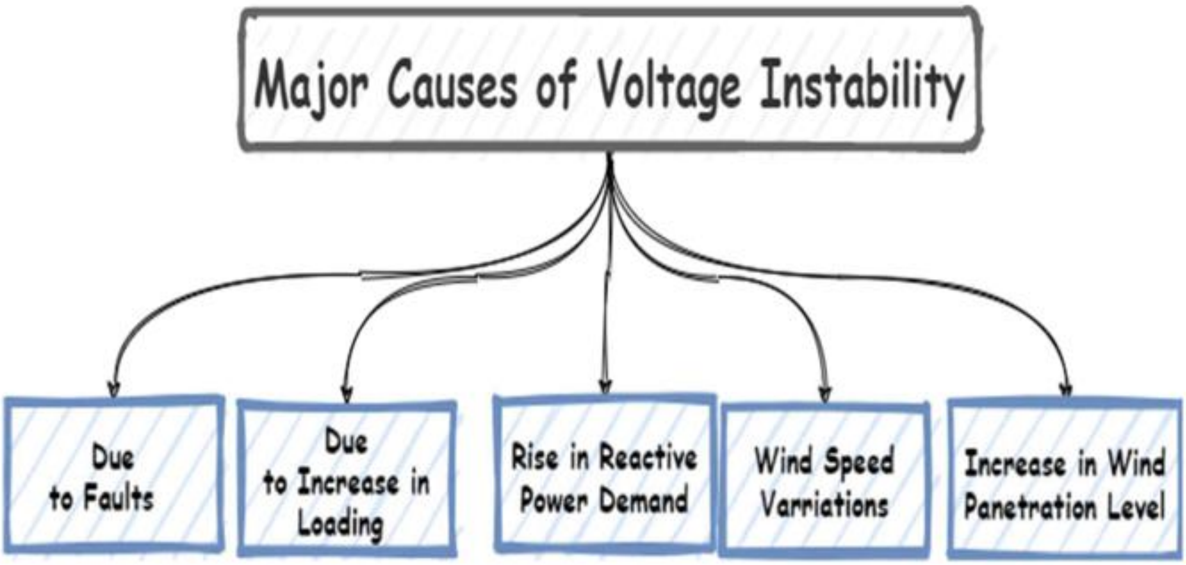


Figure 5: Causes of Voltage Stability

Roll of FACT devices

FACTS are solid state flexible devices that enhance the transmission line's power handling capability, transient stability, system dependability, load management, and power flow control. The FACTS device family members are shown in Fig. 3.

(1) Thyristor Controlled Series Compensator (TCSC)

(2) Thyristor Switched Series Reactor (TSSR)

(3) Thyristor Controlled Series Reactor (TCSR)

(4) Thyristor Switched Series Capacitor (TSSC)

(5) Static Var Compensator (SVC)

(6) Static Synchronous Compensator (STATCOM)

(7) Static Synchronous Series Compensator (SSSC)

(8) Thyristor Controlled Phase Shifting Transformer (TCPST)

(9) Unified Power Flow Controller (UPFC)

Table 3: FACT Devices Required Features for their Implementation in MATLAB

Name of FACT Device	Design Characteristics	Working of Device	Advantages and Disadvantages
TCSC	Series connected capacitor with thyristor-based controller	Controls the total Susceptance of the transmission line using the firing angle of the thyristor	(i) Enhanced real power transfer and better sub-synchronous resonance and oscillation damping. (ii) Requires bulky capacitors and reactors
SSSC	Series-connected, utilizes voltage source converter with gate turnoff switch	Compensates the transmission line reactance by means of a with gate turnoff switch	(i) Does not need big reactors and capacitors (ii) Able to inject actual electricity using a power source that is linked to its DC side. (iii) More expensive and difficult than TCSC
SVC	Shunt. Connected with various possible configurations of thyristor-controlled capacitors and reactors	Total Susceptance is controlled by controlling the firing angle This in turn controls the terminal voltage of the connected bus.	(i) Cheaper than STATCOM, with lower losses (ii) Slower response due to time delay associated with thyristor. Switching
STATCOM	Shunt connected, employs voltage source converter with pulse width modulation controller	In order to offer reactive power compensation for the linked power system, the voltage source converter transforms a DC voltage into a sinusoidal output voltage with controlled amplitude and phase angle.	(i) is more effective than SCV and has constant current characteristics at low voltages, enabling it to inject or absorb reactive power during low voltage grid conditions. (ii) Higher losses and higher cost than SVC of similar ratings.
UPFC	Series-shunt connected, combination of and shunt voltage-source inverters connected via a DC link	Provides active and reactive power flow control by means of the series and shunt converters operating via a common DC link and shunt capacitor storage system.	(i) Combines the advantages of SSSC and STATCOM. (ii) Able to inject and absorb both real and reactive Power (iii) Higher cost and complexities compared to other FACTS

