Hybrid PV– DFIG Wind Energy System for Grid Integration: MPPT Control, DC-Link Regulation, Converter Strategy and Performance Analysis

Sweta Kumari[1], Ashish Bhargava[2]

[1]M Tech Scholar, [2]Professor,
[1,2]Bhabha Engineering Research Institute, Bhopal, Madhya Pradesh, India

ABSTRACT

Wind energy is among the most sophisticated and rapidly growing renewable energy sources. This thesis presents a comprehensive investigation of Doubly Fed Induction Generator (DFIG) photovoltaic (PV) and wind energy generators, including system designs, power converters, control strategies, and the dynamic and steady-state performance of real Wind Energy Conversion Systems (WECS). The emphasis is on a technique for regulating the DC link voltage and attaining Maximum Power Point Tracking (MPPT) in a hybrid photovoltaic-wind turbine system. The examined system is a modified PV-DFIG configuration, whereby the photovoltaic output power is fed into the grid via both the grid-side and rotor-side converters of the DFIG. The suggested control technique concurrently regulates the DC-link voltage and the maximum power point tracking (MPPT) of the photovoltaic (PV) system. This method is economically reasonable since it eliminates the need for a specialized PV converter, resulting in more efficient integration of PV output electricity into the grid. The results are generated via MATLAB/SIMULINK. The dynamic model is constructed with the machine's equivalent circuit, articulated in fixed, rotor, and synchronous reference frames to assess performance. The stator of the DFIG is directly linked to the grid, and grid synchronization and power regulation are accomplished by managing the rotor voltage via a two-level back-to-back converter. The Grid-Side Converter (GSC) is designed to provide regulated power to the grid, while the Rotor-Side Converter (RSC) is managed to attain Maximum Power Point Tracking (MPPT) and Unity Power Factor (UPF). Simulations, executed with and without the photovoltaic system, provide outcomes for voltage, current, and both real and reactive power, using MATLAB.

I. INTRODUCTION

Renewable energy is obtained from natural resources, including solar, wind, wave, or geothermal energy. These materials are renewable and can be organically recycled. Consequently, in contrast to the exhaustion of conventional fossil fuels [1], these information sources are seen as endless. The global energy crisis catalyzes the development or refinement of clean or renewable energy sources. [2]. Alongside the global reduction in fossil fuel transportation, a significant factor for the ineffectiveness of fossil fuels is the pollution generated from their combustion. Conversely, it is widely recognized that renewable energy sources are cleaner than conventional energy sources, since their production does not contribute to pollution.

Solar cell or panel consists of a configuration of solar cells interconnected in series or parallel to provide the necessary currents and energy. Solar intertie photovoltaic (PV) systems are quite simple. Initially, there are panels that capture sunlight and convert it into power. The DC signals are input into an inverter, which transforms the DC into grid-compatible AC power, suitable for residential usage. Multiple switch

boxes are included for safety purposes, and the whole system is interconnected by cables and pipes.

Storage batteries may provide protective energy during times of abundant sunshine by storing excess or a portion of the electricity generated by solar panels. Solar power generating systems are used for private energy consumption, meteorological stations, broadcasting facilities, entertainment venues including theaters, hotels, restaurants, as well as communities and islands. The conventional p-n junction solar cell represents the most sophisticated technique for solar energy gathering. The underlying physics of energy input and carrier output governs the physical qualities and the corresponding electrical characteristics (i.e., the band gap).

The electron must possess energy exceeding the bandgap to promote electrons from the valence band to the conduction band. An optimal solar cell has a straight band gap of 1.4 eV to maximize photon absorption from solar radiation. The ostensibly boundless lattice generates bands of permissible energy levels; silicon forms a band gap devoid of electrons, measuring 1.1 eV in width. Nevertheless, the sun's radius approximates the black body spectrum of around 6000 K. Consequently, the majority of solar rays reaching Earth has an energy source beyond the radius of the silicon group of the sun. High-energy phonons will be mitigated by solar cells. The gap between the phonons and the silicon band will be dissipated as heat via a process known as phonon overflow, rather of being transformed into useable energy. This will provide a maximum efficiency of around 20% for an individual meeting cell. Contemporary research methodologies for executing multi-node photovoltaic design to surmount efficiency constraints seem to be a cost-effective option. A built-in photovoltaic device is only operational during daylight and requires direct sunlight for optimal efficiency.

The turbine comprises the blades, rotor hub, and other components. The drive train comprises the turbine rotor, low-speed shaft, gearbox, high-speed shaft, and generator rotor. It transmits mechanical output power from the turbine to the generator rotor, where it is turned into electrical power. The wind impacts the rotor of the horizontal-axis turbine, inducing rotation. The low-speed shaft transmits energy to the gearbox, which increases the speed and drives the high-speed shaft. The high-speed shaft induces rotation in the generator, so producing electricity. The yaw mechanism is used to orient the nacelle so that the rotor aligns with the wind direction. The low-speed shaft houses pipes for the hydraulic system that activates the aerodynamic brake. The high-speed shaft has an emergency mechanical brake used in the event of aerodynamic brake failure [12].

The generator transforms the mechanical energy of wind into electrical energy. The generator typically generates electricity at a low voltage, whereas the transformer elevates the generator's output voltage to match the grid voltage.

The transformer may be positioned at the base of the tower [4] or inside the nacelle to minimize losses [13]. Additional components of a wind turbine system include an anemometer for measuring wind speed and a wind vane for determining wind direction. Wind speed data is utilized to ascertain the conditions for turbine activation and the necessity for shutdown during high winds for safety, while wind direction measurement informs the yaw-control mechanism, which aligns the rotor with the wind direction [14]. Electric fans and oil coolers are used to dissipate heat from the gearbox and generator.

