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Implementation of DFIG Based Wind Turbine Emulator System in Real Time Embedded Controller and Chopper Fed DC Drive

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Abstract- As the power grid is significantly experiencing an increase in the penetration of renewable sources, this has an impact on grid integration and power quality. While wind energy is an abundantly available clean source of renewable energy, its increasing penetration into the utility grid introduces significant power quality issues and operational complexities. In this work, the active and reactive power flow between the supply and the supply-side converter may be independently controlled by the Doubly Fed Induction Generator (DFIG) - based Wind Energy Conversion Systems (WECS). The wind turbine is emulated as a DFIG driven by a torque-controlled DC drive. The DC motor will generate the exact torque that the wind turbine will generate based on the wind velocity and pitch angle. The wind power generation is represented by DFIG and a separately excited DC motor coupled with a utility grid. This wind emulator simulates various wind turbine scenarios to test control techniques, including wind-to-grid energy transfer, torque and speed calculations, rotor-grid synchronization, and phase angle control. A key focus of our proposed approach is the hardware optimization of the wind emulator testbench. By implementing a shared DC bus between the DC motor and DFIG, while centralizing all control tasks within a single WAVECT controller.The developed prototype of the wind energy conversion system is used to study the synchronous and sub-synchronous modes of operation under different wind speed conditions. The proposed test system also analyses various test scenarios utilizing WAVECT real-time controller boards.

Keywords Wind emulator, double fed induction generator, real time controllers, torque controlled dc drive.

1. Introduction

The massive growth in the renewable energy sector and the need for green energy sources has led to the growth of wind energy systems in different countries. As of June 2023, the World Wind Energy Association estimates that 1 million MW of wind turbines are installed worldwide [1]. The WECS consists of a wind turbine to convert wind velocity into mechanical energy, and the wind turbine generator converts the shaft speed from the gearbox to electrical energy [2]. The wind turbine system can be classified as fixed speed and variable speed wind system based on the operating conditions. The fixed speed system is simple in structure; however maximum power cannot be extracted as the power changes with changes in wind speed. This type of fixed wind speed system cannot support the grid during grid faults. The most commonly used WECS system is the variable speed wind system. In the variable type WECS, wind speed variation changes the rotor speed as a function of power coefficient to harvest the maximum wind energy [3,4,5]. Besides, during grid faults, grid recovery can be achieved by injecting reactive power to the grid and auxiliary services can be provided by the power converters. The DFIG is connected to machine shaft through a gear box to match the low speed of the wind turbine and transfer power effectively. As power and size of the wind turbine are increasing, modelling and analysing of wind generation systems has become complex [6]. Because of the severe conditions of wind farms and high costs, research and experiments on wind power generation systems are difficult to conduct. Investigating WECS remains a significant challenge in many academic settings due to the non-availability of integrated wind and mechanical components in laboratory facilities. The most convenient way to represent a WECS for research works is to emulate the wind energy system by coupling the DFIG with the separately excited DC motor [7,8,9]. DFIG is connected to the grid through the use of a power electronics converter. The rotor speed of is controlled by the power converters, and also the shaft speed is adjusted so as to harvest maximum possible energy from the wind generator. When maximum capacity is reached, either the electric power or angular speed of wind turbine can be regulated by power electronics converter that are located between electric grid and wind turbine. The DFIG with the power electronics converters and other auxiliary devices such as filter circuit, chopper circuit and protection circuit interface the rotor to the utility grid [10]. The actual wind turbine can be replaced with a wind emulator by computing the output torque developed by the wind turbine model, which has the same characteristics and provides the same equivalent wind energy.

A new second-generation Commande Robuste d'Ordre non Entier (CRONE) method of controlling variable-speed wind turbines has been proposed by the author in [11] because classical controllers do not guarantee high wind energy conversion stability and maximum energy extraction from variable-speed wind turbines under real wind profiles. Using advanced back stepping with integral action control, the author in [12] developed a robust nonlinear controller to monitor the network side during regular operations. The authors in [13,14] have proposed a wind emulator, where changes in pitch angle is emulated for various test cases. Dekali et. al., [15] has introduced a DFIG based wind emulator with dc motor drive system and the control algorithms are implemented in dspace. The results of the emulator is presented for sub-synchronous and synchronous modes of operation and concludes that the present structure of the wing emulator with DFIG and DC motor system is more effective. The author in [16], has developed an open loop wind emulator with dc motor. The control algorithm is implemented using FPGA and PWM strategy for various wind speed. A wind emulator with motor current as the variable for building the wind emulator is developed in [17]. Which considers the dynamics of the wind turbine, such as wind shear and inertia. The control algorithm is implemented in MATLAB real time control software interfaced with I/O boards. In [18], the author presents a novel BLDC based wind turbine emulator that can simulate both steady-state and dynamic wind turbine characteristics. A torque controlled BLDC model is constructed taking into account different wind speeds, turbine inertia, tower shadow, and wind shear. For dynamic and static characteristics of wind turbine emulators, different control schemes have been proposed [19-27] and the comparison of the controllers is shown in Table 1.

Table 1. Comparison of various wind turbine emulators

S. No	Parameter considered for development of wind emulator	Emulator Controller	Hardware	Remarks
1	Motor current [20]	Single phase dc drive	Matlab interfaced with I/O board	Wind turbine dynamics are considered.
2	Torque and speed [21,22]	AC drive with direct torque control	Dspace	Tip speed curve is considered for the emulator.
3	Torque and speed [23]	IGBT inverter controlled induction motor	Mıcrocontroller 80CI96KD	DC machine based DFIG with harware in loop. The emulator consists of real time physical simulator and investigated physical system.
4	Torque [24]	Dead –beat current controller	DSP TMS320F28055	Based on the DSP model, the rotor inertia effect of the system is considered.
5	Wind speed and rotor speed [25]	İnduction motor based emulator	Microcontroller PIC16F876A	Wind turnbine dynamics not considered and the emulator depends upon power and wind speed.
6	Torque [26]	Thyristor control	DSP board	Static and dynamic behavior of real WECS
7	Speed [27]	DC-DC converter	MATLAB/Xilinx System and FPGA	Rotational speed of the motor is proportional to wind speeds
8	Speed [28]	DC-DC Converter	32 bit ARM cortex board	The wind turbine is emulated using data from various sources.

