Emulation Structures and Control of Wind-Tidal Turbine Hybrid Systems for Saudi Arabia Off-shore Development

Abdulaziz Alanazi
Department of Electrical Engineering, College of Engineering, Northern Border University, Arar 73222, Saudi Arabia
afalenazy@nbu.edu.sa

Ezzeddine Touti
Department of Electrical Engineering, College of Engineering, Northern Border University, Arar 73222, Saudi Arabia
esseddine.touti@nbu.edu.sa (corresponding author),

Cristian Nichita
Groupe de Recherche en Electrotechnique et Automatique du Havre (GREAH), University Le Havre Normandie, 75 rue Bellot 76058 Le Havre Cedex, France
nichita@univ-lehavre.fr

Ashglaf Mohamed
Groupe de Recherche en Electrotechnique et Automatique du Havre (GREAH), University Le Havre Normandie, 75 rue Bellot 76058 Le Havre Cedex, France
mshoglaf@gmail.com

Received: 11 May 2024 | Revised: 21 May 2024 | Accepted: 23 May 2024

ABSTRACT

This paper presents the principles of developing an electromechanical emulator based on an original hybridization concept of a wind and tidal power system. Wind and tidal horizontal axis turbines showcase functional similarities and electromechanical coupling possibility. Tidal concepts are very close to those of wind power. Tidal turbine technology should thus reach maturity more quickly because it is possible for it to rely on a certain number of reliable and proven techniques developed for wind power. The proposed hybrid wind – tidal turbine system is electromechanically coupled on the axis of rotation of a single and common electric generator. An experimental simulation of the hybrid wind-tidal turbine system was carried out, using a developed architecture of an emulator system. The results are both numerical simulations carried out in the MATLAB/Simulink environment and tests obtained employing real-time emulators.

Keywords-wind power; tidal turbine; hybrid system; emulator; real time

I. INTRODUCTION

Saudi Arabia is exploring the potential of offshore wind farms for renewable energy production. These wind farms would harness the power of wind to generate electricity, reducing the country's reliance on fossil fuels. While the country has made significant strides in solar energy, the offshore wind energy potential in Saudi Arabia remains largely untapped. The Red Sea, with its strong and consistent winds, is an ideal location for wind and marine currents to be created, and so for tidal farms to be constructed. Saudi Arabia has developed and proposed an offshore wind installed capacity of 2,000 MW, which is enough to power approximately 1.6 million households [1, 2]. These projects are expected to significantly reduce carbon dioxide emissions helping Saudi Arabia to meet its renewable energy targets and reduce its reliance on fossil fuels [3]. Project implementation faces several challenges in various sectors, such as technical, engineering, financing, environmental, regulatory and policy frameworks, local expertise, and workforce issues [4]. The proposed project aims to contribute to the establishment of renewable energy's optimized management and to discover and integrate feasible methods into the smart electric grid. The need to formulate advanced methods for studying hybrid systems, such as simulation software [5], physical emulators of Renewable Energy Sources (RESs) [6], prototype demonstration [7], is becoming imperative and requires international working environments to be covered. Thus, the generation of innovative multi-physics emulation systems for the study of wind - tidal energy RESs linked to the optimized conversion of RESs is beneficial in research work [8, 9]. This research tool, which controls tidal and wind RESs and their connection to the electrical network, will provide a better understanding of the energy characterization of a site [10] and will evaluate its capacity to integrate photovoltaic (PV) and storage energy systems.

II. PRINCIPLES OF DEVELOPING ELECTROMECHANICAL EMULATORS FOR WIND TURBINE

Let the elementary case [7, 11] be considered as a reference, in which, the mathematical model of the wind turbine is given by the equation of motion:

$$J\frac{d\Omega}{dt}=\Gamma_e(\Omega,v)-\Gamma_s(\Omega,c) \quad (1)$$

where Γ_e is the active torque of the wind turbine, Γ_s is the load torque, J the moment of inertia, and c is a variable in relation to which the load characteristic is parameterized. For constant values of the independent (input) variables v and c, the static operating point is obtained when:

$$\overline{\Gamma}_e=\overline{\Gamma}_s \quad (2)$$

$$\overline{\Gamma}_e=\overline{\Gamma}_e(\overline{\Omega},\overline{v}) \text{ and } \overline{\Gamma}_s=\overline{\Gamma}_s(\overline{\Omega},\overline{v}) \quad (3)$$