II. PROPOSED SYSTEM

This research proposes a grid-interfaced DFIG-based wind energy conversion system for power smoothing. The rotor position calculation technique is used for rotor position estimate [24]. The work's distinctiveness arises from the regulation of the Grid Side Converter (GSC). The authors have clearly shown the control algorithm for delivering regulated power to the grid. An further critical aspect of DFIG-based WECS for power smoothing is the selection of BESS. The disparities in power output between the conventional DFIG and the proposed DFIG are shown as wind speeds increase. The system's operation has been empirically validated for regulating DFIG power under variable wind speed conditions. The Simulink design in this proposed DFIG system, both with and without solar integration.
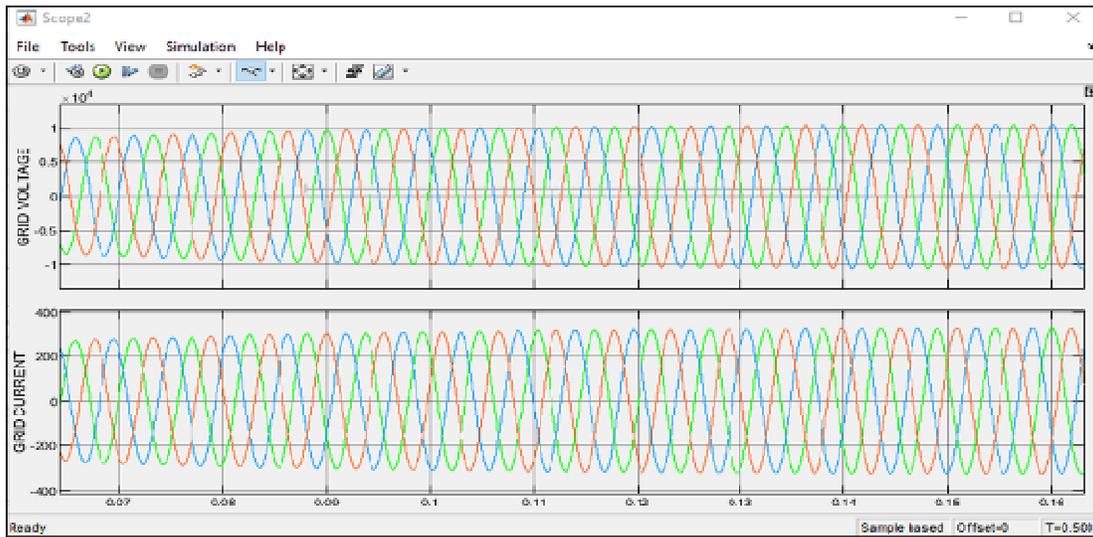
Figure 1: Proposed Simulink Model

This study presents a grid-connected DFIG-based wind energy conversion system for power smoothing. The rotor position estimate technique is used for calculating rotor position [25]. The innovation of the project is in the regulation of the Grid Side Converter (GSC). The authors have well shown the control algorithm for supplying regulated electricity to the grid. The selection of Battery Energy Storage Systems (BESS) is another critical feature of Doubly Fed Induction Generator (DFIG) based Wind Energy Conversion Systems (WECS) for power smoothing. The differences in power output with increasing wind speeds are shown by comparing the existing DFIG with the suggested DFIG. The system's functioning is experimentally confirmed for adjusting the power of DFIG, even under fluctuating wind speed situations.

III. SIMULATION RESULT

The specifications of the photovoltaic panel, wind turbine, and doubly-fed induction generator (DFIG) were simulated using MATLAB 2019b, with results shown below. The generated voltage of the solar photovoltaic system is inadequate due to the use of a boost converter for voltage elevation. A comprehensive electromechanical model of a DFIG-based wind turbine, both connected to the power grid and functioning as an autonomous system with integrated battery energy storage, is developed in the MATLAB/Simulink environment, along with its corresponding generator and turbine control structure. An exhaustive elucidation of this control mechanism and the steady-state behavior of the whole wind turbine system is provided. The consistent reactive power capacity of the DFIG.

Figure 2: Input Voltage and Current

Figure 3: Grid Voltage and Current

Figure 4 showing the Grid Voltage and Current waveform, during simulation grid voltage generate 230v
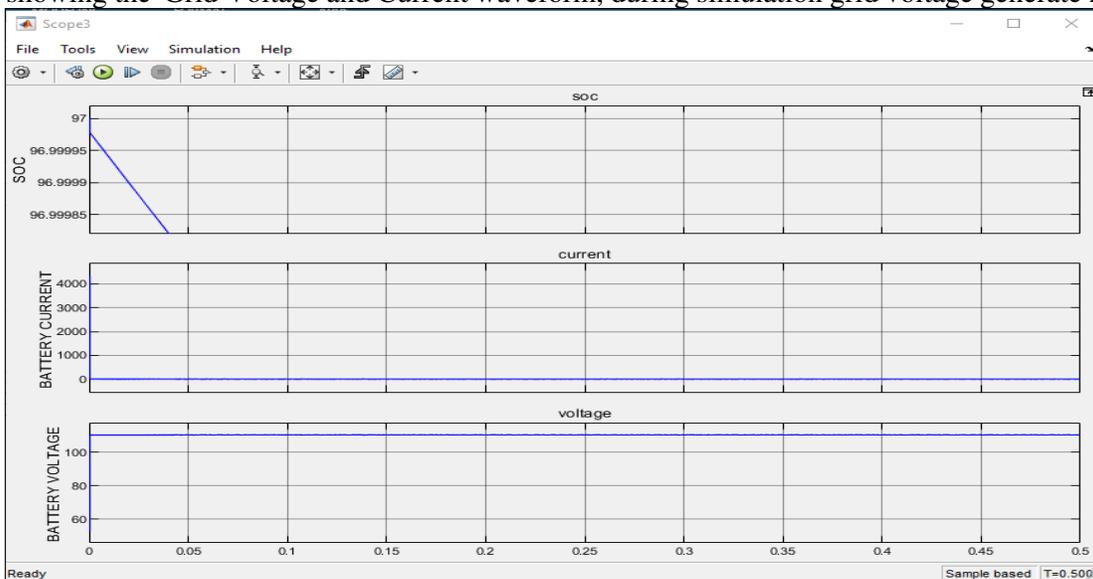

Figure 4: Battery Output

Figure 5: Battery Output showing with soc and battery voltage and current waveform, battery charge upto 97 % at discharge after 97%, State of charge (SoC) is **the level of charge of an electric battery relative to its capacity**. The units of SoC are percentage points (0% = empty; 100% = full).
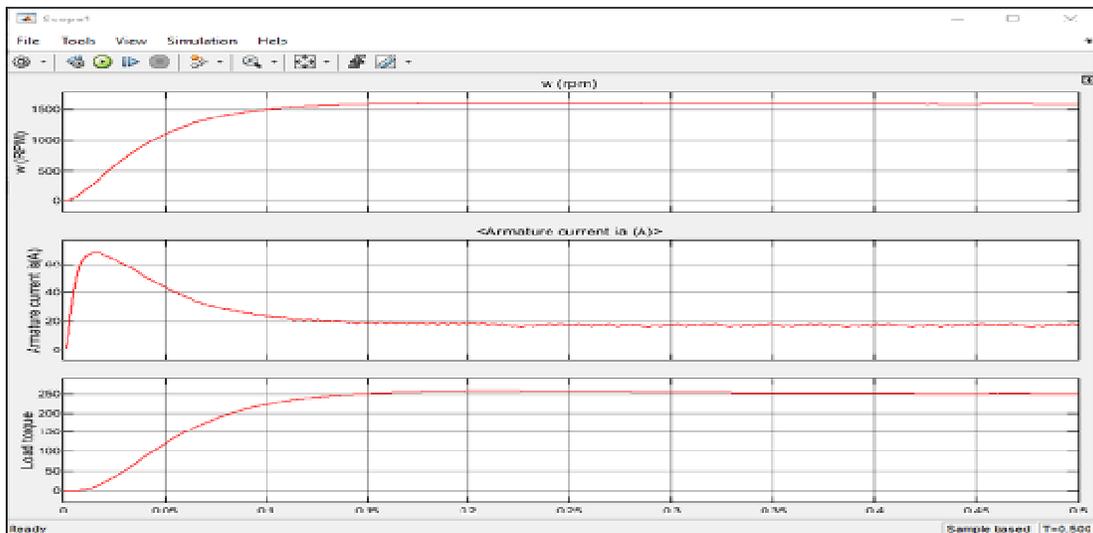