Considered MATLAB Model Analogous to Ratedi Site

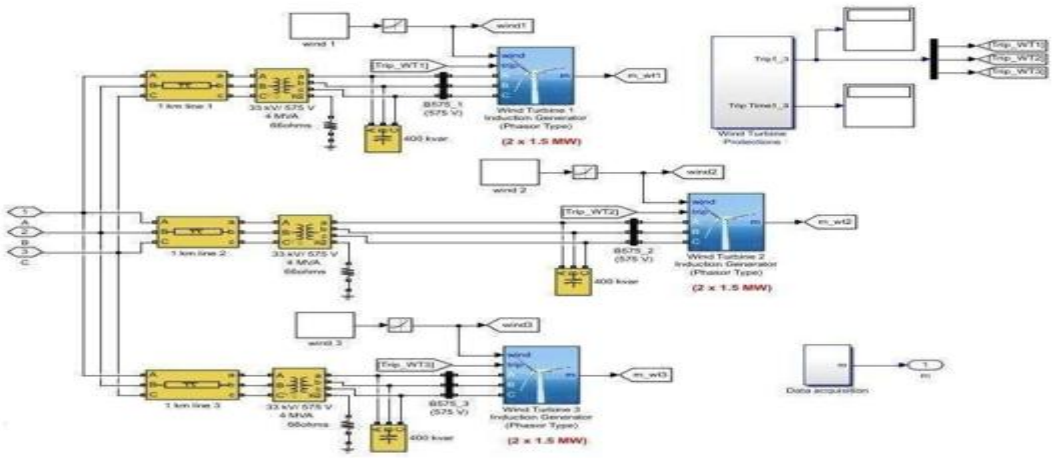


Figure 6: Simulation Model of Wind Turbine System

Wind Turbines are working very effectively in wind Power plants. [28]

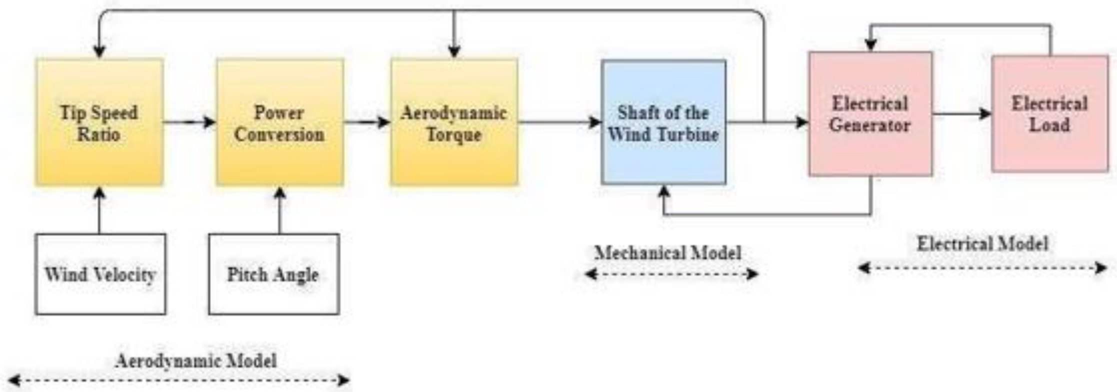


Figure 7: Mathematical Model of Wind Turbine

The power obtained from WEG’s system is:

