International Journal of Innovation in Computer Science and Information Technology
Vol.5, NO.1 , P:49-62
Received: 21 April 2024
Accepted: 15 February 2025

The Effect of Using STATCOM Controller in Wind Turbine Farms to Enhance Power Quality

Mohammad Amin Shabani Astani
Instructor, Department of Electrical Engineering, Islamic Azad University, Neka Branch, Neka, Iran (Corresponding Author)
Email: amin.shabani.990@gmail.com
Ershad Sadeghi Toosi
Faculty Member, Islamic Azad University, Neka Branch, Neka, Iran

Abstract:

The injection of wind power into the electrical grid affects voltage quality. Since the voltage level must comply with certain limits to meet essential requirements, this effect should be evaluated before installation. To assess the impact, knowledge of the electrical characteristics of wind turbines is necessary; otherwise, the result could easily be an improperly designed grid connection. The method for this evaluation is explained and demonstrated through case studies involving a 9 MW wind farm connected to a 25 kV distribution feeder. The analysis shows that the wind farm's capacity can operate without causing unacceptable voltage quality on the grid. For comparison, a simplified design criterion is considered, assuming the wind farm maintains the voltage range, which is established using a STATCOM.

Keywords: Wind turbine, STATCOM, Voltage

1. **Introduction**:

This article addresses the power quality of wind turbines. It is divided into three sections. The first section describes the electrical systems used in wind turbines. The second section presents measurement results for various wind turbines connected to different types of grids. These measurements include voltage and frequency, with discussions on variations, flicker, transients, and harmonics. The third section illustrates the impact of wind turbines.

The performance of wind turbines affects the power quality of the connected grid. Depending on the grid configuration and the type of wind turbine used, different power quality issues may arise. All wind turbines experience fluctuating power generation due to natural wind variations. For fixed-speed wind turbines, tower shadowing and wind speed gradients result in power oscillations.

Power fluctuations caused by turbines can lead to flicker problems. A disadvantage of variable-speed wind turbines is the generation of harmonic currents in the grid. The level of harmonics produced is affected by the kind of inverter employed. Current guidelines provide tools to foresee the relationship between wind turbines and the grid. When integrated with the grid, wind turbines can potentially cause power quality issues. Electrical Systems Used in Wind Turbines: The electrical systems utilized in wind turbines are typically divided into two categories: grid-connected and off-grid systems.

Grid-Connected Systems:

Although small wind turbines are typically off-grid systems, they can also be connected

International Journal of Innovation in Computer Science and Information Technology
Vol.5, NO.1 , P:49-62
Received: 21 April 2024
Accepted: 15 February 2025

to a utility company's power distribution system (the grid). These are known as grid-connected wind turbine systems. For effective operation, a small wind turbine connected to the grid requires an average annual wind speed of approximately 10 to 15 miles per hour. Grid-connected wind turbines are only allowed to operate when the electrical grid is online. In the event of a power outage, the wind turbine must shut down due to safety concerns related to islanding.

Islanding refers to a condition where a generator continues to supply power to a location even when the main grid is offline. This can pose a risk to utility workers who might not realize that a circuit is still live. A grid-connected wind turbine project requires collaboration with the utility company to establish the connection. Utility companies have developed interconnection standards that specify the special equipment and meters to be installed for the service. Additionally, an electrical inspector must approve the system before the utility company allows it to be connected to the grid. The inspector must ensure that all electrical work is completed by a licensed electrician.