Figure 5: DC Machine Output

Figure 6: DC Machine Output rpm, armature current and load voltage, the stator consists of field windings while the rotor (also called the armature) consists of an armature winding. When both the armature and the field windings are excited by a DC supply, current flows through the windings and a magnetic flux proportional to the current is produced.
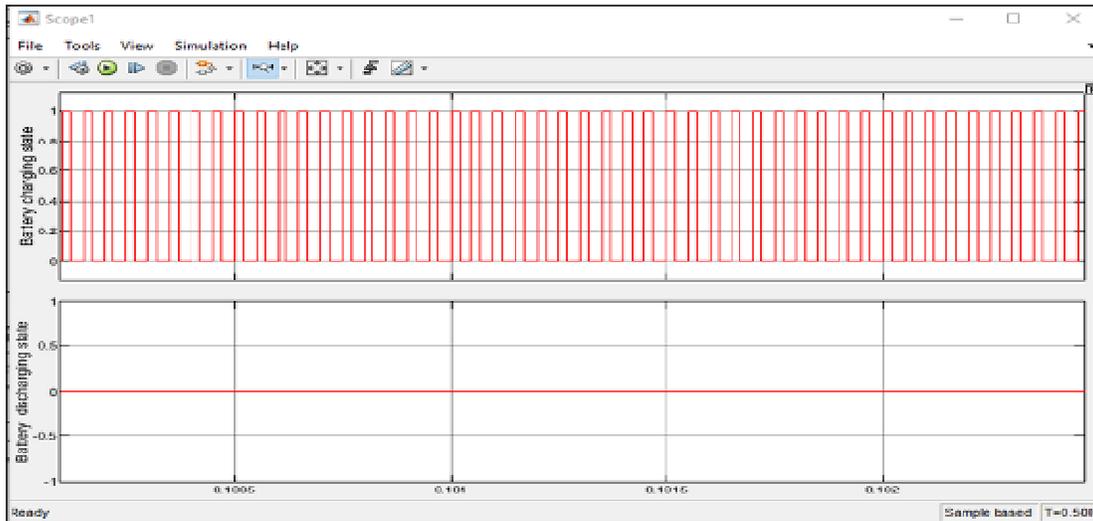
Figure 6: Battery Charging and Discharging States

Figure 7 showing the Battery Charging and Discharging States, battery discharge at 0% and charging at 100%, The direction of current through the battery determines whether it is charging or discharging. The battery is trying to push current in a particular direction. If the current flows in that direction, the battery is discharging. If the current flows in the other direction, the battery is charging.
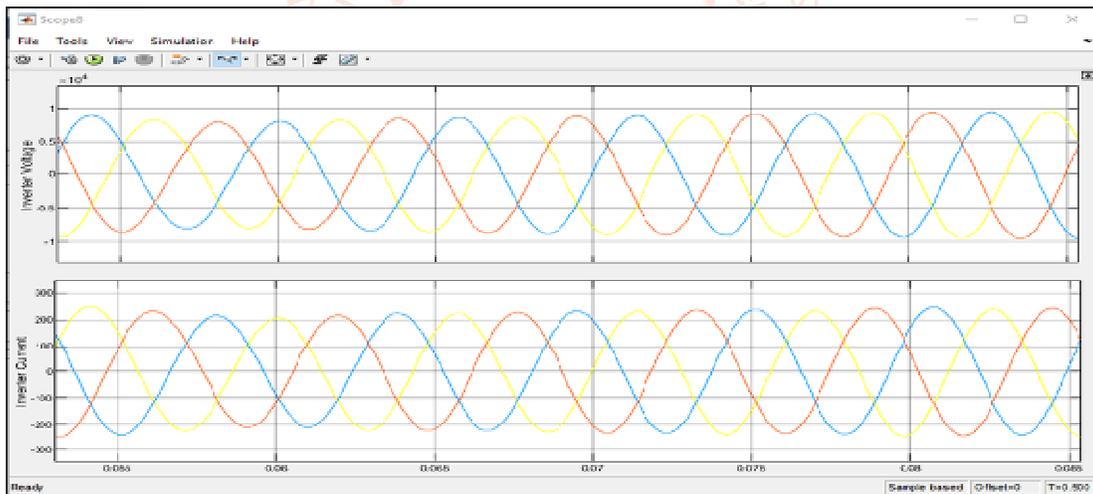
Figure 7: Inverter Current and Voltage

Figure 8 showing the three phase Inverter Current and Voltage, A three-phase inverter converts a DC input into a three-phase AC output. Its three arms are normally delayed by an angle of 120° so as to generate three-phase AC supply. The inverter switches each has a ratio of 50% the maximum power point tracker is an electronic DC to DC converter that optimizes the match between the solar array (PV panels), and the battery bank or utility grid.