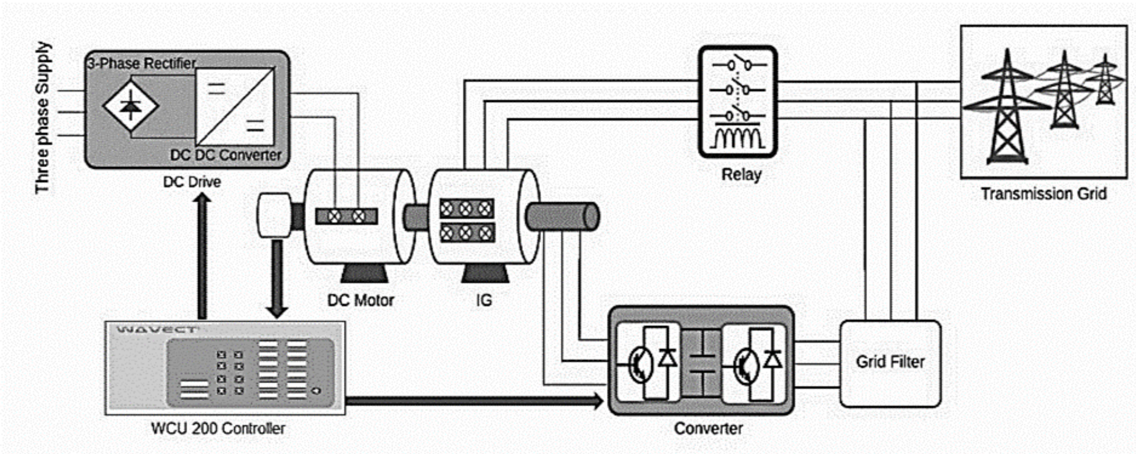


Fig. 1. Grid-connected DFIG based wind emulator.

Proposed Methodology:

- In the proposed work, the DFIG based WECS emulator is developed using Wavect real time controller boards and different test conditions are analysed.
- The different test conditions considered are : synchronous speed, sub-synchronous speed and different speed of operation.
- The proposed hardware setup is also simulated in MATLAB simulation with 1.5 Mw grid connected wind system.
- The control parameter of the proposed wind emulator variable rotor speed.
- The emulator control algorithm is developed in WCU300 FPGA base WAVECT controller.

In the proposed work, the DC motor is coupled with the DFIG considering motor speed and torque as input variables and generate torque equivalent to the wind velocity and pitch angle under different wind speeds. The reference signal is generated in two ways: First, the wind turbine's mathematical model is used to determine the reference speed and the control system to track the same. Second, wind turbine inertia is used to generate the reference torque and the motor adapts the control scheme to tracks the reference torque.

2. Design and Development of Proposed WECS Emulator

The proposed WECS emulator consists of DC motor, DFIG based system, Chopper fed DC drive, three phase voltage source inverter on both the grid side and rotor side. In addition, the proposed emulator has WAVECT real time digital controller board, data acquisition systems, grid side interfaces and sensors. The input parameters to the proposed wind emulator includes the wind velocity, wind speed and dc-link reference voltage, Grid Side Converter (GSC) voltage and current. The schematic representation of grid connected wind emulator is shown in Fig.1.

The proposed WAVECT controller generates an analog signal by comparing the rotor speed and current with their set points and these signals are the inputs to the dc driver control unit. The driver unit converts this signals into pulses and fed to the thyristor controlled bridge rectifier and the rotor side rectifier circuit.

Based on the desired reference speed of the rotor, the DC drive regulates the armature voltage of the separately excited DC motor. And hence the DC motor coupled with DFIG emulates the wind turbine. In the proposed emulator, the wind turbine is represented as slip ring induction generator coupled with dc motor. The dc motor is responsible for the generation of the speed and torque with reference to the induction motor. The separately excited DC motor with a chopper or rectifier circuit is used to develop a wind emulator. The wind speed is a variable parameter, hence the varying speed causes fluctuations and the output mechanical power delivered by wind turbine is as follows:

$$P_m = \rho\pi R^2 v_t^3 C_p(\lambda,\beta) \quad (1)$$

Where, ρ is air density in kg/m^3, R is the turbine radius in meters, v_t is wind velocity in m/sec. The power coefficient, $C_p(\lambda,\beta)$ depends on tip speed ratio (λ) of the turbine and blade pitch angle, β**.** The tip speed ratio of the wind turbine is given as,

$$\lambda = \frac{R\omega}{\vartheta} \quad (2)$$

Where, ω is the speed of the turbine in rad/ sec. The torque developed by wind turbine is expressed as,

$$T = \frac{P_m}{\omega} \quad (3)$$

Substituting (1) and (2) in equation (3), Torque is expressed as follows:

$$T = \frac{\rho\pi R^2 \vartheta_t^3 C_p(\lambda,\beta)}{\omega} \quad (4)$$

$$\omega = \frac{\rho\pi R^2 \vartheta_t^3 C_p(\lambda,\beta)}{T} \quad (5)$$

The speed described in equation (5) is reference speed of the rotor at certain wind speed. The torque versus various wind speeds is as shown in Fig.2.

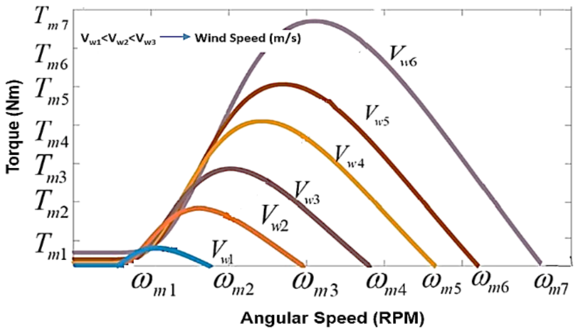


Fig. 2. Torque versus angular speed.

The flux, φ_f produced in the motor is constant under steady state condition as given in equation (6) and the power from the motor is a function of armature voltage and speed.

$$\varphi_f = k_\varphi * I_f \quad (6)$$

The armature terminal voltage is,

$$U_t = i_a R_a + L_a \frac{di_a}{dt} + E_b \quad (7)$$

$$E_b = k_\varphi \varphi \omega \quad (8)$$

The relationship between the motor torque and torque developed due to the effects of the load is given by:

$$T_a = J\frac{d\omega}{dt} + T_r \quad (9)$$

Where, T_a is the torque developed by the dc motor, J is the moment of inertia and T_r is generated torque of wind turbine.

The speed of the dc motor is completely dependent on load applied to the armature of the machine. Hence, torque developed by the motor is directly proportional to armature current and flux. The machine torque given in the above equation can be written as follows:

$$T_a = k_a \varphi I_a \quad (10)$$

Since the dc motor shaft is coulpled to wind generator, the speed of the generator is same as that of the dc motor. The structure of the proposed wind emulator is shown in Fig.3. The DC motor is to emulate the dynamic behaviour of the wind turbine. The main components of wind energy system are, the dc motor, rotor side converter and stator side converter. The wind emulator has two subsystems, first is the Graphical User Interface developed using MATLAB 2023a with input and output communication cards from Wavect real–time control. The WAVECT controller board is a real time versatile and compact prototyping board, consisting of a dual core CPU for control and communication, a high-end FPGA for quick computation, I/O cards, scalable integrated voltage and current sensors, PWM outputs, and fast I/Os. Hence the wind emulator is formed by integrating the dc motor with induction generator.