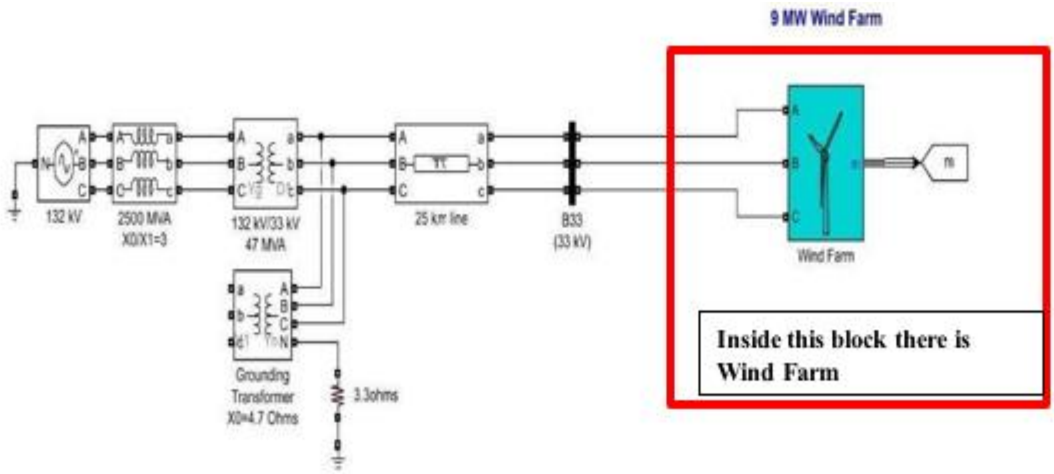
$P = 1/2\ \rho\ V^3$

$P_m = 0.5 T_p (\lambda, \beta)\ \rho A V W^3$

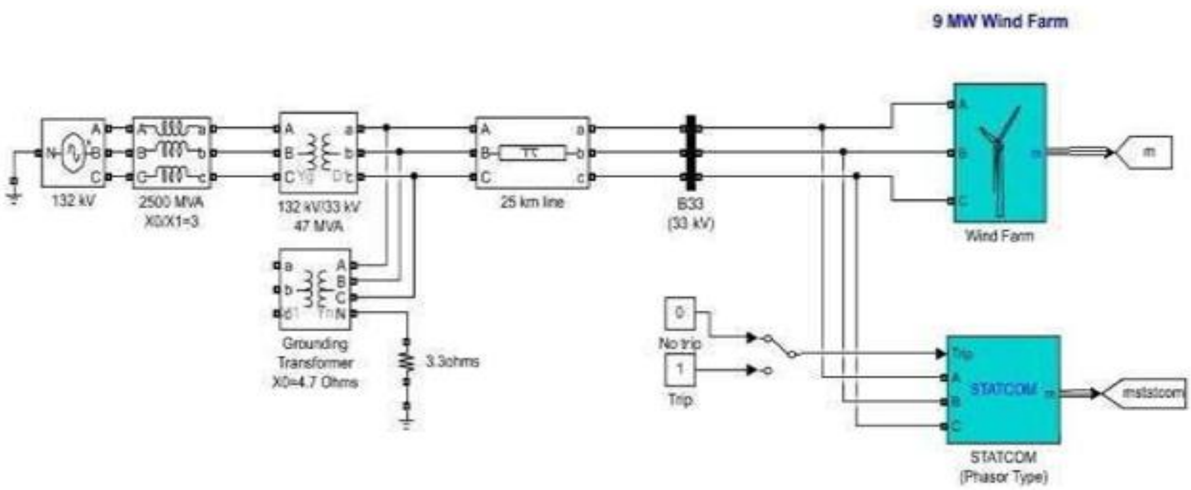
The MATLAB software model of WT's System is shown in Figure 6. Six wind generators, each with a 1.5 MW capacity, are connected in this concept. They are connected in groups of three, each of which has two 1.5 MW generators. A portion of 9 MW is made up of all these groups. Transformers are used to connect all of these generators to the grid. They are related to a variety of data monitoring and safety equipment.

Simulation Model of Considered Site

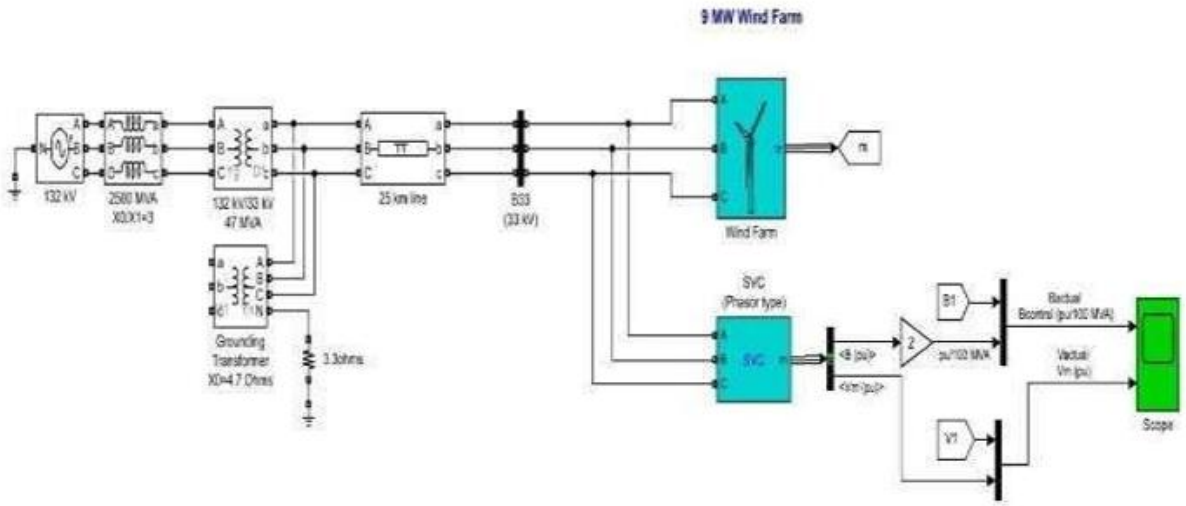
This study examines the voltage stability of a subset of wind power plants in Ratedi Village, Dewas District, Madhya Pradesh, India. MATLAB software is used to create the simulation model. This wind power plant has a 9 MW capacity. The generator's output is sent to a step-up transformer with a 47 MVA (33/132 KV) capacity via a 25 km transmission line, and one load is attached. MATLAB R2021a is used to simulate this model. Figure 6 shows the simulation model.