The dynamic properties of the turbine, at small variations of the state and input variables ΔΩ, Δv, and Δc around the considered static point, are described by the model portrayed in Figure 1, where:

$$T=\frac{J}{\delta}\ ;\ K_v=\frac{1}{\delta}\frac{\partial\overline{\Gamma_e}}{\partial v}\ ;\ K_s=\frac{1}{\delta}\frac{\partial\overline{\Gamma_s}}{\partial c} \quad (4)$$
$$\delta=\frac{\partial\overline{\Gamma_s}}{\partial\Omega}-\frac{\partial\overline{\Gamma_e}}{\partial\Omega}$$

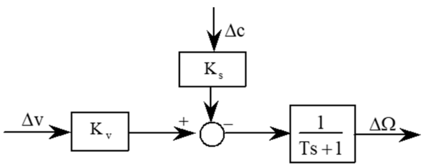

Fig. 1. Wind turbine model linearized around a static point.

The emulator consists of the following subsystems (Figure 2): a servomotor D coupled mechanically with an electric generator G that produces the load torque $\Gamma_s(t)$, the soft emulator, which calculates, based on the motion equation (1), the command value of the servomotor C_s, and a transducer mounted on the servo motor shaft, whose signal is transmitted to the soft emulator [10].

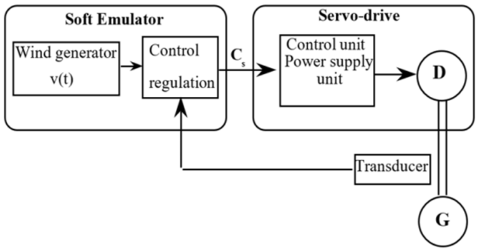

Fig. 2. The structure of a wind turbine emulator.

The control of the servomotor can be executed in two ways [11], either in speed or in torque. In the first case, the servo motor receives a command C_s at the input which, in stationary mode, is proportional to the speed Ω, and the transducer mounted on the shaft transmits a torque signal. In the second case, the command C_s is proportional to the torque and the transducer transmits a speed signal.

A. Linearized Model of the Speed-Controlled Emulator

It will be assumed that the link $C_s(t)\rightarrow\Omega(t)$ has a dynamic described by the transfer function $H_0^{\Omega}(s)$. It is considered that the link $\Omega(t)\rightarrow\Gamma_s(t)$ is without dynamics and ($\Gamma_s(t)$ is the load torque in (1) [10]. In the linearized model, the link $\Delta C_s\rightarrow\Delta\Gamma_s$ is given by the transfer function $H_1(s)$:

$$H_1(s)=K_{\Omega}^{s}\cdot H_0^{\Omega}(s) \quad (5)$$

where:

$$\Delta\Omega=H_0^{\Omega}(s)\cdot\Delta C_s \text{ and } K_{\Omega}^{s}=\frac{\partial\overline{\Gamma_s}}{\partial\Omega} \quad (6)$$

The block diagram is depicted in Figure 3, in which: $K_{\Omega}^{e}=\frac{\partial\overline{\Gamma_e}}{\partial\Omega}$.

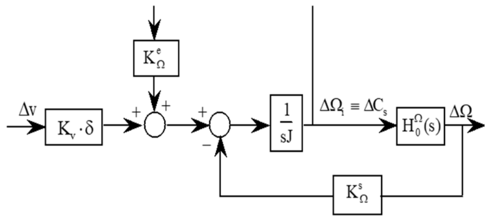

Fig. 3. Linearized model of the speed-controlled emulator.

Let it be the case when $H_0^{\Omega}(s)=1$, i.e. the servo motor has ideal dynamics. In this case, the diagram in Figure 5. leads to the following transfer function:

$$H(s)=\frac{\Delta\Omega(s)}{\Delta V(s)}=K_v\cdot\delta\frac{1}{Js+(K_{\Omega}^{s}-K_{\Omega}^{e})}=\frac{K_v}{Ts+1} \quad (7)$$

Then the mathematical model of the wind turbine, from Figure 1, is reproduced by the emulator without errors. In the case when $H_0^{\Omega}(s)\neq 1$, the diagram in Figure 5 demonstrates that the connection $\Delta v\rightarrow\Delta\Omega$, obtained through the emulator, differs from the mathematical model adopted for wind power.