By regulating wind turbine power output, the GSC ensures that the grid is supplied with both active and reactive power. The GSC control has two cascaded Proportional Integral (PI) controllers for controlling the inner current control loops which regulates the grid current and outer control loop which regulates the dc-link voltage to its nominal value. Thus the inverter current and dc voltage is regulated by PWM pulses generated by d-axis and q-axis currents. Usually, the inverter can be operated to deliver maximum active power to the grid by setting unity power factor.

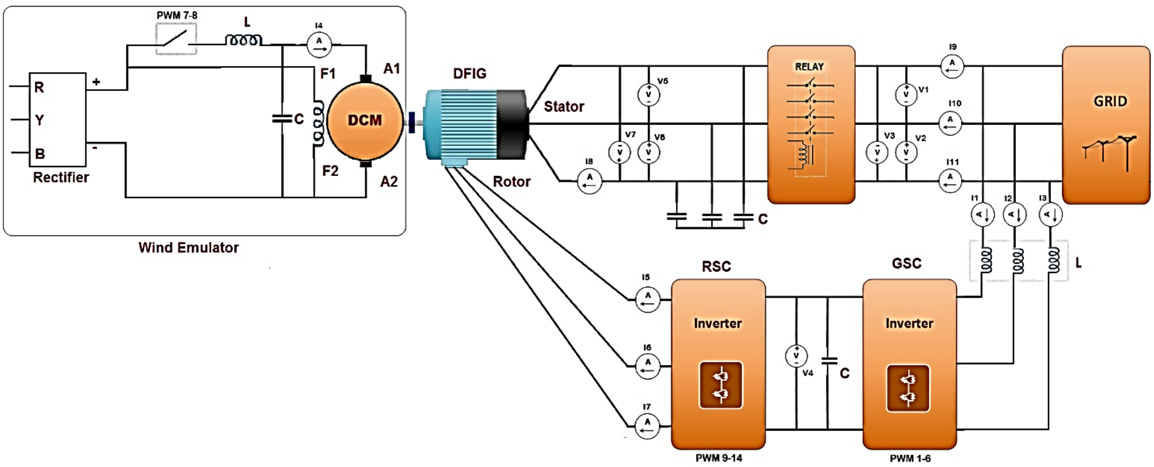


Fig. 3. Basic structure WECS.

2.1. Grid Side Converter Control

The proposed GSC is shown in Fig.4, which regulates the voltage at dc-link and reactive power flow between the grid and converter. The inner loop and outer loop both consists of PI controller. The outer loop has two controls, first is the dc-link voltage control and the other is reactive current control. The inner loop enables the PI controller with grid voltage as input and converter voltage.

The expression for voltage between the grid and the GSC is as follows:

$$V_{abc} = R_f I_{abc} + L_f \frac{dI_{abc}}{dt} + V_{gabc} \qquad (11)$$

Where V_{abc} denotes the grid voltage and V_{gabc} denotes the converter voltage.

2.2. Rotor Side Converter Control

The power delivered to the grid is controlled by a cascaded control loop in the GSC. The observed active and reactive currents are compared with the reference currents to determine the dq axis voltages as indicated in Fig.5. The reactive power control is achieved by regulating the reference of q axis reactive current (I_{qr_ref}).

2.3. DC Drive Circuit Control

The dc drive control circuit with reactive current control using a PI controller is shown in Fig.6. This control circuit makes sure that the wind speed is same as that of synchronous speed of the machine. Under steady state, the emulator current and power are matched with reference current and power, respectively. In accordance with the wind speed, the shaft speed on the machine varies.

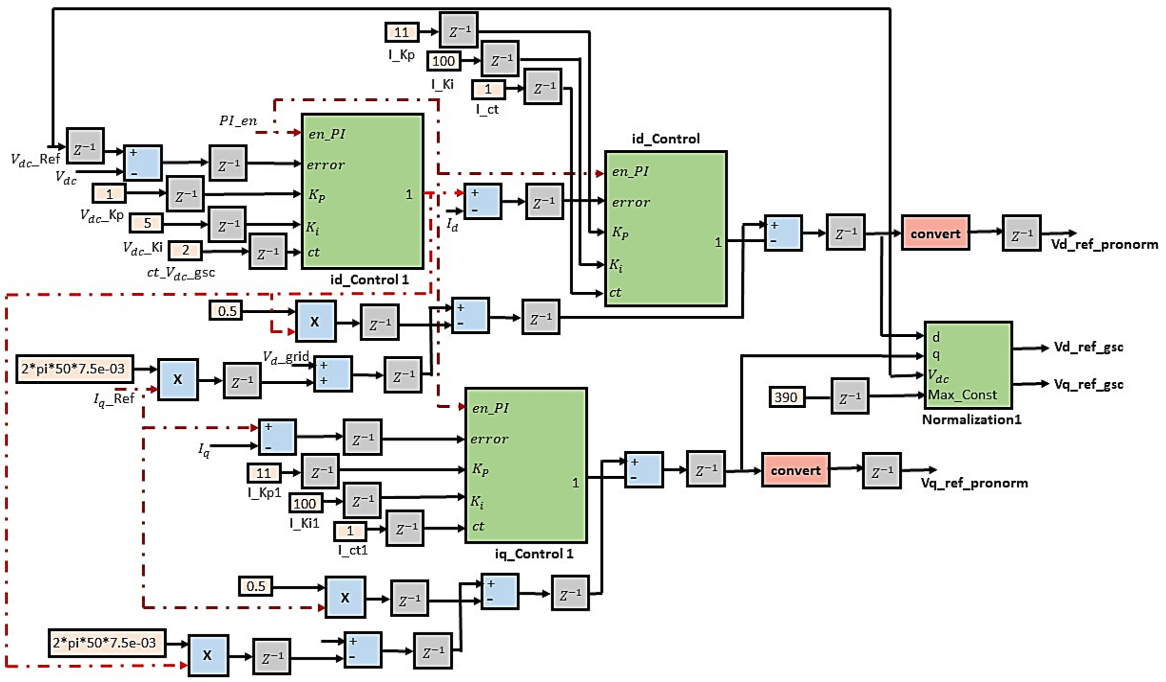


Fig. 4. Proposed GSC control scheme in WECS.