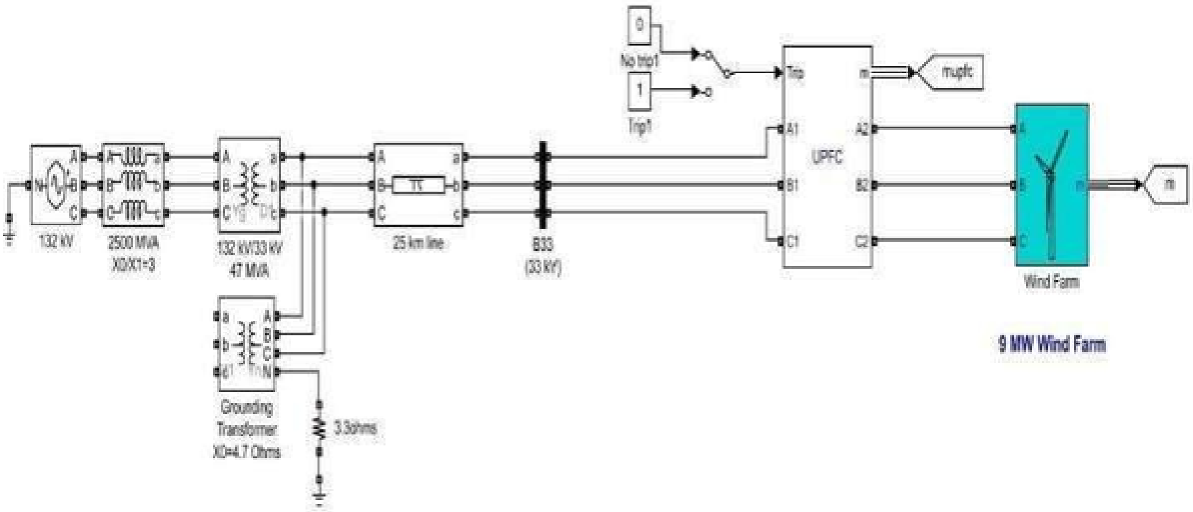
(a) Wind farm with no FACT Device



(b) Wind farm with FACT device {STATCOM}



(c) Wind farm with FACT device {SVC}



(d) Wind farm with FACT device {UPFC}

Figure 7: Grid connected Wind Farm; (a) Wind farm with no FACT Device (b) Wind farm with FACT device {STATCOM} (c) Wind farm with FACT device {SVC} (d) Wind farm with FACT device {UPFC}

The purpose of this research is to investigate how various pieces of equipment might improve the voltage stability of the Ratedi Wind Farm, a portion of a distributed generation site. As mentioned in the last chapter, MATLAB software is used to create simulation models for a portion of the Ratedi Wind Power Plant. The following conditions are taken into the account for simulation:

- ✓ Case 1 (Under Normal Operating Condition): In this scenario, there are no disruptions and the system is operating normally.
- ✓ Case 2 (Under malfunction Condition): In order to examine the anomalous operating conditions, the simulated system experiences a malfunction after 15 seconds, which results in a decrease in system voltage.
- ✓ Case 3 (With Statcom): We can raise the system voltage level by utilizing an appropriate FACTS device. In this instance, Statcom is attached to the simulated system to raise the voltage value that has been lowered because of the malfunction.
- ✓ Case 4 (With SVC): In this scenario, we attach SVC to the simulated system in spite of Statcom in order to increase the voltage that is decreased as a result of the fault.
- ✓ Case 5 (With UPFC): In this instance, an increase in voltage in the simulated subsection of the site under consideration is associated with UPFC.