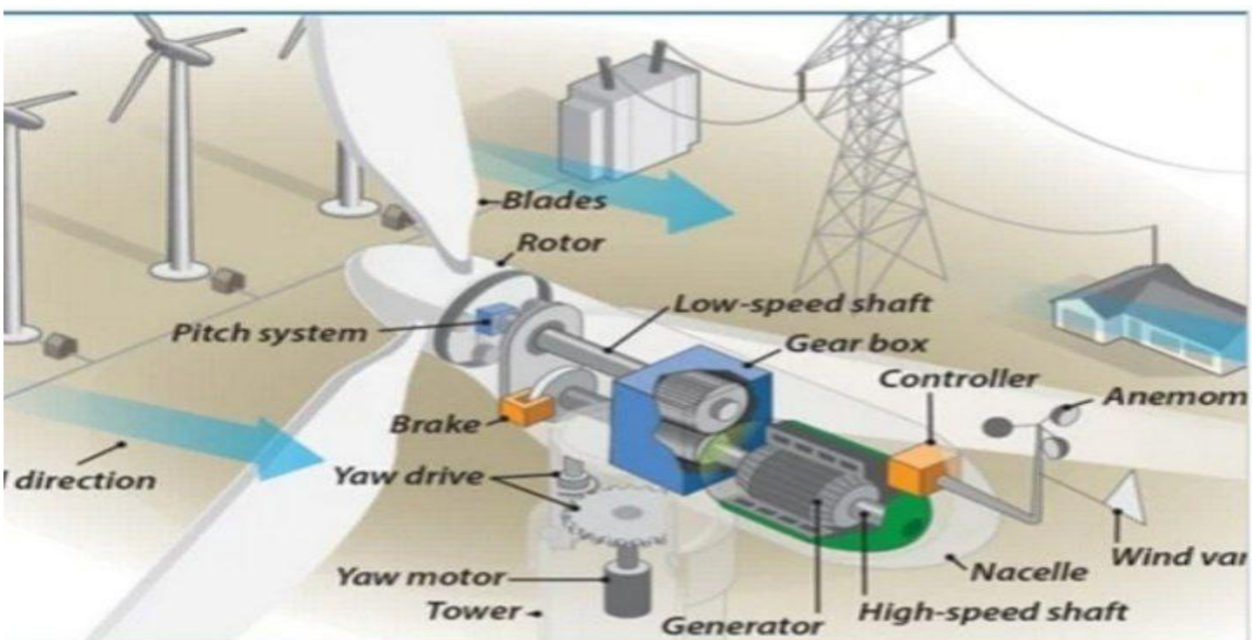

Figure 1: A Wind Farm with an Internal View of a Wind Turbine

International Journal of Innovation in Computer Science and Information Technology
Vol.5, NO.1 , P:49-62
Received: 21 April 2024
Accepted: 15 February 2025

Off-Grid Systems:

Small wind turbines that are not connected to the grid are known as off-grid wind turbine systems, also referred to as standalone systems. Off-grid wind systems can be installed to achieve energy independence from the grid. However, homeowners must be comfortable with the uncertainty of power generation due to fluctuations in wind speed. Off-grid wind systems can be combined with solar PV systems to create a more reliable hybrid electrical system. Wind and solar PV energy production, along with battery storage, can further enhance the efficiency and reliability of off-grid systems. Off-grid wind turbine systems are generally smaller and less expensive than grid-connected systems. Small wind turbines used in off-grid systems require annual maintenance, which typically involves climbing the wind turbine tower. However, small wind turbines with tilt-up towers can be lowered to the ground for maintenance. Wind's kinetic energy is converted into electrical energy using a wind turbine. Fundamentally, there are two types of wind turbines, differentiated by the orientation of their axis or shaft. A horizontal-axis wind turbine (HAWT) usually consists of a set of three blades mounted on a horizontal shaft connected to an electric generator. This traditional windmill-style turbine is used in a variety of applications, ranging from 5 MW wind farms to 100 kW residential setups.

In fixed-speed wind turbines, the generator is typically of the induction type, directly connected to the grid. Synchronous generators were used in some early designs, but induction machines have become widely adopted due to their lower cost, improved environmental durability, and superior mechanical compatibility with rapid wind fluctuations. The generator, along with a gearbox, is housed in a nacelle atop the tower. The gearbox's role is to convert the low rotational speed of the turbine into a high rotational speed for the generator. The rotational speed of an induction generator is usually 1000 or 1500 revolutions per minute (RPM) [1]. The turbine's speed depends on the rotor diameter; for instance, a 200 kW turbine has a rotational speed of approximately 50 RPM, while a 1000 kW turbine operates at around 30 RPM. Figure 2 illustrates the main components of a fixed-speed wind turbine.

A fixed-speed wind turbine is designed to achieve maximum efficiency at a specific wind speed, which provides the optimal tip speed ratio for the rotor's airfoil. To harness more energy, some fixed-speed turbines have two different rotational speeds. This can be achieved using two separate generators or a single generator with two windings.

International Journal of Innovation in Computer Science and Information Technology
Vol.5, NO.1 , P:49-62
Received: 21 April 2024
Accepted: 15 February 2025

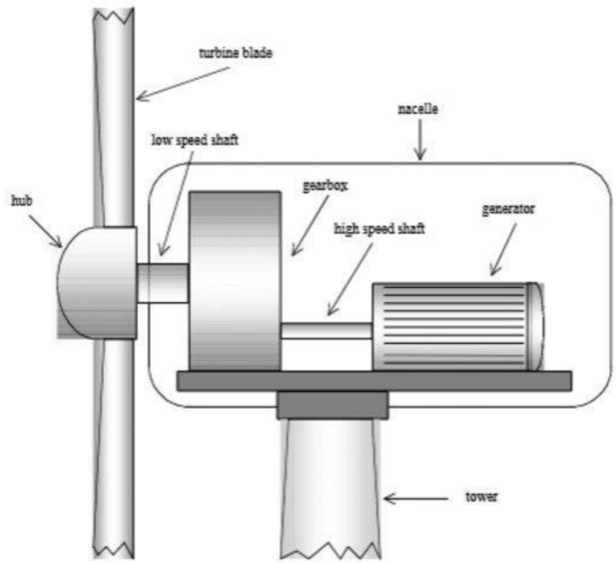

Figure 2: A View of a Typical Fixed-Speed Wind Turbine

Flicker:

One of the most critical issues in the power quality of wind turbines is flicker, or voltage fluctuations [2]. Flicker is defined as: "The effect caused by fluctuations in lighting or changes in the spectral output of a lamp, as perceived by the human eye" [3]. Flicker can lead to consumer dissatisfaction and is considered a factor in limiting the connection of wind turbines to weak grids.