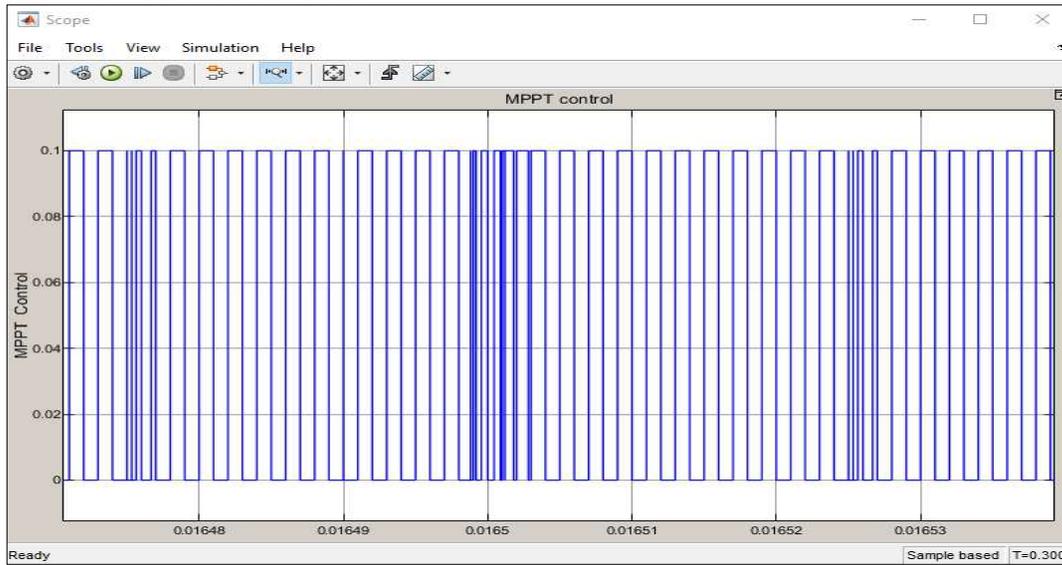Simulation Result with Solar and DFIG
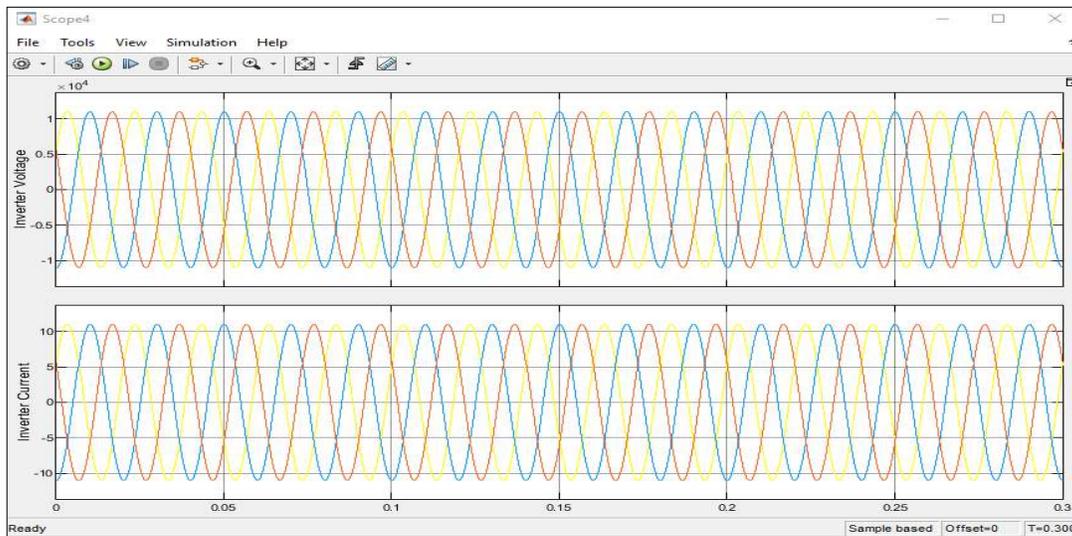

Figure 8: MPPT Control
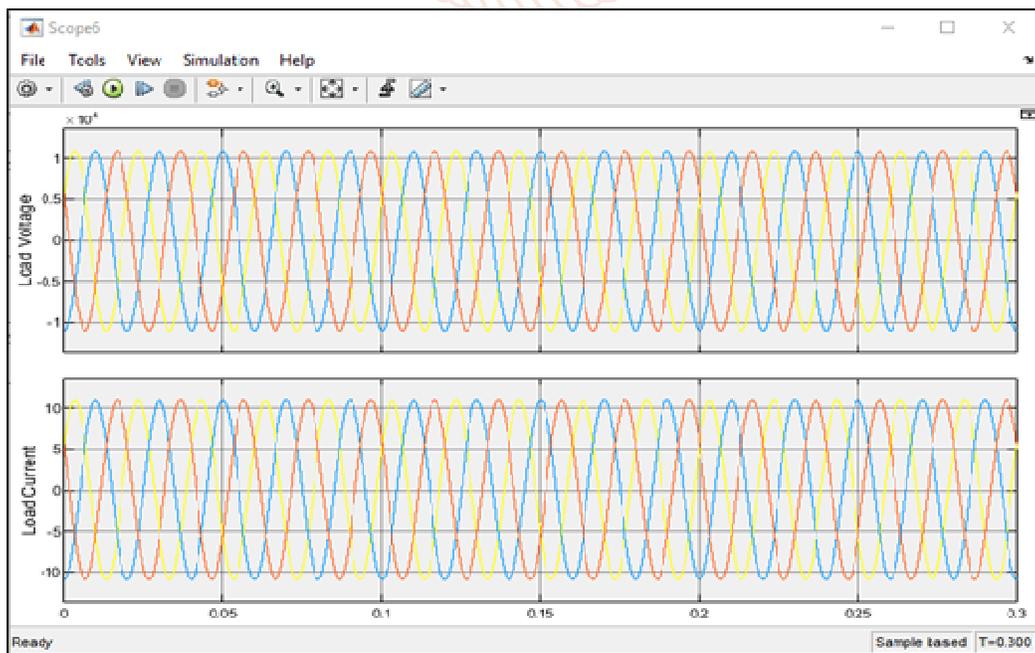

Figure 9: Input Voltage and Current

Figure 10: Load Voltage and Current

the amount of current" drawn by the thing that is connected to the output of the circuit. The actual power supply voltage that can be used when switching a load or continuously in an OFF state. The actual power supply voltage that can be used when switching a load or continuously in an OFF state.
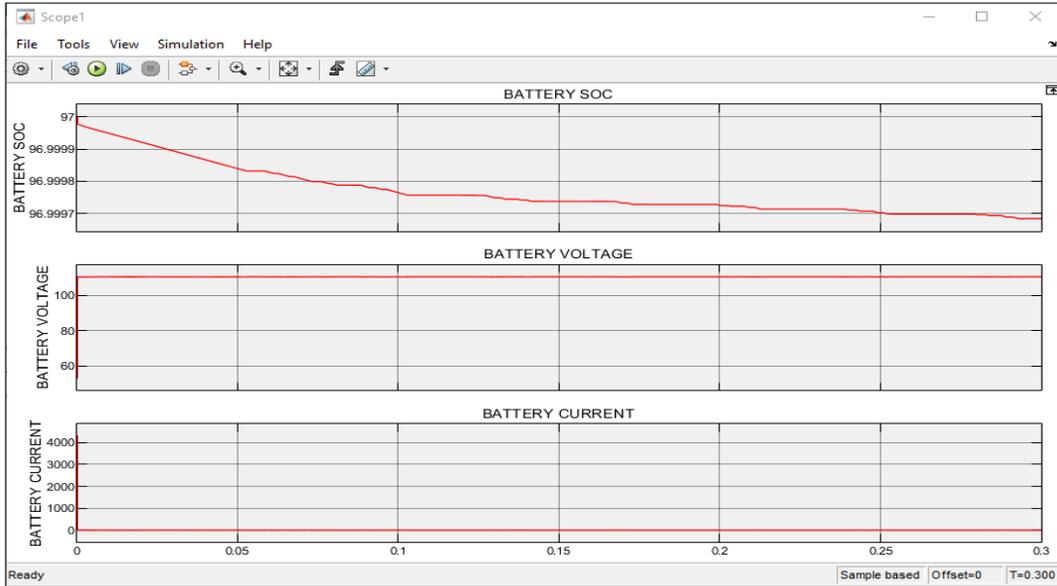

Figure 11: Battery Output

Fig 11 showing the battery output, Power capacity is how much energy is stored in the battery.