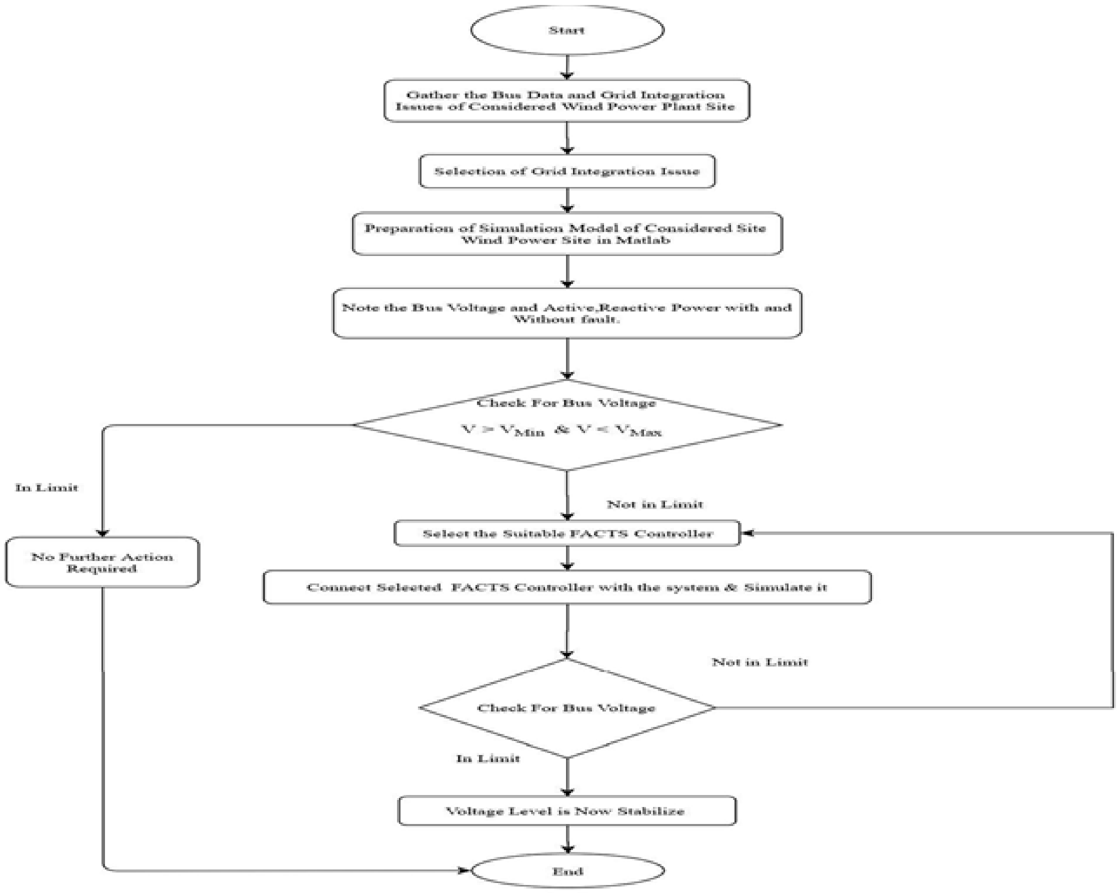


Figure 8: Flow Chart Implemented in MATLAB for all the Above Models While using various FACT Devices

Analysis Outcomes

In India, the use of renewable energy sources (RES) to generate electricity has significantly expanded. When this kind of generating station is used in tandem with the grid, voltage instability issues arise. It is mostly noticed when a weak grid is connected to this system.

Table 4: Magnitude of Bus Voltage in Various Operating Modes

S.No.	State of Sub Section of Considered Site	Value of Bus Voltage (in per Unit)
1	Normal Condition	0.995
2	Under Fault Condition	1.116
3	With Statcom	1.054
4	With SVC	1.127
5	With UPFC	1.497