The errors that appear are due to the non-ideal dynamic behavior of the servomotor (presuming that the errors in the computer emulator are zero).

$$H_0^\Omega(s) = \frac{1}{T_0^\Omega s + 1} \tag{8}$$

which results to:

$$H_1(s) = \frac{\Delta\Omega(s)}{\Delta V(s)} = \frac{K_v}{TT_0^\Omega s^2 + (T - \frac{K_\Omega^e}{\delta} T_0^\Omega)s + 1} \tag{9}$$

Since K_Ω^e <0 (in the working region of the mechanical characteristic of the wind turbine), the time constant T of the turbine is of the order of seconds (0.5 ... 1.5 s) and $T_0^\Omega << T$, the transfer function (9) can be put in the form:

$$H_1(s) = \frac{K_v}{(T's+1)(T_0's+1)} \tag{10}$$

where $T' \cong T$ and $T_0' << T'$.

The dynamic error of the emulator, introduced by the non-ideal behavior of the servomotor, is:

$$\begin{aligned} \varepsilon_\Omega(s) &= [H(s) - H_1(s)]\Delta V(s) \cong \frac{K_v}{Ts+1}\left(1 - \frac{1}{T's+1}\right)\Delta V(s) \\ \varepsilon_\Omega(s) &\cong \frac{K_v T's}{(Ts+1)(T's+1)}\Delta V(s) \end{aligned} \tag{11}$$

A similar result is acquired when, in the diagram in Figure 4 (and therefore also in Figure 5.), the measured angular velocity Ω is transmitted to the block Γ(Ω,v) rather than the angular velocity Ω^i calculated in the software emulator. In this case, the block diagram of Figure 4 is obtained:

$$H_1(s) = \frac{K_v}{TT_0^\Omega s^2 + Ts + 1} \tag{12}$$

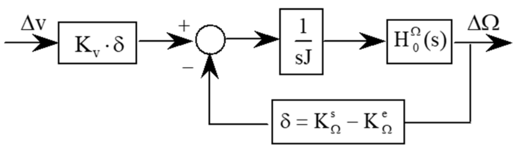

Fig. 4. Simplified linearized model of the speed-controlled emulator.

If $T_0^\Omega << T$ is considered, the transfer function $H_1(s)$ becomes:

$$H_1(s) \cong \frac{K_v}{(Ts+1)(T_0^\Omega s+1)} \tag{13}$$

The error $\varepsilon_\Omega(s)$ has the form:

$$\varepsilon_\Omega(s) \cong \frac{K_v T_0^\Omega s}{(Ts+1)(T_0^\Omega s+1)}\Delta V(s) \tag{14}$$

From the observations made, it can be implied that that the dynamic error of the servo motor T_0^Ω is smaller than the main time constant T of the servo motor. For the linearized model of the torque-controlled emulator, the procedure is the same and the results can be observed in [11]. Consequently, two essential conclusions may act as a basis for the emulator to be developed:

1. It is useful for the electromechanical process to be in a closed circuit since the dynamics of the regulation loop are faster than in the case of the open circuit control of the process.
2. Tuning the adjustment loops, to obtain dynamic behaviors corresponding to the smallest possible time constants T_0^Ω, represents an essential means for increasing the accuracy of the reproduction of wind turbine dynamic properties by the emulator.

III. REFERENCE STRUCTURES FOR THE SIMULATION OF WIND TURBINES

Based on the results acquired above, the simplest structures for wind turbine emulators, known as reference structures, will be presented. The following hypotheses were accepted:

- The electromechanical subsystem is based on a servomotor M.
- The computer emulator uses the motion equation (1) according to which one variable is generated inside the emulator (wind speed v(t)) and another variable is provided by the electromechanical subsystem.

The reference scheme of the emulator for speed control of the servo motor is given in Figure 5.

An Electric Generator (GE in Figure 5) is driven by the emulator shaft. The servo motor is controlled in a closed loop. The computer emulator receives the signal from the torque transducer Tr_Γ (the term Γ_s in (1)) and provides the reference Ω^{ref} for the speed loop.