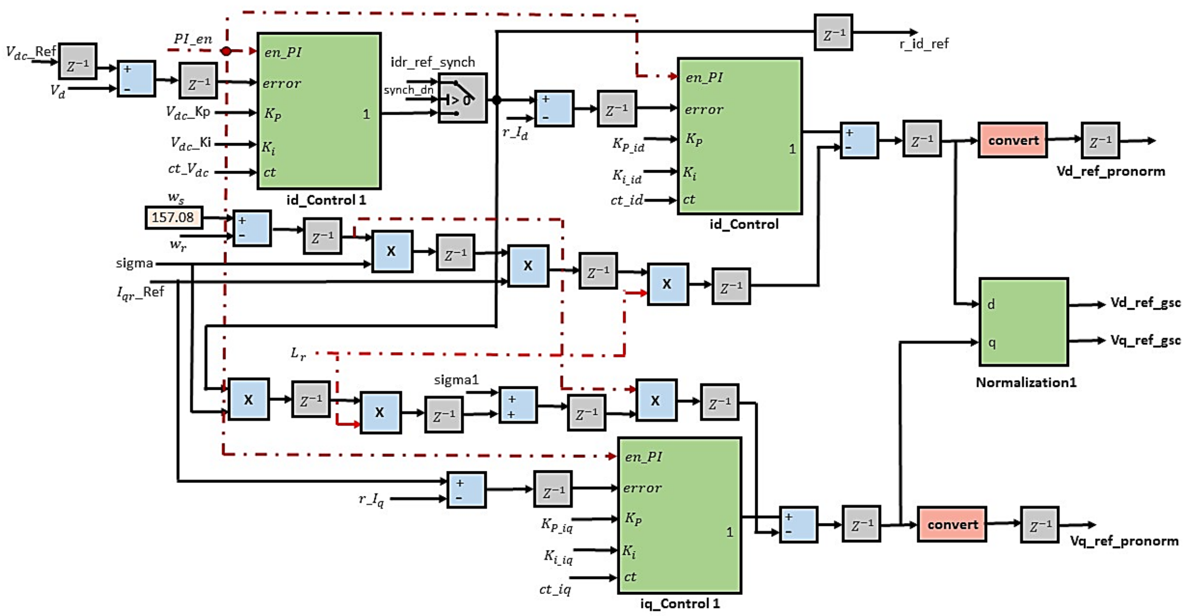


Fig. 5. Proposed RSC control scheme WECS

3. Description of Wind Emulator Test system

The grid connected wind emulator consists of two three-phas+9e inverters for rotor side and grid side of the emulator. The DC motor coupled DFIG system can deliver up to 1 kW power at synchronous speed. This entire setup is connected to the grid through a WAVECT controller as shown in Fig.7.

The wind emulator is forced to operate in three modes of operation namely, synchronous mode, sub-synchronous mode and at different speeds of operation to study the performance of the emulator. The configuration of the wind emulator is show Table 2. Fig.8 shows the hardware setup of the wind emulator. Fig.9 shows the setup of the WAVECT controller which has 8 current sensor and 8 voltage sensor terminals with 8 individual digital to analog converter, analog to digital converter, relays and 2 encoders. It also has 2 Control Area Network (CAN) and Local Area Network (LAN) terminals with 12 PWM channels. Fig.10, 11 and 12 displays the dashboard details of the DC motor, GSC and grid synchronization details respectively.

Table 2. Wind emulator system parameters

Equipment's	Parameters
Double fed induction generator	415 V, 2,2 kW, 1000 rpm
DC Motor	220 V, 2.5 kW, 1500 rpm.
IGBT BASED Converter	Rectifier: 415 V (AC), 560 V (DC), 45 A Chopper: 600 V (DC), 30 A Inverter: 600 V(DC-link), 415 V (AC output, 30 A 220 V, 2.5 kW, 1500 rpm, switching frequency: 2 kHz
WAVECT FPGA controller (WCU 300)	12 V, 24 PWM, 8 AIO and 8 DIO
Encoder for speed feedback	1024 PPR, RS422

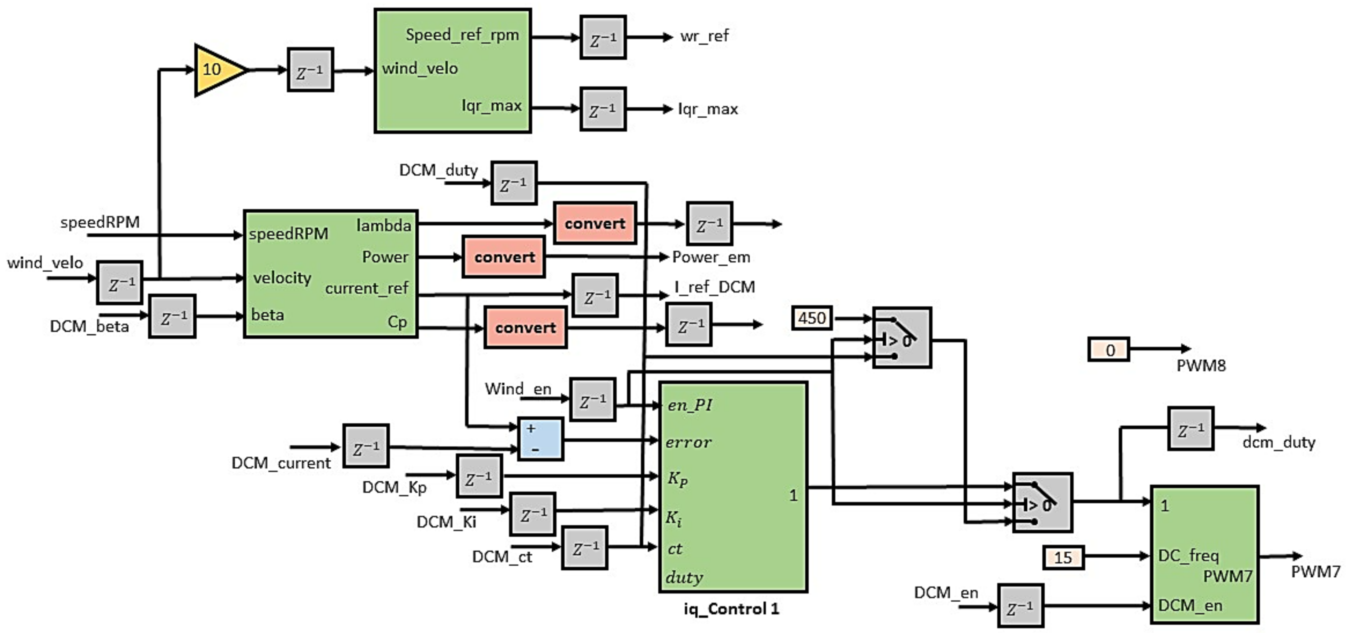


Fig. 6. Proposed DC driver control scheme in WECS.