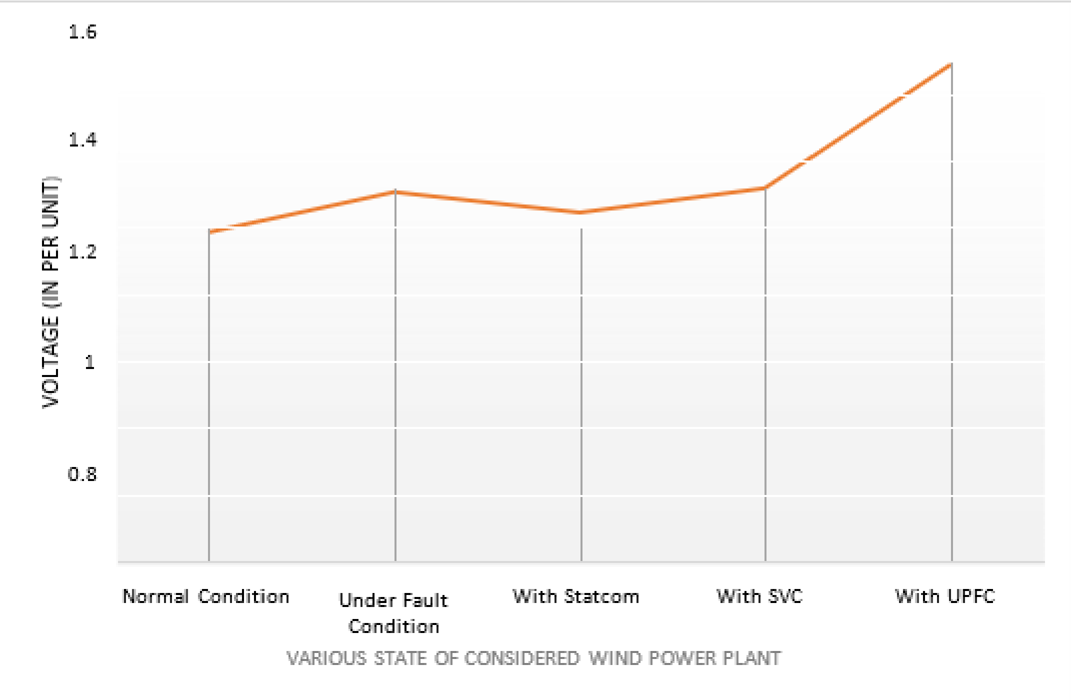
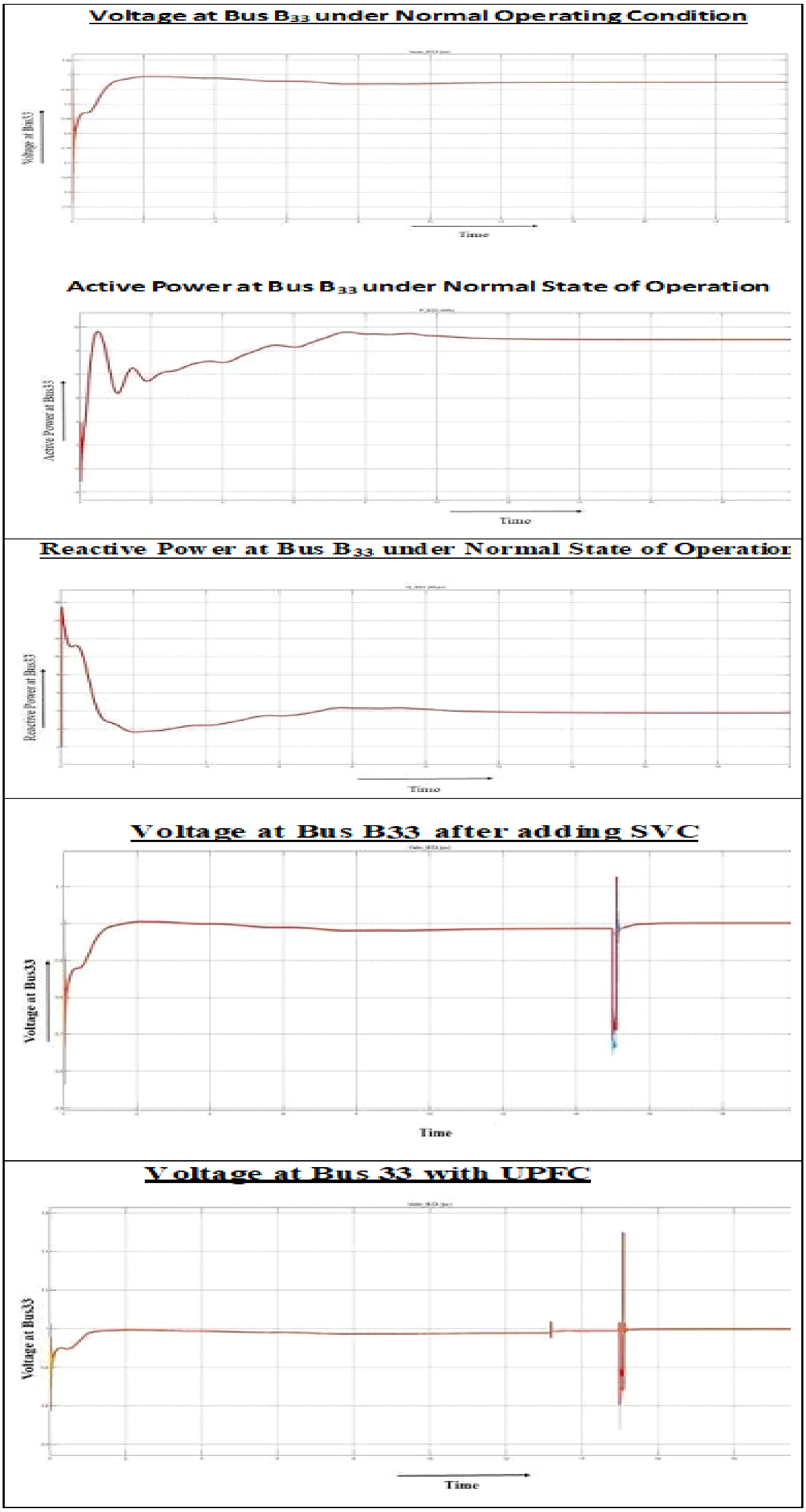
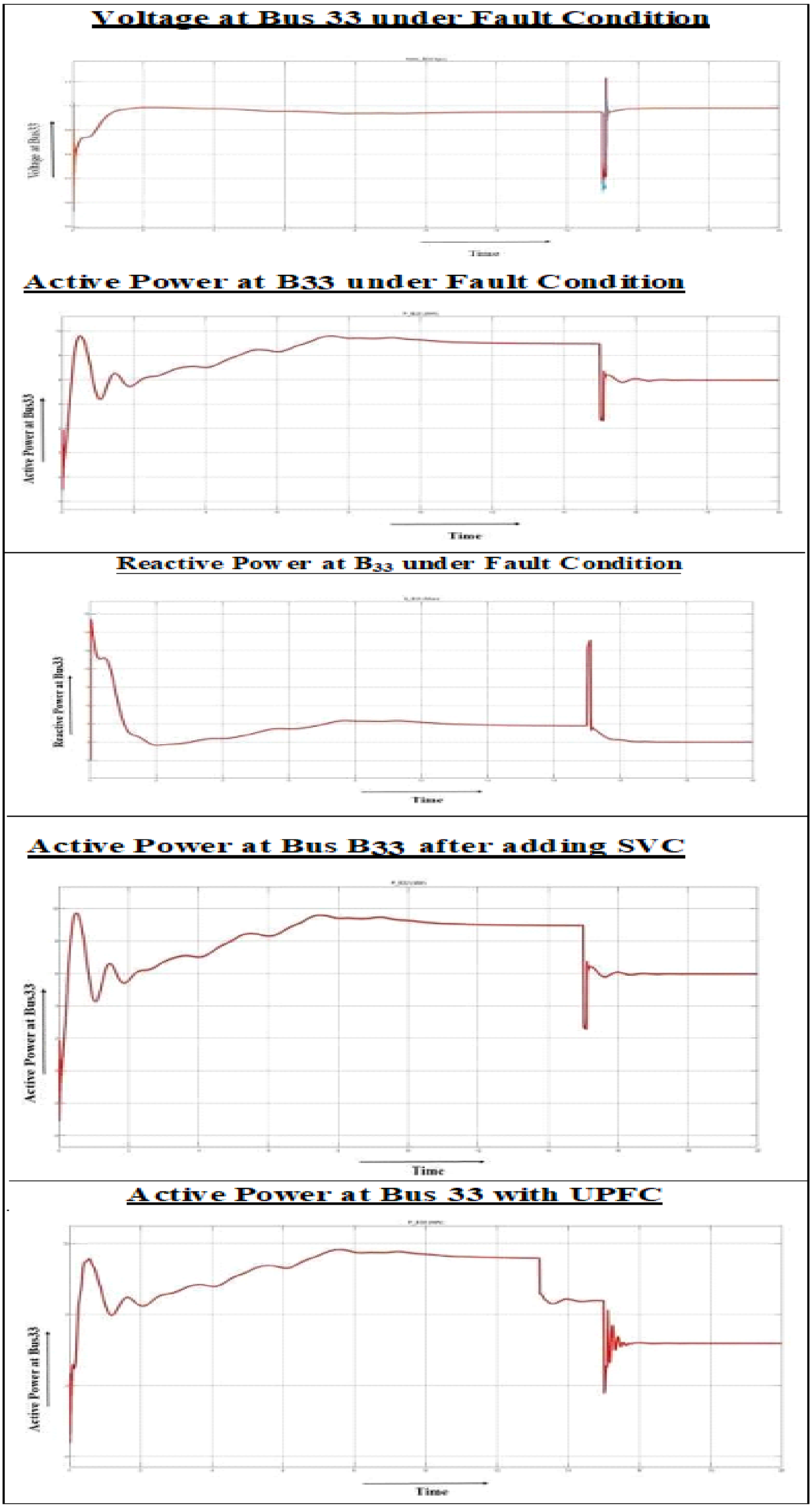