Flicker emissions from grid-connected wind turbines during steady-state operation are caused by active power output fluctuations, which result from disturbances in wind speed and the shadowing effect of the turbine tower. Factors such as wind characteristics (average wind speed and turbulence intensity) and grid conditions (short-circuit level and grid impedance angle) significantly influence flicker propagation. Additionally, the type of wind turbine affects the level of flicker in the power network. Variable-speed wind turbines perform better in flicker mitigation compared to fixed-speed turbines [4].

Several methods have been proposed to improve the power quality of DFIG wind turbines, particularly in reducing flicker, including:

• Using FACTS devices such as STATCOM alongside the turbine to mitigate flicker [5].

• Utilizing the grid-side converter as an active parallel filter to improve voltage harmonics in the grid [6].

• Employing the rotor-side converter and controlling rotor current to enhance

International Journal of Innovation in Computer Science and Information Technology
Vol.5, NO.1 , P:49-62
Received: 21 April 2024
Accepted: 15 February 2025

harmonic suppression and address voltage imbalance [7, 8, 9].

• Leveraging the turbine's inertia to reduce output voltage fluctuations [10].

Transient State:

Transients primarily occur during the startup and shutdown of fixed-speed wind turbines [??]. The startup sequence for a fixed-speed wind turbine is carried out in two stages. First, the generator is switched on. To prevent high inrush currents, a soft starter is used. Once the soft starter is activated and the generator is connected to the grid, shunt capacitor banks are switched on.

The shunt capacitor banks are directly connected to the grid without any soft-switching devices. When the shunt capacitor banks are engaged, a large current spike occurs, as shown in Figure 3.

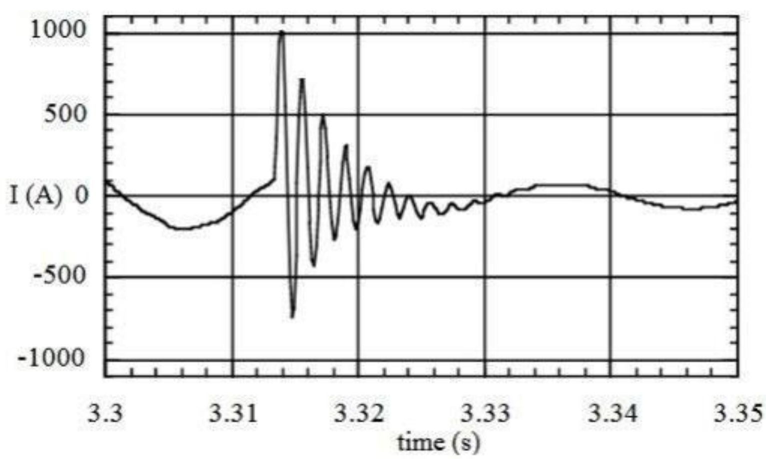

Figure 3: Oscillatory Current Measured Due to the Connection of Shunt Capacitors During the Startup of a 225 kW Wind Turbine

This transient can sometimes reach up to twice the rated current of the wind turbine and may significantly impact the voltage of the low-voltage grid. Transient voltage can disrupt sensitive equipment connected to the same part of the grid [???].

The magnitude of the current caused by the switching of an unloaded capacitor is determined by the grid impedance and the capacitor's capacity. The transient frequency can be approximately calculated by:

International Journal of Innovation in Computer Science and Information Technology
Vol.5, NO.1 , P:49-62
Received: 21 April 2024
Accepted: 15 February 2025

$$f = \frac{1}{2\pi}\sqrt{\frac{1}{LC}} \quad (1)$$

Harmonics:

The injection of electricity from grid-connected wind turbines significantly impacts power quality. The methods for measuring and evaluating the main parameters involved in the power quality characteristics of a wind turbine are described in the IEC 61400-21 standard. These tests are designed to be as generic as possible, ensuring that the power quality characteristics measured for a wind turbine at the test site can be considered valid at other locations as well.