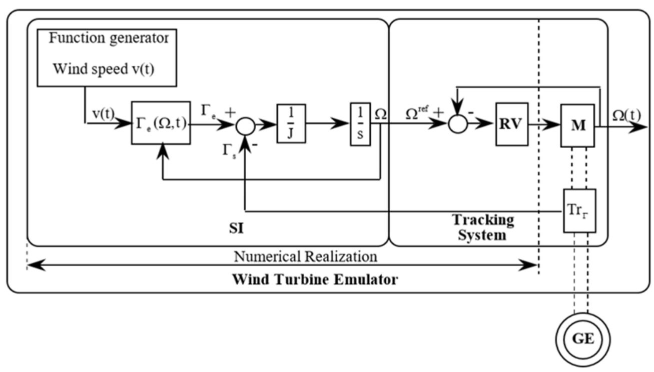

Fig. 5. Wind turbine emulator, speed control variant.

The reference scheme of the emulator for torque control of the servo motor is illustrated in Figure 6. In this case, the computer emulator receives a signal from a torque transducer (not included in Figure 6) and provides the reference for a torque loop Γ_{ef}^{ref}.

Figures 5 and 6 are complementary: in the first case, the informatic sub-system emulator SI receives a signal proportional to the torque and elaborates the speed reference; in the second case, the SI receives a signal proportional to the speed and elaborates the torque reference.

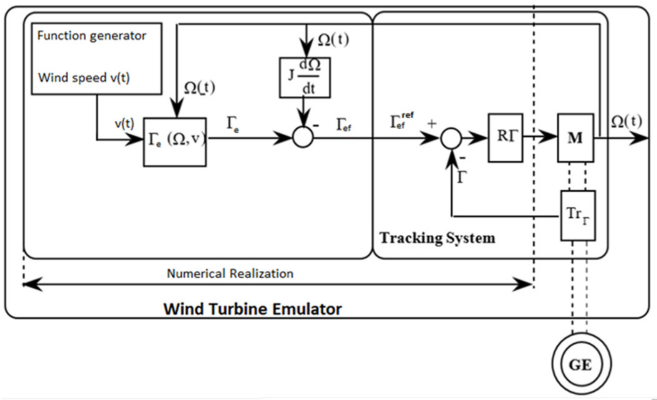

Fig. 6. Wind turbine emulator, torque control variant.

A. *Wind Speed-Controlled Emulator*

The electromechanical subsystem is based on servo systems, whereas the informatics subsystem is composed by units implementing models and controlling programs for the investigated physical system.

Figure 7 manifests the first variants of the experimental emulator of a wind turbine generator system [13]. It mainly consists of a permanent magnet synchronous generator and a servomotor. The wind turbine is simulated by the servomotor. The servomotor should reproduce the static characteristic of the wind turbine on its shaft by deploying an electromagnetic powder brake with fast dynamics, which provides adjustable torque on the common axis of the emulator. The latter is controlled by an informatics subsystem on which the static characteristics of the wind turbine are implemented after modeling off-line. This subsystem sends the servomotor the reference values of the turbine speed for a given wind speed.

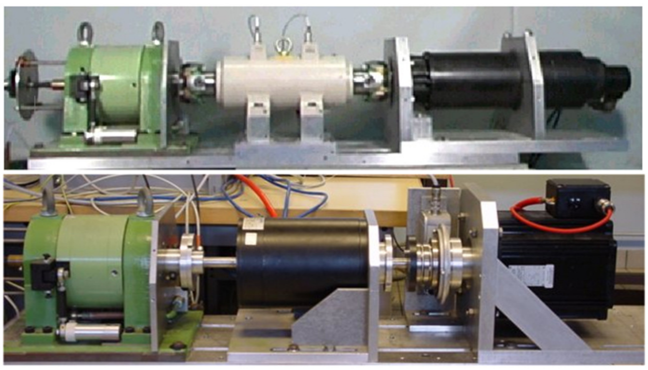

Fig. 7. The wind turbine experimental emulators.

IV. WORK FEEDBACK ON HARDWARE IN THE LOOP EMULATION OF HORIZONTAL AXIS WIND-TIDAL SYSTEMS

This section presents a methodology based on Hardware In the Loop Simulation (HILS) for wind-tidal energy system emulation. Utilizing the HILS concept, the platforms developed are generally structured in two sub-systems: an electromechanical subsystem that emulates the shaft behavior of wind or tidal horizontal axis turbines, associated to a control and a supervision subsystem, called informatics subsystem.

In Figure 8, the last experimental realization is presented. The latter, thanks to its versatility and flexibility, allows emulations either of a wind turbine or of a tidal turbine whose characteristics are modeled and implemented in the calculation and control units of the system [14].