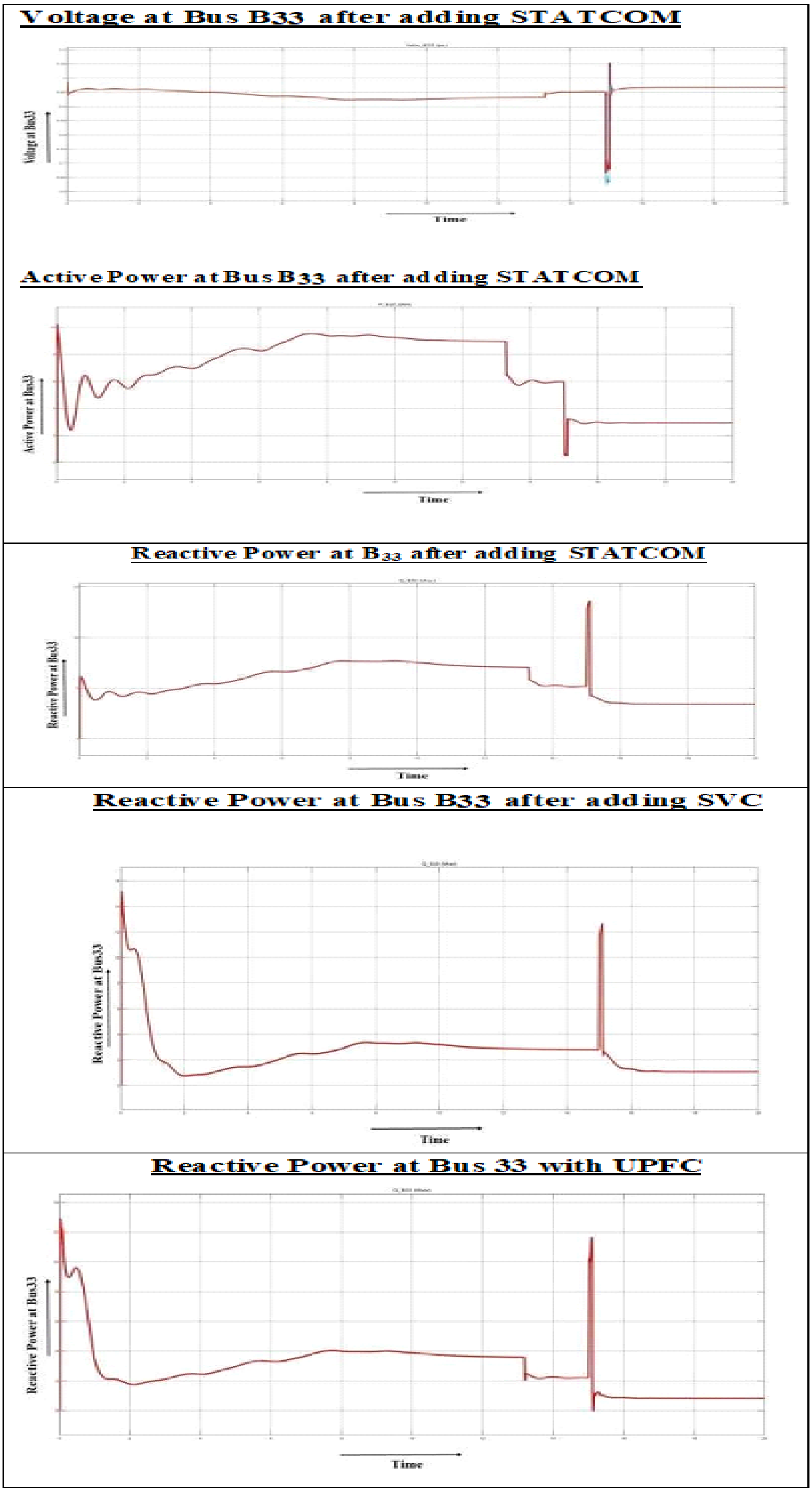
Figure 9: Comparative Analysis between Voltage Values