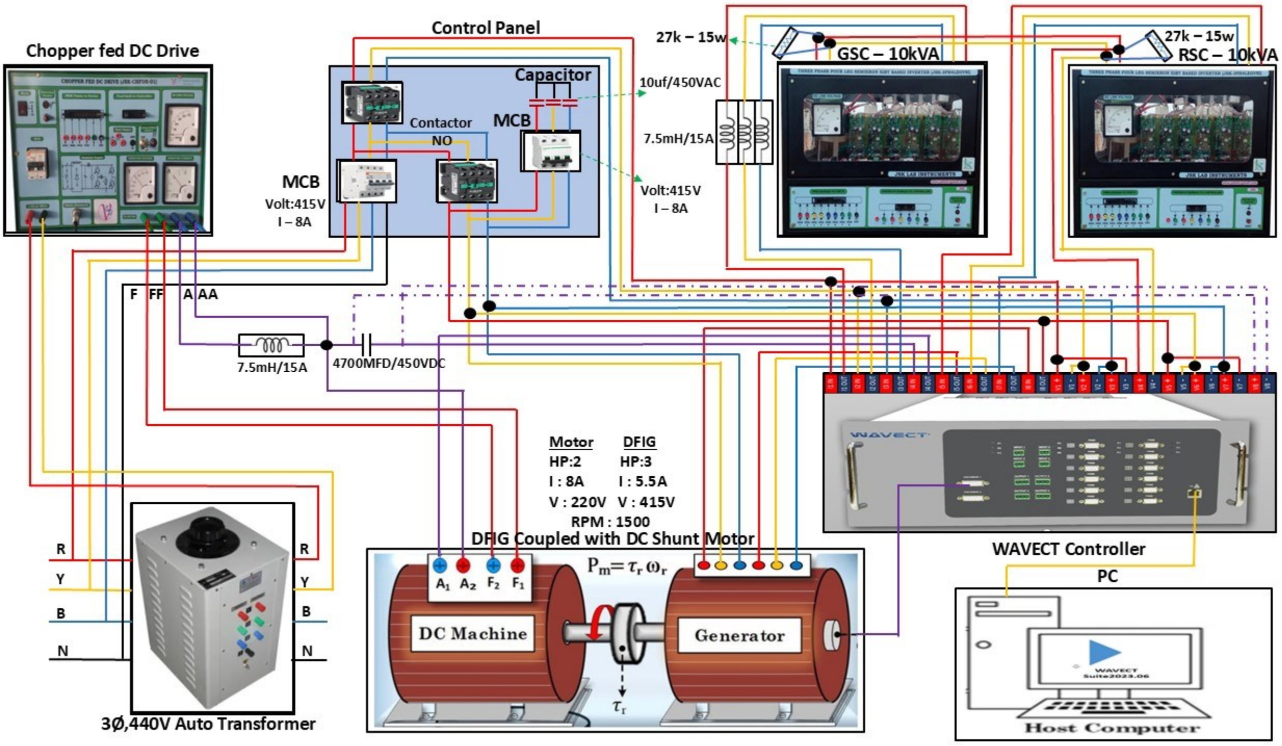


Fig. 7. Wind emulator test system.

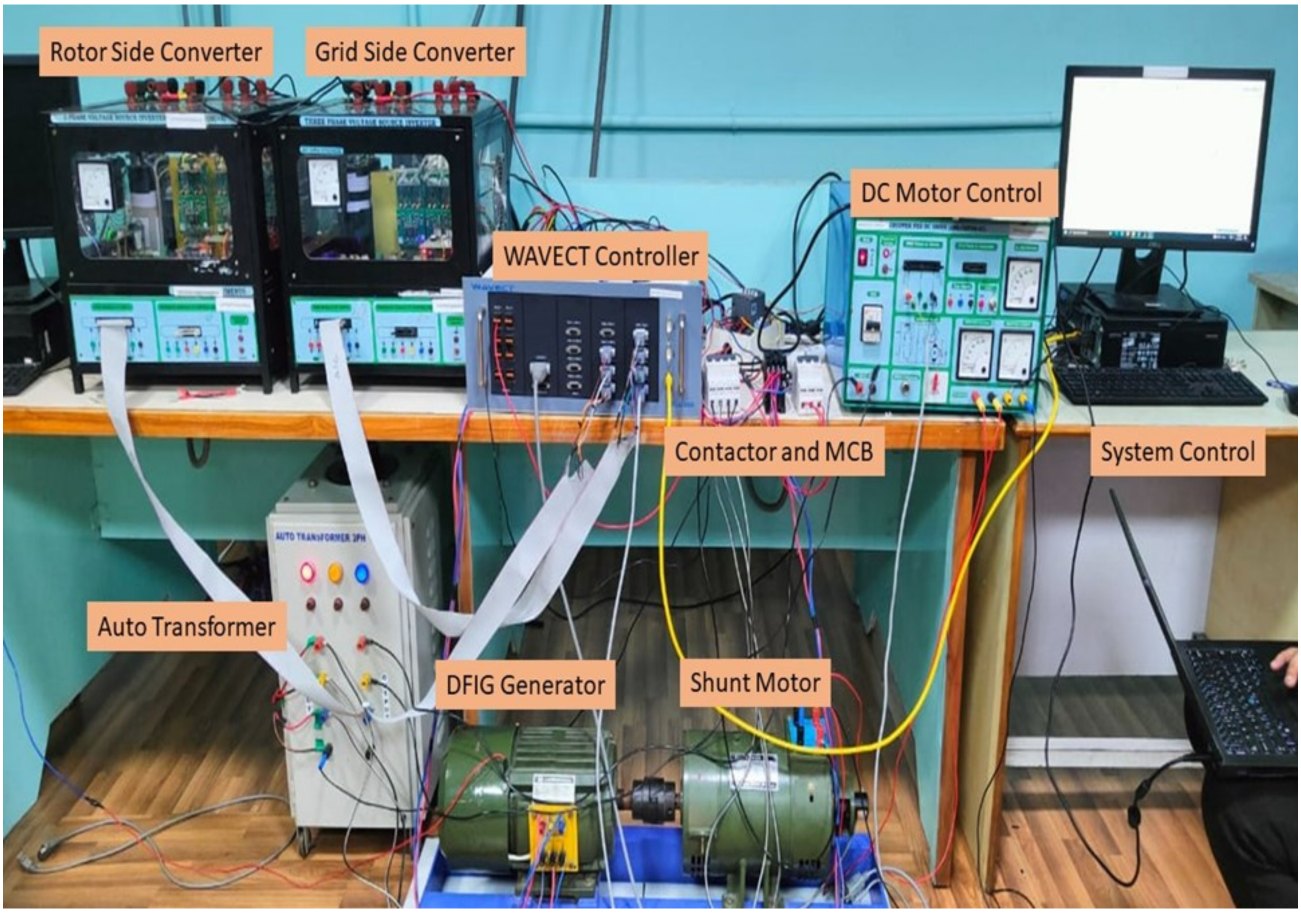


Fig. 8. Proposed wind emulator hardware setup.