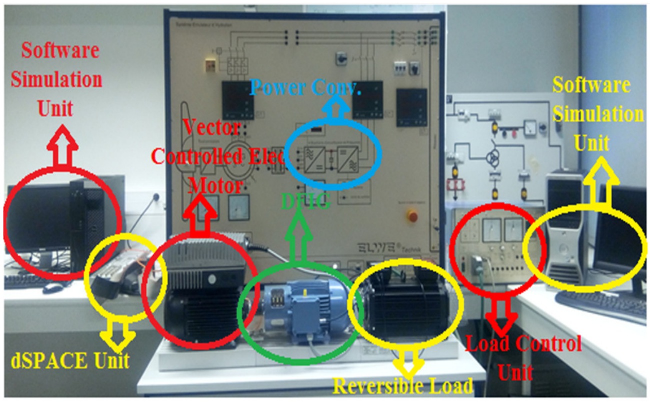

Fig. 8. The wind/tidal turbine generic emulator.

A. *Concept of the Electromechanical Wind-Tidal Hybrid Emulator*

The similarities on the energy conversion principles between horizontal axis wind and tidal (marine current) turbines enable the modeling study for a HILS "generic," flexible, and versatile conversion system. The functional concepts of horizontal tidal turbine are close to those of a wind turbine. Therefore, a fast development could be expected for the tidal power generation system, depending on the already established technologies of the wind power systems [14]. Both wind and tidal horizontal turbines operate based on the same double energy conversion principle: the kinetic energy of a fluid is converted into mechanical energy and then this energy is transformed into electrical energy. Given that a horizontal axis turbine is considered, the tidal conversion chain is reminiscent of that of the wind energy conversion chain, with the resources obviously being different (wind and marine current). Due to the intermittent of the natural resources, these resources can be modeled as stochastic inputs with different statistical properties whose energetic complementarity should be studied theoretically. The evaluation of the static characteristics is attained with Rankine - Froude theory contemplating incompressible fluids that allow the simplification of the source models implemented in real time emulators. Based on this approach, a simulation software was developed. The particular software makes it possible for this study to obtain the power-shaft speed static characteristics of a hybrid system consisting of a wind turbine of 3 kW for a rated wind speed of v = 13 m/s, and a tidal turbine of 3.5 kW, for a rated marine current of 4 m/s. In Figure 9, the principle of wind and tidal turbines coupled on the same shaft of a common electrical generator can be noticed.

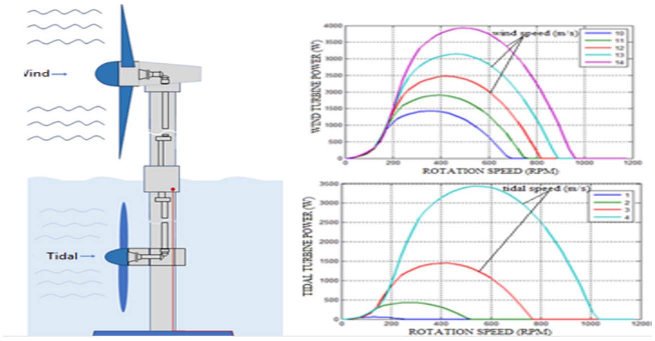

Fig. 9. Similar characteristics of wind and tidal turbines.

B. Electro-Mechanical Coupling Experimental Results

Simultaneous coupling of wind and tidal turbine requires the presence of a precise and fast-tracking control system, to regulate the rotation speed of each turbine according to wind and tidal speeds. If the wind speed at a certain moment is just enough to let the wind turbine function at a speed very close to the generation speed and the rotation speed of the tidal turbine is lower than the generation speed, then it would be better to decouple the tidal turbine, because it will act as a mechanical load and will slow down the rotation speed of the wind turbine and vice versa. This scenario can be also approached through exchanging the roles of the wind and the tidal turbines. The proposed electro-mechanical coupling was experimentally emulated on the hardware simulator. The wind turbine was emulated by the vector-controlled servomotor, whereas the tidal turbine was emulated by the permanent magnet synchronous motor. These two turbines are coupled on the same shaft with the Doubly Fed Induction Generator (DFIG), as mentioned above. Stochastic profiles of wind and tidal currents were used. When the measured rotation speed and reference speed (Figure 10.) are more than 1500 rpm, the electrical machine functions in generator mode and produces electrical power as displayed in Figure 11. When the reference speed is lower than the generation speed, the rotation speed of the DFIG is imposed by the electrical grid and the electrical drive operates as an electrical motor.