Figure 12: Real Power and Reactive Power

The active power is the real power consumes by the load. Whereas, the reactive power is the useless power. The active power is the product of the voltage, current and the cosine of the angle between them. Whereas, the reactive power is the product of voltage and current and the sine of the angle between them.
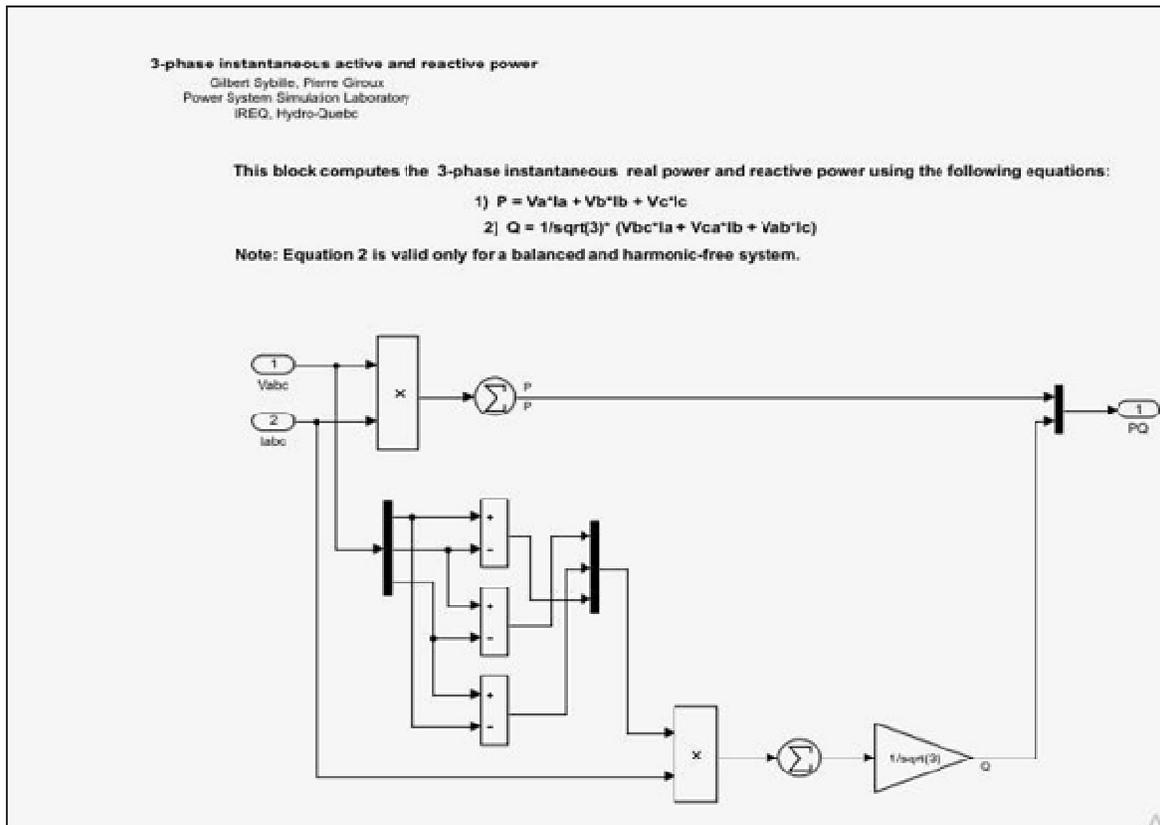
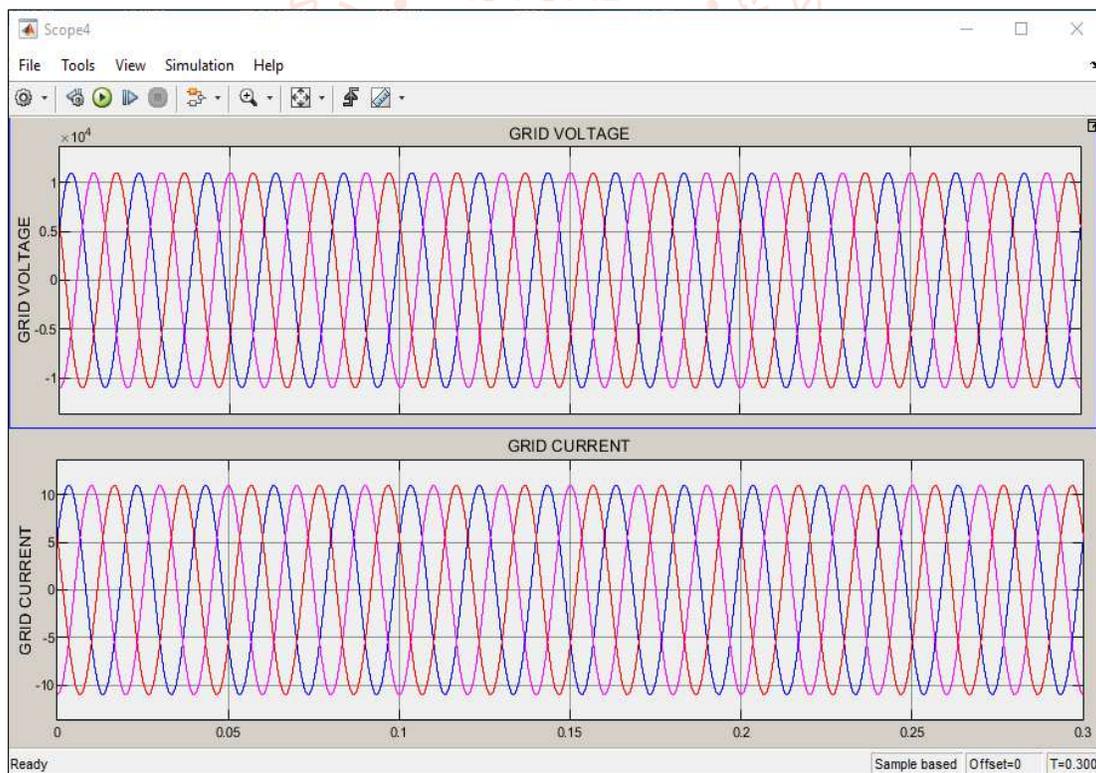**Figure 13: Phase Instantaneous Active and Reactive Power**