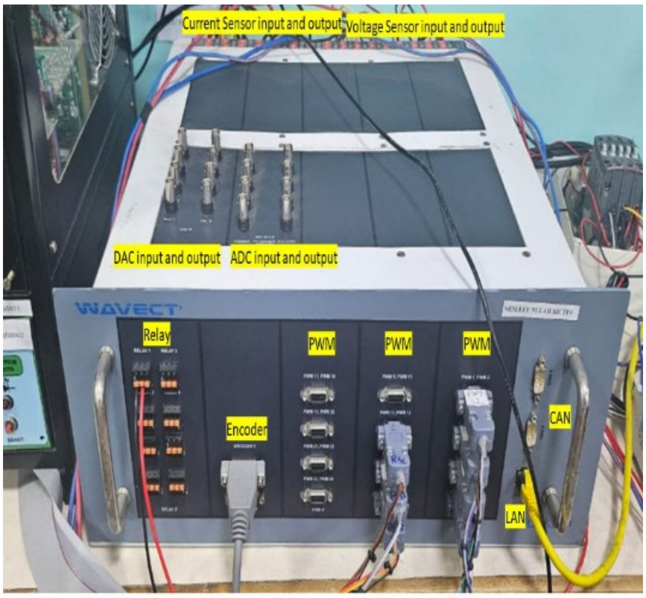


Fig. 9. Hardware setup of WAVECT controller.

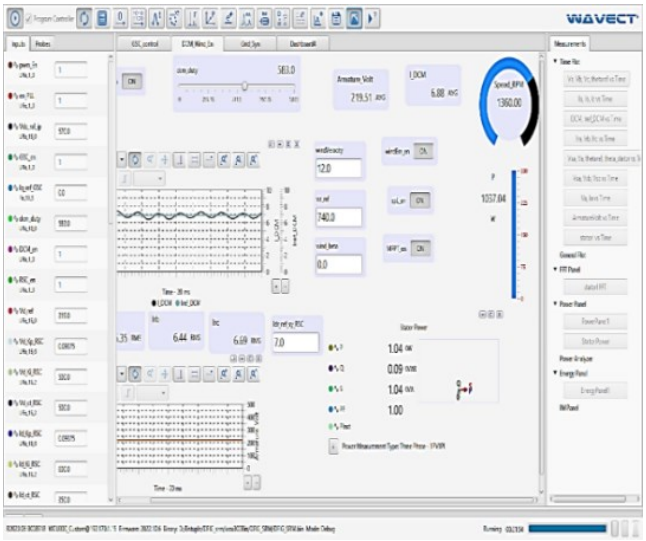


Fig. 10. DC Machine and wind speed dashboard details of the proposed wind emulator at synchronous speed.

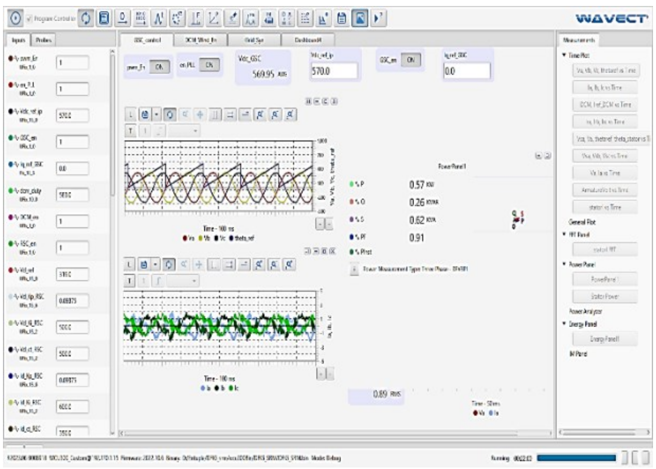


Fig. 11. Grid side converter control dashboard details of the proposed wind emulator at synchronous speed.

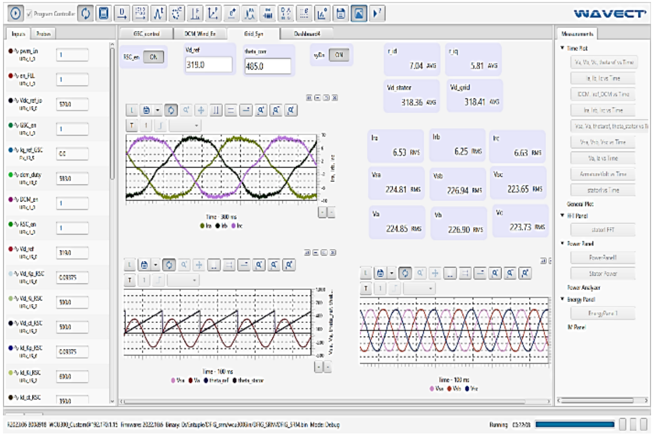


Fig. 12. Grid synchronization dashboard details of the proposed wind emulator at synchronous speed.

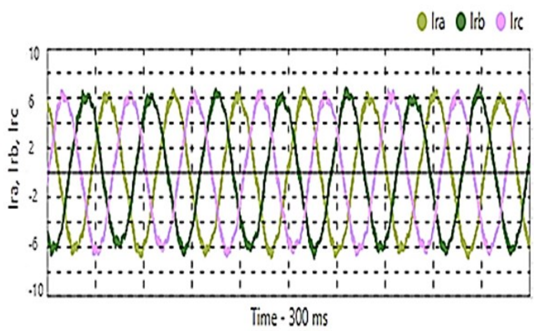
4. Discussion on Hardware Results

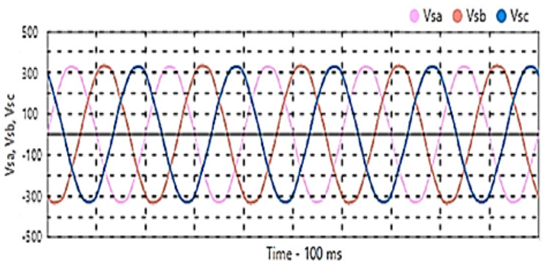
Mode 1: Synchronous Speed of Operation

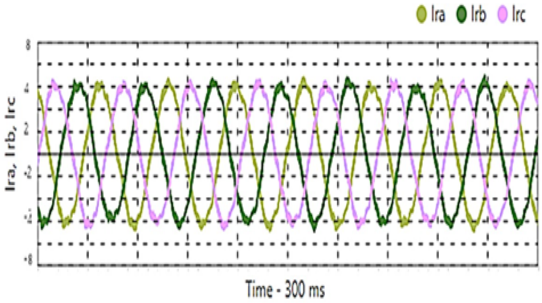
The rotor speed is set at 1500 rpm initially and, the voltage and phase angle of the machine needs to be checked for synchronization. The Synchronization of voltage and phase angle can be achieved by changing the reference dc-link voltage (V_{dcref}), such that this V_{dcref} is same as the d axis grid voltage ($V_{d\ grid}$). The phase angle synchronization can be achieved by fixing the ϴ of the machine with $ϴ_{ref}$. After synchronization of the machine, wind velocity of the emulator is set to 12 m/s, to generate the maximum power of 1.02 kW and 0.14 kVAR. Table 3 gives the performance analysis of the proposed wind emulator at synchronous speed. The rotor speed is 1362 RPM, dc-link voltage is maintained at 605.98V. The grid side voltage is 333.41V and grid current is 6.24 A with 0.99 power factor as shown in Fig.13.