The validity of the measurement method depends on the proper establishment of test conditions. The wind turbine must be directly connected to the medium-voltage (MV) grid, and the measurement of electrical characteristics must be conducted at the wind turbine terminals. It is essential to specify the nominal data of the wind turbine, including:

• Rated active power (Pn)

• Rated apparent power (Sn)

• Rated phase-to-phase voltage (Un)

• Rated current (In)

Additionally, the location of the wind turbine terminals and the specific configuration of the evaluated turbine, including relevant control parameter settings, must be clearly stated in the test report.

According to the standard, there are seven parameters that impact the power quality characteristics required for a wind turbine:

• Voltage fluctuations (flicker)

• Harmonics and interharmonics

• Voltage dips

• Active power

• Reactive power

• Grid protection

• Reconnection time

In the following sections, these parameters and the methods defined for their measurement are explained, with an emphasis on the most relevant issues affecting the evaluation of harmonic and interharmonics content, as well as flicker.

Voltage and Current Harmonics

Harmonics in voltage and current are commonly present in power grids. Non-linear and electronic loads, rectifiers, and inverters are sources that generate harmonic content. The effects of harmonics include overheating, malfunctioning protection systems, equipment failure, or interference

International Journal of Innovation in Computer Science and Information Technology
Vol.5, NO.1 , P:49-62
Received: 21 April 2024
Accepted: 15 February 2025

with communication systems. This standard specifically defines various methods for evaluating harmonics, interharmonics, and higher frequency components for a wind turbine operating under steady conditions and with reactive power as close to zero as possible. This means that, where possible, the reactive set point control should be set to zero.

These parameters are not considered during switching operations because harmonic content is not sufficiently harmful when the disturbance duration is limited to a short time period. The values for individual current harmonics, interharmonics, and higher frequency components, as well as total harmonic current distortion (THC), should be expressed as a percentage of In and provided for wind turbine operation at active power buckets of 0%, 10%, 20%, … up to 100% of Pn, where the 0%, 10%, 20%,… 100% points represent mid-range values.

The harmonic current components should be specified as RMS sub-group values for frequencies up to 50 times the grid's fundamental frequency. The THC factor should be calculated from these values as follows:

$$THC = \sqrt{\sum_{h=2}^{50} i_{sg,h}^2} \cdot 100 \quad (2)$$

Compensation Algorithms for Harmonics and Imbalance

To eliminate or reduce the imbalance and harmonic content in current and voltage, various compensation algorithms have been proposed for the Rotor Side Converter (RSC) and Load Side Converter (LSC). The compensation algorithm in the RSC works by injecting harmonic components into the rotor current that correspond to the existing imbalance and harmonics in the stator voltage. Although the stator voltage waveform becomes sinusoidal and balanced, both the rotor and stator currents become non-sinusoidal and unbalanced, which causes the issues mentioned earlier [11, 12].

Various compensation algorithms have been proposed for the LSC with the goal of eliminating the imbalance and harmonics in the stator current [13, 14]. The compensation in these studies is either for unbalanced loads or for non-linear loads. To distinguish the negative sequence and harmonics (5^{th} and 7^{th}) from the positive sequence and fundamental frequency, different frames (−ω, −5ω, −7ω) and band pass filters or notch filters are used

International Journal of Innovation in Computer Science and Information Technology
Vol.5, NO.1 , P:49-62
Received: 21 April 2024
Accepted: 15 February 2025

[13, 14], which increase the response time and instability of the control system.

2. STATCOM (Static Synchronous Compensator)

The Static Synchronous Compensator (STATCOM) is a parallel compensation device used in transmission networks. This device uses power electronics to form a voltage-source converter, which can act as a source or absorb/reactive AC power to the power grid. STATCOM is one of the members of the FACTS (Flexible AC Transmission Systems) family of devices.

STATCOM as a Replacement for Other Reactive Power Devices

STATCOM devices serve as a replacement for other passive reactive power devices such as capacitors and inductors (reactors). They have a variable reactive power output, which can change in milliseconds, and they can both supply and absorb capacitive and inductive reactive power. While they can be used for voltage support and power factor correction, their speed and capability make them more suitable for dynamic situations, such as supporting the grid during faults or potential events.

For some time, the use of voltage-source-based FACTS devices was preferred because they help overcome the limitations of current-source-based devices, where the reactive output decreases with the system voltage. However, technological limitations historically hindered the widespread adoption of STATCOM. When Gate Turn-Off Thyristors (GTOs) became widely available in the 1990s and could be switched on and off at higher power levels, the first commercially available STATCOM appeared. These devices typically used 3-level topologies and Pulse Width Modulation (PWM) to simulate voltage waveforms.

Modern STATCOMs now use Insulated Gate Bipolar Transistors (IGBTs), enabling faster switching at high power levels. 3-level topologies have been replaced by Modular Multilevel Converter (MMC) topologies, which allow for more voltage waveform levels, reducing harmonics and improving performance.