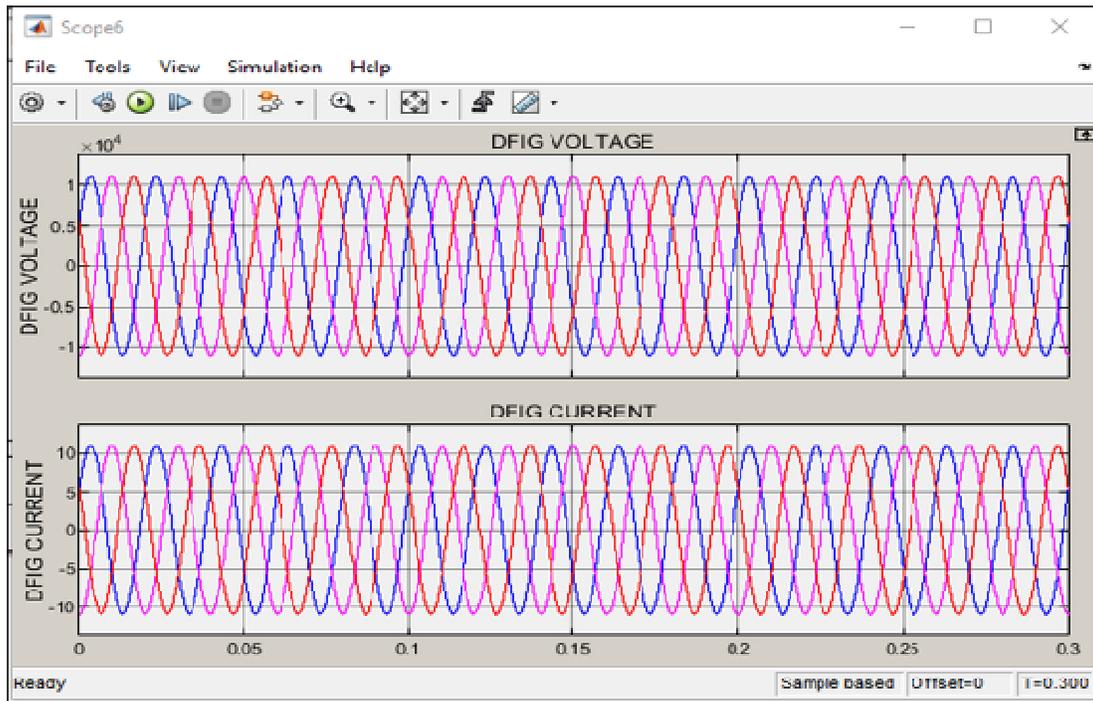**Figure 14: Grid Voltage and Current**

Figure 14: DFIG Voltage and Current

The DFIG consists of a 3 phase wound rotor and a 3 phase wound stator. The rotor is fed with a 3 phase AC signal which induces an ac current in the rotor windings.
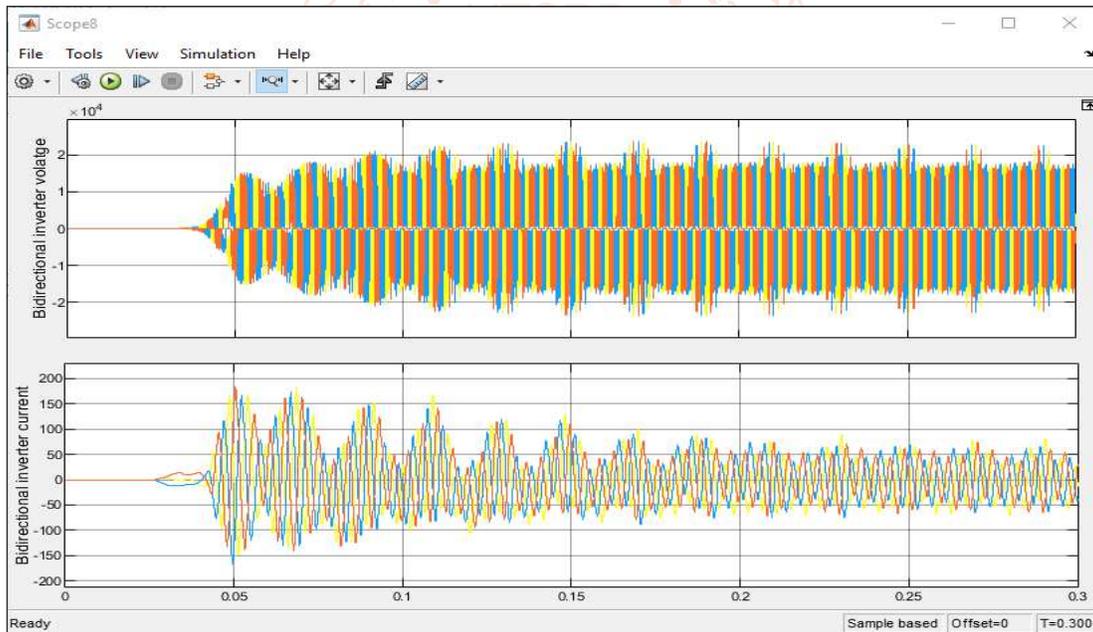

Figure 16: Bidirectional Inverter Current and Voltage

The bidirectional DC-AC inverter transfers power from the DC stage to the connected AC grid while the DC loading requirement is small. Or, the inverter transfers the power from the connected AC grid to the DC stage if the DC energy is insufficient for the DC loading requirement.
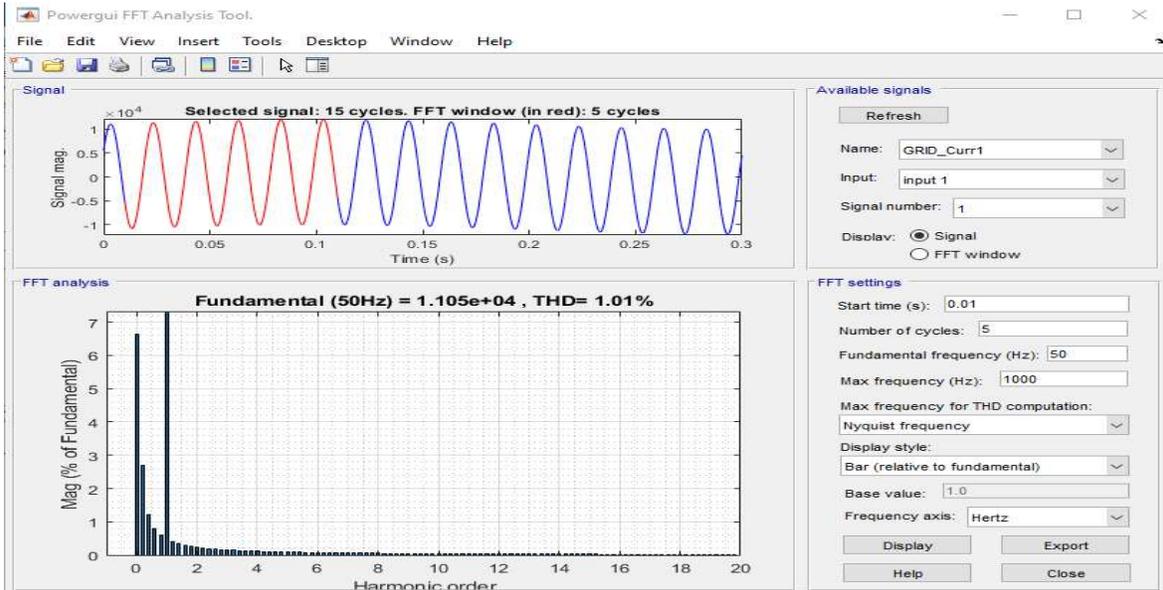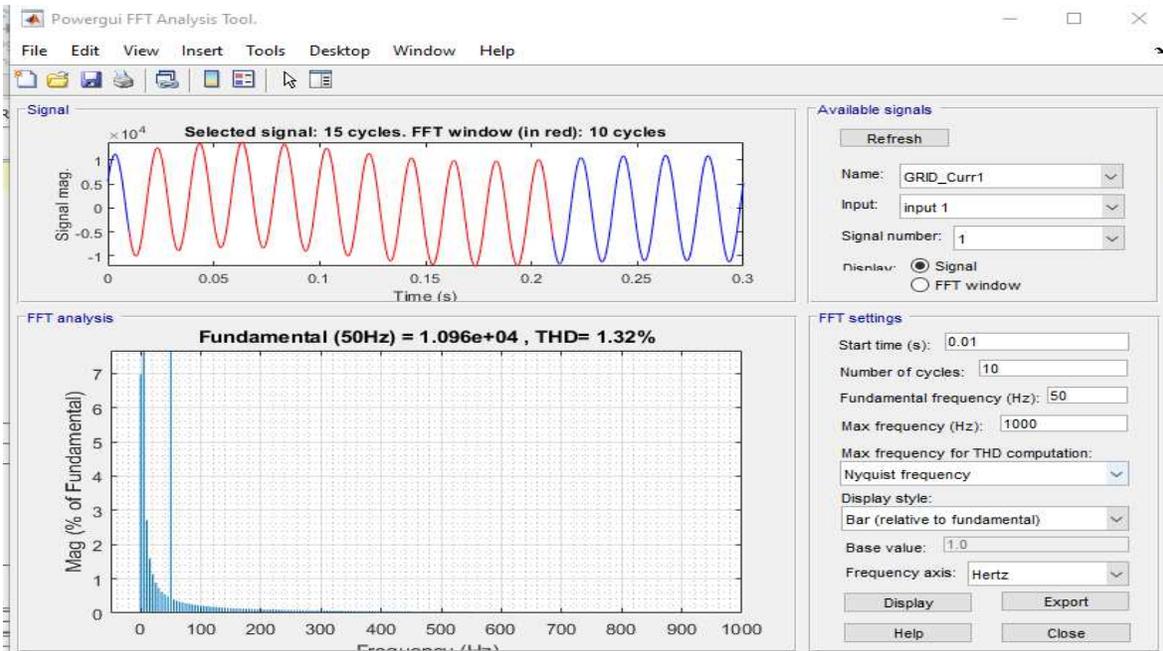
Figure 17: with solar thd