Table 3. Wind emulator performance at synchronous speed.

System Parameter	Performance
Wind Speed (m/Sec)	12
Speed (rpm)	1362
P (kW)	1.05
Q (kVAR)	0.14
Power factor	0.99
DC_link Voltage (Volt)	605.98
Grid Voltage (Volt)	333.41
Grid Current (Amps)	6.24







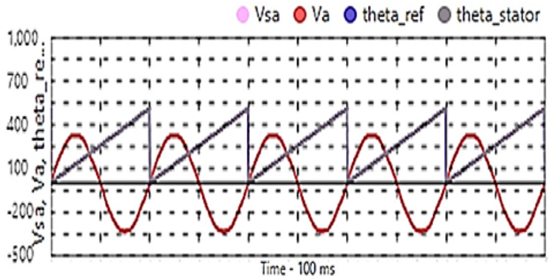


Fig. 13. Peformance of the system during synchronous speed of operation.

Mode 2: Sub-Synchronous speed of operation

The rotor is made to run at a speed less than the synchronous speed, by adjusting the input to the machine through an autotransformer. Once the synchronization is achieved, the speed of the wind emulator is set to 7 m/s, to generate power of 0.2 kW and 0.25 kVAR. Table 4 gives the performance details of the proposed wind emulator at sub synchronous speed. The rotor speed is 754 RPM, dc-link voltage is maintained at 605.98V. The grid side voltage is 334.16V and grid current is 4.28 A with 0.69 power factor as shown in Fig.14.

Table 4. Wind emulator performance at sub synchronous speed

System Parameter	Performance
wind Speed (m/Sec)	7
Speed (rpm)	754
P (kW)	0.2
Q (kVAR)	0.25
Power factor	0.69
DC_link Voltage (Volt)	605.98
Grid Voltage (Volt)	334.16
Grid Current (Amps)	4.28

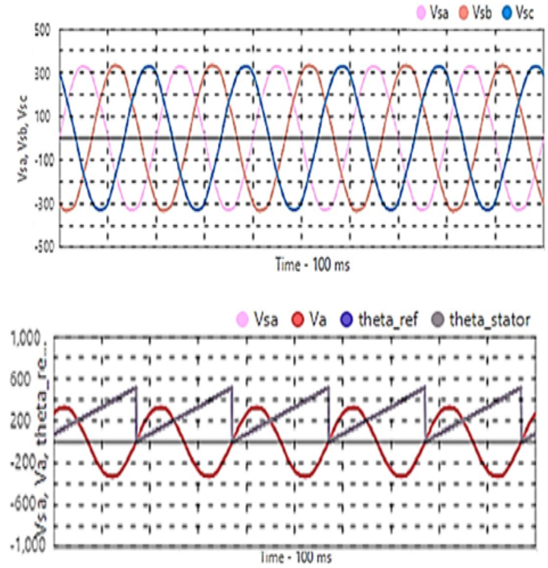


Fig. 14. performance of the wind emulator during sub-synchronous speed of operation.

Mode 3: At Different wind speed Conditions

The rotor is made to run at different speeds by varying the input voltage of the machine and the wind emulator characteristics are observed. The different speeds considered are 8, 9, 10 and 11 m/s. Table 5 shows the performance of the emulator action under various wind profile. Fig.15 shows the performance of the system at 11m/s speed.

Table 5. Wind emulator performance at different wind speeds

Wind Speed (m/s)	Rotor Speed (RPM)	Active Power (kW)	Reactive Power (kVAR)	Power Factor	DC-Link Voltage (V)	Grid Voltage (V)	Grid Current (A)
11	1241	0.86	0.07	1.00	605.98	333.59	5.74
10	1161	0.73	0.05	1.00	605.98	333.82	5.26
9	1018	0.54	0.07	0.99	605.98	333.92	4.92
8	766	0.26	0.15	0.86	605.98	333.95	4.38

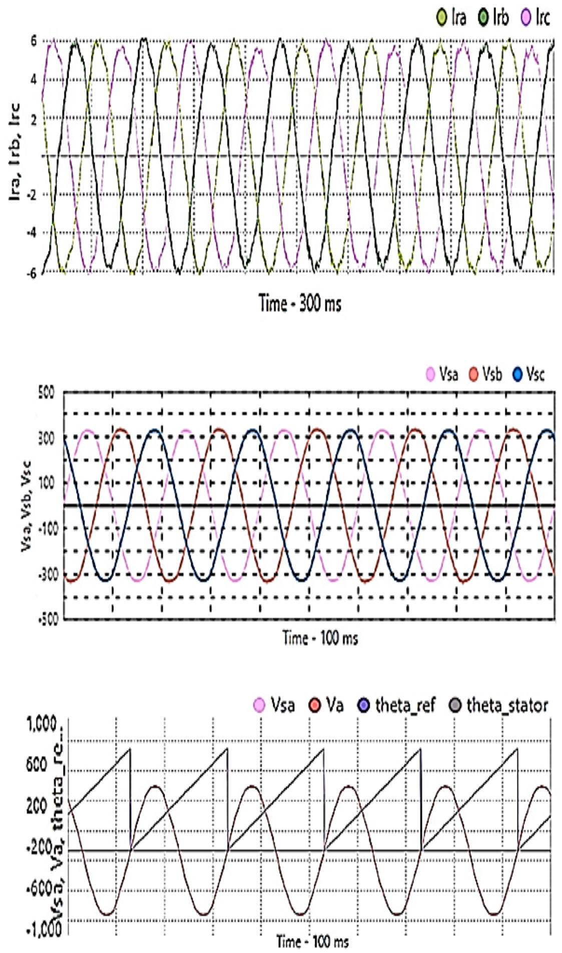


Fig. 15. Performance of the wind emulator at 11 m/s speeds.

5. Conclusion

This paper is based on the design and development of hardware setup of DFIG based wind energy conversion emulator. In this work, the investigation analysis of wind emulator is carried out under sub synchronous and synchronous modes with varying wind speeds. The proposed WECS based wind emulator is developed using DC motor coupled to a DFIG, which generates torque equal to wind velocity and pitch angle is based on motor speed and torque. The developed emulator is controlled by controllers in the rotor side and grid side converter of WECS. The developed wind based emulator is tested under different performance analysis and the results are satisfactory with proven effectiveness. The system parameters of the test system is obtained and investigated which shows good results closer to the actual wind system. The future scope of the work is to investigate the different controllers in the testbed and compare the results under normal and fault conditions.

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Author Contributions

Dr. V. Vignesh Babu was responsible for the conceptualization, design, analysis, interpretation of data, writing original draft and validation. Dr. J. Preetha Roselyn and Dr. C. Nithya jointly contributed to the methodology, formal analysis, investigation, review and editing, visualization and supervision. All authors have read and agreed to the published version of the manuscript.