STATCOM, which stands for Static Synchronous Compensator, is one of the most important and well-known FACTS (Flexible AC Transmission Systems) devices, primarily used to improve voltage profiles in power systems. It is commonly referred to as a static synchronous condenser. The device operates as a voltage-source converter (VSC) and is designed to provide dynamic reactive power compensation, which helps to stabilize the voltage in the grid.

STATCOM is mainly employed in electrical networks that suffer from low power factor and significant voltage drops. Its primary application is in voltage stability, where it regulates and maintains the desired voltage levels in transmission networks.

One of its key advantages is the ability to free up transmission line capacity. Reactive power consumed by loads occupies transmission lines, reducing their efficiency. By using STATCOM, reactive power can be supplied closer to the load (near power plants), thus preventing transmission lines

International Journal of Innovation in Computer Science and Information Technology
Vol.5, NO.1 , P:49-62
Received: 21 April 2024
Accepted: 15 February 2025

from becoming congested. This results in more active power being transmitted through existing lines, eliminating the need for additional transmission lines. As a result, STATCOM provides significant economic benefits to power systems by improving efficiency and reducing infrastructure costs.

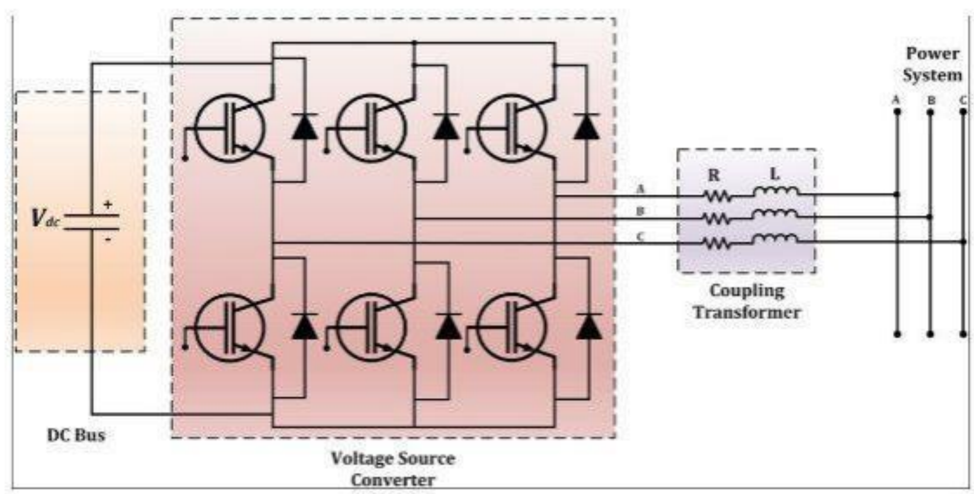

Figure 4. A two-level STATCOM design.

One of the earliest topologies was the two-level converter, which was derived from a three-phase bridge rectifier. This rectifier is also called a 6-pulse rectifier and is capable of switching AC voltage through various IGBT paths. When used as a rectifier to convert AC to DC, it allows both the positive and negative halves of the waveform to be converted to DC. When used in a STATCOM, a capacitor can be connected across the DC side to produce a square wave with two levels. This, in isolation, does not provide any substantive benefit for the STATCOM, as the Voltage value continues to be constant. Nonetheless, should the IGBTs be capable of being switched with sufficient rapidity, Pulse Width Modulation (PWM) may be employed to regulate the voltage level.

By changing the duration of the pulses, the effective voltage waveform can be controlled. Since PWM still only generates square waves, harmonic generation is very important. Some reduction of harmonics can be achieved with analytical techniques applied to different switching patterns. However, this is limited by the complexity of the controller. Each level of the two-level converter typically includes several series

International Journal of Innovation in Computer Science and Information Technology
Vol.5, NO.1 , P:49-62
Received: 21 April 2024
Accepted: 15 February 2025

IGBTs to generate the required final voltage, so coordination and timing between individual devices can be challenging.