Figure 18: Without solar THD

Table 1 showing the comparison result in between proposed wok and exiting work, solar irradiance and grid power compare with the existing work, in the proposed work grid power showing higher as compare to existing work

Table 1 Power comparison with existing work

	Technique	Solar Irradiance	Grid power
Proposed system	MPPT, P& O	1000 rad/S	20 KW
Existing system	Predictive MPPT	1000 rad/S	15 W

Table 2 THD comparison With Solar and without solar

MODEL	THD
With Solar	**1.01**
Without Solar	**1.32**

Table 2 Showing The THD Comparison With And Without Solar, In The Proposed System Two Model Designed As DFIG With Solar And DFIG Without Solar, With Solar THD Showing Better As Compare To Without Solar.

CONCLUSION

This research presents a novel way for regulating the frequency of a microgrid using a Doubly Fed Induction Generator (DFIG). The droop control, executed in the Grid-Side Converter (GSC) in conjunction with a Battery Energy Storage System (BESS) linked to the DC bus of the DFIG's back-to-back converter, effectively managed the microgrid's frequency during disruptions. By implementing droop control on the GSC of the DFIG, the wind turbine consistently operated at the maximum power extraction point, while the BESS supplied the necessary power for frequency regulation. The droop control exhibited superior performance in frequency regulation, effectively lowering reaction time and enhancing the frequency nadir in both super-synchronous and sub-synchronous modes, compared to a microgrid without DFIG intervention. Furthermore, the use of BESS enhanced the operational efficiency of the wind system. When the DFIG is integrated with the grid and functions in super-synchronous mode, the battery may be charged while the BESS regulates the DC link voltage to preserve stored energy for frequency stabilization. During sub-synchronous operation, the Battery Energy Storage System (BESS) drains the battery to regulate the DC connection voltage.

References

[1] Dan Wu; Gab-Su Seo; Lie Xu; Chi Su, "Grid integration of offshore wind power: Standards, control, power quality and transmission," IEEE Open J. Power Electron., vol. 5, pp. 583–604, 2024.

[2] K. Rajkumar, K. Ambika, K. Abhinaya, A. Nafeeza Begum, K. Teena, and U. Viveka, "Hybrid solar and wind power generation system using ANFIS algorithm," in 2023 Intelligent Computing and Control for Engineering and Business Systems (ICCEBS), 2023, pp. 1–6.

[3] Z. Li, H. Xu, Z. Wang, and Q. Yan, "Stability assessment and enhanced control of DFIG-based WTs during weak AC grid," IEEE Access, vol. 10, pp. 41371–41380, 2022.

[4] Youssef Moumani, Abdeslam Jabal Laafou, Abdessalam Ait Madi Modeling and Backstepping Control of DFIG used in Wind Enegry Conversion System 2021 7th International Conference on Optimization and Applications (ICOA) Year: 2021 | Conference Paper | Publisher: IEEE DOI:10.1109/ICOA51614.2021.9442625.

[5] Abdeslam Jabal Laafou; Abdessalam Ait Madi; Adnane Addaim Dynamic Control of DFIG used in Wind Power Production, based on PI regulator 2020 IEEE 2nd International Conference on Electronics, Control, Optimization and Computer Science (ICECOCS) Year: 2020 | Conference Paper | Publisher: IEEE DOI:10.1109/ICECOCS50124.2020.9314563.

[6] Jitheesh P Gopalan, Binitha Joseph Mampilly, "A Versatile STATCOM for SSR Mitigation and Dynamic Reactive Power Management in DFIG Based Wind Farm Connected to Series Compensated Line 2020 IEEE International Power and Renewable Energy Conference Year: 2020 | Conference Paper | Publisher: IEEE DOI:10.1109/IPRECON49514.2020.9315202.

[7] Pandian, Ch. Rami Reddy Cuckoo Search Optimization based MPPT for Integrated DFIG-Wind Energy System B. Srikanth Goud; P. Srinivasa Varma; B. Loveswara Rao; M. Sai Krishna Reddy; A. 2020 International Conference on Decision Aid Sciences and Application (DASA) Year: 2020 | Conference Paper | Publisher: IEEE DOI:10.1109/DASA51403.2020.9317072.

[8] Youssef Baala, Seddik Bri DFIG-Based Wind Turbine Control Using High-Gain Observer 2020 1st International Conference on Innovative Research in Applied Science, Engineering and Technology (IRASET) Year: 2020│Conference Paper | Publisher: IEEE DOI:10.1109/IRASET48871.2020.9092280.

[9] Subinay Vajpayee, Nihar Ranjan Panda, Prasanajit Behera, Sarat Chandra Swain "Implementation of PLL algorithm in DFIG based wind turbine connected to utility grid 2020 Second International Conference on Inventive Research in Computing Applications" (ICIRCA) Year: 2020 | Conference Paper | Publisher: IEEE DOI:10.1109/ICIRCA48905.2020.9182961.