Conflict of Interest

The author(s) declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

References

[1] World Wind Energy Association (WWEA), "Global Wind Installations," Available: https://wwindea.org/, accessed Aug. 23, 2023.

[2] H. Garg, N. Sharma, and R. Dahiya, "Design and simulation of wind turbine emulator," in Proc. 2018 IEEE 8th Power India Int. Conf. (PIICON), 2018, pp. 1–6.

[3] J. G. Slootweg, S. W. H. De Haan, H. Polinder, and W. L. Kling, "General model for representing variable speed wind turbines in power system dynamics simulations," IEEE Trans. Power Syst., vol. 18, no. 1, pp. 144–151, 2003.

[4] O. Alkul, D. Syed, and S. Demirbas, "A review of wind energy conversion systems," in Proc. 2022 10th Int. Conf. Smart Grid (icSmartGrid), 2022, pp. 72–77.

[5] M. Allouche, S. Abderrahim, H. Ben Zina, and M. Chaabane, "A novel fuzzy control strategy for maximum power point tracking of wind energy conversion system," Int. J. Smart Grid, vol. 3, no. 3, pp. 120–127, 2019.

[6] A. Ramanath, J. D. M. Deivanayagam, S. Raju, and N. Mohan, "An extremely low-cost wind emulator," in Proc. IECON 2018 – 44th Annual Conf. IEEE Industrial Electronics Society, 2018, pp. 1675–1680.

[7] G. Liu, S. Wang, and J. Zhang, "Design and realization of DC motor and drives based simulator for small wind turbine," in Proc. Asia-Pacific Power and Energy Engineering Conf., 2010, pp. 1–4.

[8] S. Kouadria, S. Belfedhal, Y. Meslem, and E. M. Berkouk, "Development of real time wind turbine emulator based on DC motor controlled by hysteresis regulator," in Proc. Int. Renewable and Sustainable Energy Conf. (IRSEC), 2013, pp. 246–250.

[9] F. Blaabjerg, M. Liserre, and K. Ma, "Power electronics converters for wind turbine systems," IEEE Trans. Ind. Appl., vol. 48, no. 2, pp. 708–719, 2011.

[10] I. Nouira, A. Khedher, and A. Bouallegue, "A contribution to the design and installation of a universal platform of a wind emulator using a DC motor," Int. J.

Renewable Energy Research, vol. 2, no. 4, pp. 797–804, 2012.

[11] M. Yessef, B. Bossoufi, M. Taoussi, S. Motahhir, A. Lagrioui, H. Chojaa, S. Lee, B. G. Kang, and M. Abouhawwash, "Improving the maximum power extraction from wind turbines using a second-generation CRONE controller," Energies, vol. 15, p. 3644, 2022.

[12] A. Loulijat, H. Chojaa, M. El Marghichi, N. Ettalabi, A. Hilali, A. Mouradi, A. Y. Abdelaziz, Z. M. S. Elbarbary, and M. A. Mossa, "Enhancement of LVRT ability of DFIG wind turbine by an improved protection scheme with a modified advanced nonlinear control loop," Processes, vol. 11, p. 1417, 2023.

[13] H. Dahiya and R. Dahiya, "Development of wind turbine emulator for standalone wind energy conversion system," in Proc. IEEE 6th Int. Conf. Power Systems (ICPS), New Delhi, India, 2016, pp. 1–6.

[14] M. El Mokadem, V. Courtecuisse, C. Saudemont, B. Robyns, and J. Deuse, "Experimental study of variable speed wind generator contribution to primary frequency control," Renewable Energy, pp. 833–844, 2009.

[15] Z. Dekali, L. Baghli, A. Boumediene, and M. Djemai, "Control of a grid connected DFIG based wind turbine emulator," in Proc. 5th Int. Symp. Environment-Friendly Energies and Applications (EFEA), Rome, Italy, 2018, pp. 1–6.

[16] J. Castelló, J. M. Espí, and R. García-Gil, "Development details and performance assessment of a wind turbine emulator," Renewable Energy, vol. 86, pp. 848–857, 2016.

[17] M. Monfared, H. Madadi Kojabadi, and H. Rastegar, "Static and dynamic wind turbine simulator using a converter controlled DC motor," Renewable Energy, vol. 33, pp. 906–913, 2008.

[18] H. Guo, B. Zhou, J. Li, F. Cheng, and L. Zhang, "Real-time simulation of BLDC-based wind turbine emulator using RT-LAB," in Proc. Int. Conf. Electrical Machines and Systems, Tokyo, Japan, 2009, pp. 1–6.

[19] Y. E. A. Eldahab, H. Saad, and A. Zekry, "Assessing wind energy conversion systems based on newly developed wind turbine emulator," Int. J. Smart Grid, vol. 4, no. 4, 2020.

[20] M. Monfared, H. Rastegar, and B. Moradzadeh, "A more accurate dynamic wind energy conversion system emulator," in Proc. Int. Conf. Electrical and Control Technologies (ECT), Kaunas, Lithuania, 2007, pp. 151–156.

[21] N. Muntean, L. Tutelea, D. Petrila, and O. Pelan, "Hardware-in-the-loop wind turbine emulator," in Proc. Int. Aegean Conf. Electrical Machines and Power Electronics, Istanbul, Turkey, 2011, pp. 53–58.

[22] R. Nair and G. Narayanan, "Emulation of wind turbine system using vector controlled induction motor drive," IEEE Trans. Ind. Appl., vol. 56, pp. 4124–4133, 2020.

[23] L. Chang, R. Doraiswami, T. Boutot, and H. Kojabadi, "Development of a wind turbine simulator for wind energy conversion systems," in Proc. Canadian Conf. Electrical and Computer Engineering, Halifax, Canada, 2000, pp. 550–554.

[24] V. T. Ha, V. H. Phuong, N. T. Lam, and N. P. Quang, "A dead-beat current controller based wind turbine emulator," in Proc. Int. Conf. System Science and Engineering (ICSSE), Ho Chi Minh City, Vietnam, 2017, pp. 169–174.

[25] A. Mesbahi, M. Khafallah, A. Saad, and A. Nouaiti, "Emulator design for a small wind turbine driving a self-excited induction generator," in Proc. Int. Conf. Electrical and Information Technologies (ICEIT), Rabat, Morocco, 2017, pp. 1–6.

[26] I. Moore and J. Ekanayake, "Design and development of a hardware based wind turbine simulator," in Proc. 45th Int. Universities Power Engineering Conf. (UPEC), Cardiff, UK, 2010, pp. 1–5.

[27] I. Moussa, A. Bouallegue, and A. Khedher, "New wind turbine emulator based on DC machine: Hardware implementation using FPGA board for an open-loop operation," IET Circuits Devices & Systems, vol. 13, pp. 896–902, 2019.

[28] G. Gökkuş and A. Kulaksız, "Design and implementation of a wind turbine emulator using an induction motor and direct current machine," Int. J. Renewable Energy Research, vol. 10, 2020.