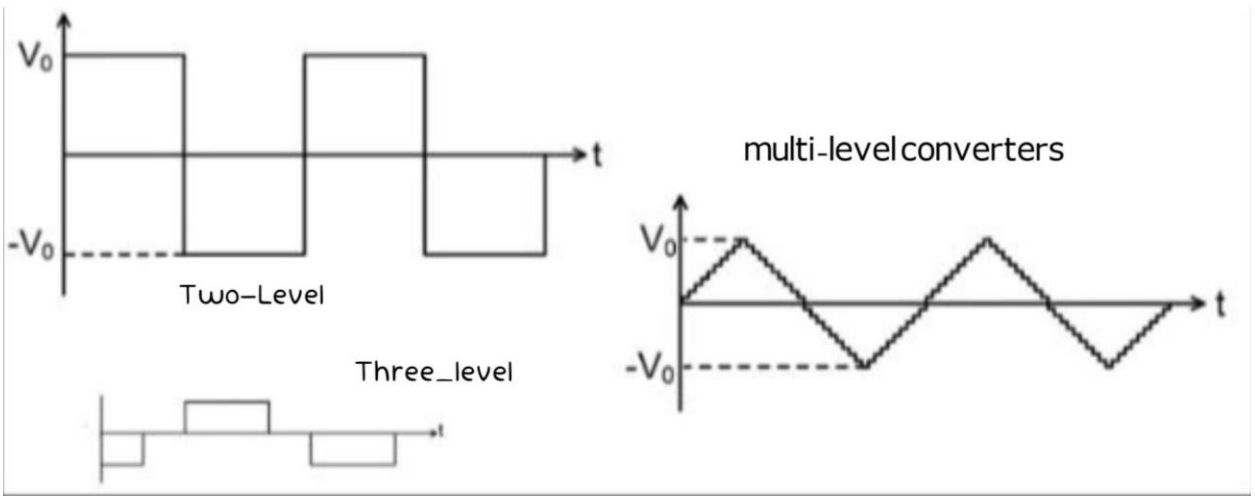

Figure 5. Output of Two-Level, Three-Level, and Multilevel Converters

STATCOM, as a fast, dynamic, and multi-quadrant reactive power source, can be used for various applications; however, it is more suitable for supporting the grid during faults, transient events, or potential disturbances. One common application is placing a STATCOM along a transmission line to improve the system's power flow. Under normal conditions, the STATCOM does very little work, but in the event of a fault on an adjacent line, the power previously being supplied is transferred to the other transmission lines. This usually leads to an increase in voltage drop due to increased current, but with an available STATCOM, it can supply reactive power to boost the voltage until the fault is cleared (if temporary) or until a fixed capacitor is activated (if the fault is permanent). In some cases, the STATCOM can be installed at a substation to support multiple lines instead of just one, helping reduce protection complexity on the line with STATCOM in place.

3. Simulation Results

International Journal of Innovation in Computer Science and Information Technology
Vol.5, NO.1 , P:49-62
Received: 21 April 2024
Accepted: 15 February 2025

A 9-megawatt wind farm is shown in Figure 4. A wind farm, also known as a wind park or wind power plant, is a group of wind turbines located in the same area used to generate electricity. Wind farms vary in size from a few turbines to several hundred turbines covering large areas. Wind farms can be onshore or offshore. These wind turbines operate based on a very simple principle, making maximum use of the wind's force, which in this case acts as the primary energy source. By rotating their blades, they generate kinetic energy, which is then converted into electrical energy by a generator.

The amount of energy a wind farm can produce depends on the location, the size of the turbines, and the length of their blades. Over time, the capacity of wind turbines has increased thanks to research and development in the field. In 1985, the most common turbine model had a capacity of 0.05 megawatts (MW) and a rotor diameter of 15 meters. Large-scale wind energy projects now feature turbines with capacities of over 5 MW.

The faster the average wind speed, the more electricity a wind turbine will generate, so faster winds are generally more economically suitable for developing wind farms. The balancing factor is that strong gusts and high turbulence require more expensive, stronger turbines; otherwise, there is a risk of damage. Average power in the wind is not proportional to the average wind speed. Therefore, the ideal wind conditions could involve strong but steady winds with low turbulence from one direction.

Continuous advancements in the construction and design of wind turbines, along with improvements in infrastructure, have significantly reduced the cost of wind energy and solidified its position as a key driver in energy transition. According to a Wind Europe report, in 2021, European wind farms generated 437 terawatt-hours (TWh) of electricity, covering an average of 15% of demand. However, in several countries, the coverage exceeded 20%, such as in Portugal (26%), Spain (24%), and Germany (23%).

The wind farm used in this paper has a production capacity of 9 megawatts of energy and is connected to a 25-kilovolt grid. The 25-kilovolt feeder is connected to a 30-kilometer-long line, which in turn is connected to a 120-kilovolt generator. The transmission substation has a 120/25 transformer, which is connected to our feeder.

At seconds 12 to 1.12, a network fault occurs, affecting the grid voltage. The wind farm is connected to a FACTS device called a STATCOM, which can maintain its output within the 1 pu range. Outside of this time, the STATCOM can control the grid.