[10] Md Aktarujjaman, M. E. Haque, S. Saha, M. Negnevitsky "Impact of DFIG Based Wind Generation on Grid Voltage and Frequency Support" 2020 International Symposium on Power Electronics, Electrical Drives, Automation and Motion (SPEEDAM) Year: 2020 | Conference Paper | Publisher: IEEE DOI:10.1109/SPEEDAM48782.2020.9161867.

[11] Răzvan Beniugă, Oana Beniugă, Dragoç Machidon Assessment of DFIG wind turbine overvoltage protection system for grid stability

2019 8th International Conference on Modern Power Systems (MPS) Year: 2019 | Conference Paper | Publisher: IEEE DOI:10.1109/MPS.2019.8759781.

[12] Jinxin Ouyang; Ting Tang; Jun Yao; Mengyang Li Active Voltage Control for DFIG-Based Wind Farm Integrated Power System by Coordinating Active and Reactive Powers Under Wind Speed Variations IEEE Transactions on Energy Conversion Year: 2019 | Volume: 34, Issue: 3 | Journal Article | Publisher: IEEE.

[13] Anjali V. Deshpande, V. A. Kulkarni Simplified Model of DFIG in Wind Integrated Power System 2019 3rd International Conference on Computing Methodologies and Communication (ICCMC) Year: 2019 | Conference Paper | Publisher: IEEE DOI:10.1109/ICCMC.2019.8819670.

[14] Sobhy S. Dessouky, Walid S. E. Abdellatif, Saad A. Mohamed Abdelwahab, Marwa A. Ali, "Maximum Power Point Tracking Achieved of DFIG-Based Wind Turbines Using Perturb and Observant Method" 2018 Twentieth International Middle East Power Systems Conference (MEPCON) Year: 2018 | Conference Paper | Publisher: IEEE DOI:10.1109/MEPCON.2018.8635206.

[15] Essam. H. Abdou, Abdel-Raheem Youssef, Salah Kamel, Mohamed M. Aly, "Sensorless Wind Speed Control of 1.5 MW DFIG Wind Turbines for MPPT" 2018 Twentieth International Middle East Power Systems Conference (MEPCON) Year: 2018 | Conference Paper | Publisher: IEEE DOI:10.1109/MEPCON.2018.8635209.

[16] Xie Hua, Xu Hongyuan, Li Na, "Control strategy of DFIG wind turbine in primary frequency regulation" 2018 13th IEEE Conference on Industrial Electronics and Applications (ICIEA) Year: 2018 | Conference Paper | Publisher: IEEE DOI:10.1109/ICIEA.2018.8397992.

[17] Jin Ma, Dawei Zhao, Liangzhong Yao, Minhui Qian, Koji Yamashita, Lingzhi Zhu Analysis on application of a current-source based DFIG wind generator model CSEE Journal of Power and Energy Systems Year: 2018 | Volume: 4, Issue: 3 | Journal Article | Publisher: CSEE DOI:10.17775/CSEEJPES.2018.00060.

[18] Panneer Selvam Manickam, Prakasam Periasamy Tracking the Maximum Wind Power

Point using Neuro-Fuzzy Control with DFIG-BESS for Wind Energy System 2018 Conference on Emerging Devices and Smart Systems (ICEDSS) Year: 2018 | Conference Paper | Publisher: IEEE DOI:10.1109/ICEDSS.2018.8544358.

[19] Younes Sahri, Salah Tamalouzt, Sofia Lalouni Belaid Direct Torque Control of DFIG Driven by Wind Turbine System Connected to the Grid 2018 International Conference on Wind Energy and Applications in Algeria (ICWEAA) Year: 2018 | Conference Paper | Publisher: IEEE DOI:10.1109/ICWEAA.2018.8605083.

[20] Wuyang Su, Bin Liu, Zhen Li, Xuefei Mao, Meng Huang, Guoqing He, Xiangdong Liu Dynamic State Estimation for DFIG Wind Turbine with Stochastic Wind Speed in Power System 2018 IEEE International Symposium on Circuits and Systems (ISCAS) Year: 2018 | Conference Paper | Publisher: IEEE DOI:10.1109/ISCAS.2018.8351791.

[21] Ganesh P. Prajapat, "Generator Speed Response under Turbulent Wind" 2017 14th IEEE India Council International Conference (INDICON) Year: 2017 | Conference Paper | Publisher: IEEE DOI:10.1109/INDICON.2017.8487485.

[22] Chakraborty, S. Kumar, B. Tudu, K. K. Mandai, I. Mukherjee Dynamic response analysis of a back-to-back converter based DFIG wind farm under variable wind speed 2017 2nd International Conference on Communication and Electronics Systems (ICCES) Year: 2017 | Conference Paper | Publisher: IEEE DOI:10.1109/CESYS.2017.8321246.

[23] Minh Quan Duong, Gabriela Nicoleta, "Sava Coordinated reactive power control of DFIG to improve LVRT characteristics of FSIG in wind turbine generation" 2017 International Conference on Electromechanical and Power Systems (SIELMEN) Year: 2017 | Conference Paper | Publisher: IEEE DOI:10.1109/SIELMEN.2017.8123328.

[24] Basem E. Elnaghi, M. El-shahat Dessouki, Fathy A. Elkader, "Experimental investigation of pitch angle controller for DFIG based wind energy conversion system" 2017 Nineteenth International Middle East Power Systems Conference (MEPCON) Year: 2017 | Conference Paper | Publisher: IEEE DOI:10.1109/MEPCON.2017.8301378.

[25] Preeti Sonkar; O. P. Rahi Investigation on DFIG based wind turbine for short term frequency

regulation techniques 2017 4th International Conference on Power, Control & Embedded Systems (ICPCES) Year: 2017 | Conference Paper | Publisher: IEEE DOI:10.1109/ICPCES.2017.8117659.

[26] Viral Patel, Manish Chaturvedi, Sanjay Srivastava, Comparison of SUMO and SiMTraM for Indian Traffic Scenario Representation, Transportation Research Procedia, Volume 17, 2016, Pages 400-407, ISSN 2352-1465, https://doi.org/10.1016/j.trpro.2016.11.081.

[27] Pradeep Kumar Dongre, Viral Patel, Upendra Bhoi, Nilesh N. Maltare, An outlier detection framework for Air Quality Index prediction using linear and ensemble models, Decision Analytics Journal, Volume 14, 2025, 100546, ISSN 2772-6622, https://doi.org/10.1016/j.dajour.2025.100546.

[28] Viral Patel and Nilesh Maltare, From Algorithms to Connectivity: A Comprehensive Review of Traffic Signal Optimization and Communication Based Cooperative Control, Archives of Computational Methods in Engineering, Volume 32, 2025, ISSN: 1134-3060, https://doi.org/10.1007/s11831-025-10455-w