Voltage at Bus B33 under Normal Operating Condition
Voltage at Bus33
Time
Active Power at Bus B33 under Normal State of Operation
Active Power at Bus33
Time
Reactive Power at Bus B33 under Normal State of Operatior
Reactive Power at Bus33
Time
Voltage at Bus B33 after adding SVC
Voltage at Bus33
Time
Voltage at Bus 33 with UPFC
Voltage at Bus33
Time

(a)


Voltage at Bus 33 under Fault Condition
Voltage at Bus33
Time
Active Power at B33 under Fault Condition
Active Power at Bus33
Time
Reactive Power at B33 under Fault Condition
Reactive Power at Bus33
Time
Active Power at Bus B33 after adding SVC
Active Power at Bus33
Time
Active Power at Bus 33 with UPFC
Active Power at Bus33
Time

(b)


Voltage at Bus B33 after adding STATCOM
Voltage at Bus33
Time
Active Power at Bus B33 after adding STATCOM
Active Power at Bus33
Time
Reactive Power at B33 after adding STATCOM
Reactive Power at Bus33
Time
Reactive Power at Bus B33 after adding SVC
Reactive Power at Bus33
Time
Reactive Power at Bus 33 with UPFC
Reactive Power at Bus33
Time

(c)

Figure10: Results obtained after Running the simulation model for all the three FACT devices (a) with STATCOM (b) With SVC (c) with UPFC for Examining their Behavior under Normal and Faulty Conditions [The voltage profile ,Active Power and Reactive Power Compensation is Examined in MATLAB, the fault L-L-G is subjected at 15 seconds and at 15.1 second it was removed so the above results are for that durational behavior of FACT device for Ratedi Site ,WEC E-31 Convertor wind FARMS]

Conclusion

In the modern period, wind power is always employed to generate electricity. It is clean and environmentally favorable when compared to other sources like diesel and thermal power plants. The utilization of renewable energy sources is increasing daily in India. India has a lot of potential for wind power. The only issue with power is that wind's fluctuating characteristics have an impact on the total amount of power generated. These days, a number of wind power projects are run in tandem with the grid. Because wind power plants produce varying amounts of power, these energy sources require effective power regulation. During a fault phase, wind turbines must be able to continue operating without cutting off from the grid.

An attempt has been made to address the issue of voltage stability at the site of concern in this research. With the aid of simulation models, the voltage level of the grid-connected wind power plant under consideration is being examined under various operating scenarios. MATLAB software is used for all simulation tasks.

In this paper, a segment of the WEG system's voltage stability is investigated under various conditions using MATLAB software. The capacity of fact devices such STATCOM, SVC, and UPFC to improve the voltage stability of the wind-based DG system operating in grid integration is also examined in this paper. Different control mechanisms and modeling are being discussed.

The study's findings demonstrate how well STATCOM regulates the system's voltage and controls Q (reactive power). It increases the transmission system's dependability and aids in system stabilization even after a short circuit fault occurs. Out of the three devices tested in this investigation, STATCOM is shown to be the most effective fact device for enhancing the voltage stability of the site under consideration.

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