International Journal of Innovation in Computer Science and Information Technology
Vol.5, NO.1 , P:49-62
Received: 21 April 2024
Accepted: 15 February 2025

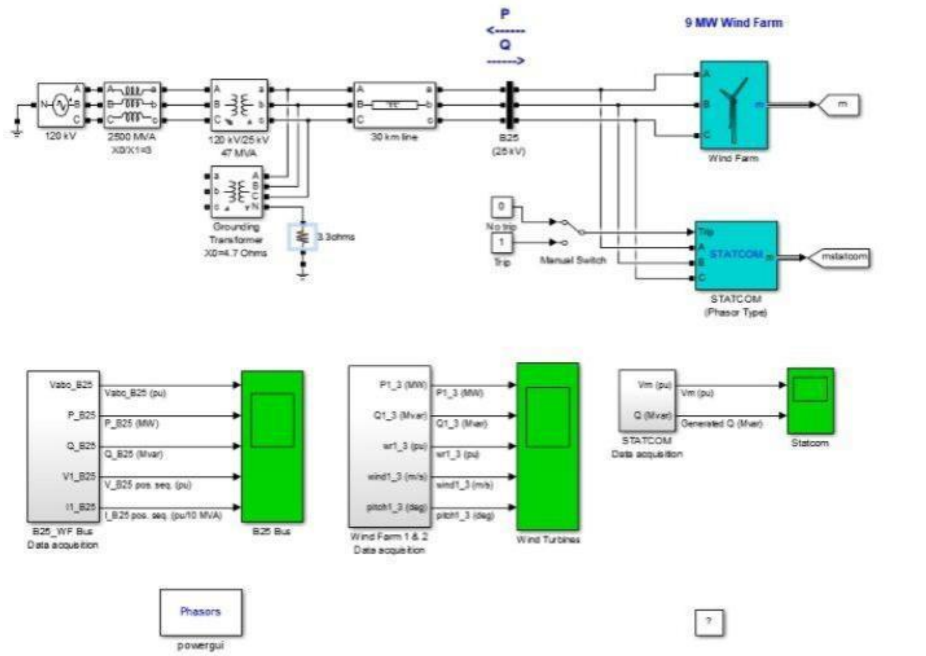

Figure 6. A wind farm with STATCOM.

By executing the program, the output will be as shown below. In Figure 5, the FACTS device is not included in the circuit. Therefore, the output exhibits significant fluctuations, and at second 12, a fault occurs in the system. Figure 7 shows the line voltage connected to the STATCOM controller, with no reactive power being injected into the system. The voltage remains uncontrolled.

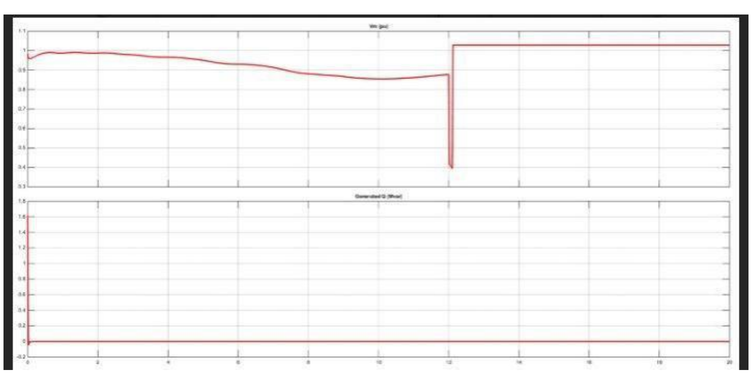

Figure 7. Voltage output and reactive power produced by STATCOM.

International Journal of Innovation in Computer Science and Information Technology
Vol.5, NO.1 , P:49-62
Received: 21 April 2024
Accepted: 15 February 2025

However, with the introduction of STATCOM, the output is controlled, and the voltage remains within the permissible range. It is worth mentioning that during the fault, the controller is unable to maintain the voltage within the range. The injected power is shown in Figure 8.

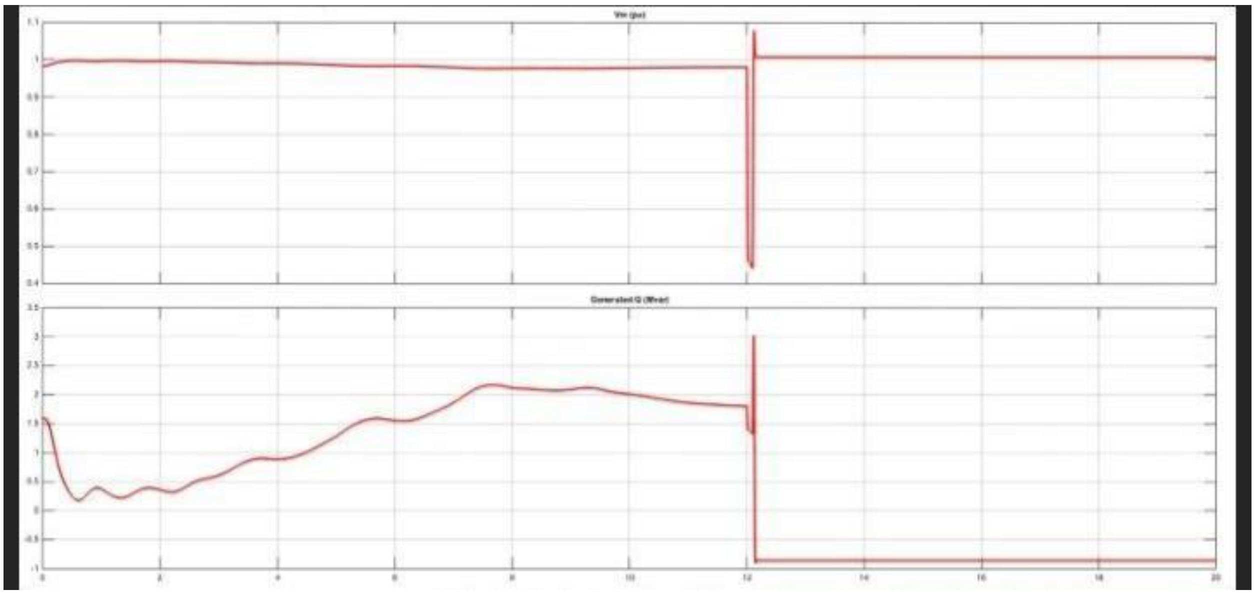

Figure 8. Controlled output using STATCOM.

Conclusion:

The assessment shows that the wind farm's capacity can commence without causing unacceptable voltage quality in the grid. For comparison, a simplified design standard is considered, assuming that the wind farm can generate acceptable voltage. Nonetheless, the desired voltage range wasn't achieved according to the voltage difference standard. Therefore, FACTS devices, especially STATCOM, were used to create the required voltage range, which was achieved through the injection of reactive voltage.

References :

[1] Walker, M. K., "Electric Utility Flicker Limitation", in Proceeding of the Power Quality Conference, Long Beach, California, October 1989, p. 602 – 613.

[2]] Tao Sun, Zed Chen, "Flicker study on variable speed wind turbines with Doubly Fed Induction Generators", IEEE Transaction on Energy Conversion, Vol. 20, No. 4, December 2005, pp. 896-905.

[3] L. Rossetto , P.Tenti, and A. Zuccato, "Electromagnetic compatibility issues in industrial equipment," IEEE lnd.Appl.Mag., vol. 5 No..6, pp.34-46, Nov./Dec. 1999.

[4] A.Larsson, "Flicker emission of wind turbines during continuous operation," IEEE Tran. Enargy Convers., vol. 17, No.1, pp. 114-118, Mar. 2002

[5] T. Sun, Z. Chen, F. Blaabjerg, "Flicker mitigation of grid connected wind Turbine using STATCOM", Second International conference on power electronic and drive (PEMD 2004), April 2004.

[6] E. Tremblay, A. Chandra, "Grid-Side converter control of DFIG wind turbine to enhance power quality of distribution network", Power Engineering Society General Meeting IEEE, Juan 2006.

[7] Ted Brekken, Ned Mohan, "Control of a Doubly Fed Induction Generator under unbalanced grid voltage conditions", IEEE Transaction on Energy Conversion,Volume 22, Issue 1, March 2007 Page(s):129 – 135.

[8] B. Toufik, M. Machmoum, "Doubly Fed Induction Generator with active filtering function for wind energy conversion system", European Conference on Power Electronics and Application, Sept. 2005.

[9] Mehdi T. Abolhassani, Hamid A. Toliyat, Prasad Enjeti, "Stator Flux Oriented Control of an Integrated Alternator/Active Filter for wind power applications", IEEE International conference on power electronic and drive (IEMDC 2003), June 2003.

[10] L. Ran, J.R. Bumby, P.J. Tavner, "Use of turbine inertia for power smoothing of turbines with a DFIG", 11th International Conference on Harmonics and Quality of Power, Sept. 2004.

[11] 9-Phan, Lee.:"Control Strategy for Harmonic Eliminationin Stand-Alone DFIG Applications WithNonlinear Loads", IEEETRANS. POWER ELECTRONICS, VOL. 26, NO. 9, SEPT 2011

[12] 10- Phan, Lee. :"Performance Enhancement of Stand-Alone DFIGSystems With Control of Rotor and Load

SideConverters Using Resonant Controllers", IEEE TRANS INDUSTRY APPLICATIONS, VOL. 48, NO. 1, JANUARY/FEB 2012

[13] 11- R. Pena, R. Cardenas, E. Escobar, J. Clare, P. Wheeler, Control system for unbalanced operation of stand-alone doubly fed induction generators, IEEE Trans.Energy Conv. 22 (2) (2007) 544–545.

[14] 12- A. Jain and V. Ranganathan, "Wound rotor induction generator with sensorless control and integrated active filter for feeding nonlinear loads in astand-alone grid," IEEE Trans. Ind. Electron., vol. 55, no. 1, pp. 218–228,Jan. 2008