Figure 11 illustrates the electrical power generated by each turbine. There are some intervals when the wind turbine produces electrical power and some others when the tidal turbine also generates electrical power. When the reference rotational speed is greater than the synchronism speed, the electric machine operates in generator mode [14, 15]. When the energy provided to the grid by each turbine is insufficient, the electrical machine will function in motor mode. In this case, the electrical machine is decoupled from the network to avoid motor mode, or some energy storage unit must be added to overcome these production declines.

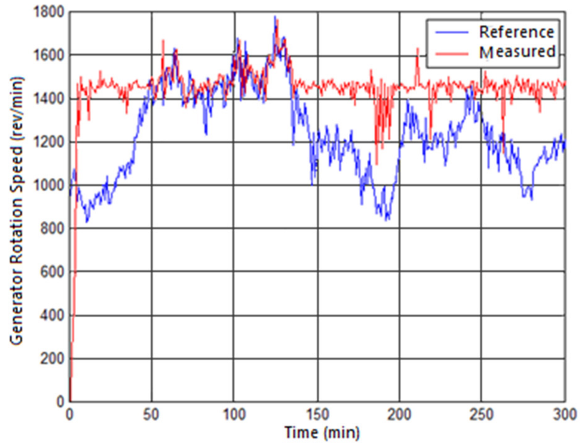

Fig. 10. Reference and measured rotation speed of the DFIG.

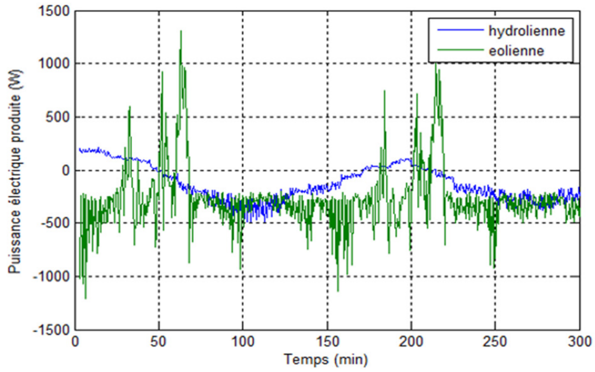

Fig. 11. Electrical power supplied to the network by wind and tidal turbines.

V. CONCLUSIONS

The objective of this paper is to present a methodology and its experimental validation, for developing a multi-hardware emulation architecture that could be used to study wind, tidal and wind-tidal hybrid system turbines.

An experimental simulation of a wind-turbine hybrid system was carried out, based on an electromechanical coupling on the same shaft with a single generator. Hence, the DFIG is utilized as an electric generator of the hybrid system. Stochastic profiles of wind and ocean currents are selected so that their energy potentials are considered complementary.

It is concluded that, in order to generate electrical power both resources must be at a sufficient level, i.e. the shaft speed of one of them must be high enough to lead the other one and keep the system functioning in generation mode. Otherwise, the system consumes electrical energy rather than generating it. In addition, when one of the resources is lower, it would be better to disconnect it or replace this shortage by deploying energy storage units. On the other hand, if one of the resources overrides the nominal speed up to the cut-off speed, then, it is advised to keep the two turbines coupled, and thus slow down the rotation speed and force the slow rotating turbine to act as a mechanical load or breaks.

The necessity for an energy storage system to be manufactured is highlighted in order to ensure power generation, when one of the main energy sources is declining or suddenly cut off.

ACKNOWLEDGEMENT

The authors gratefully acknowledge the approval and the support of this research study by the grant no. ENGA-2023-12-2002 from the deanship of scientific research at Northern Border University, Arar, K.S.A.

REFERENCES

[1] I. Tlili, "Renewable energy in Saudi Arabia: current status and future potentials," *Environment, Development and Sustainability*, vol. 17, no. 4, pp. 859–886, Aug. 2015, https://doi.org/10.1007/s10668-014-9579-9.

[2] A. Lachheb, R. Marouani, C. Mahamat, S. Skouri, and S. Bouadila, "Fostering Sustainability through the Integration of Renewable Energy in an Agricultural Hydroponic Greenhouse," *Engineering, Technology & Applied Science Research*, vol. 14, no. 2, pp. 13398–13407, Apr. 2024, https://doi.org/10.48084/etasr.6939.

[3] Y. H. A. Amran, Y. H. M. Amran, R. Alyousef, and H. Alabduljabbar, "Renewable and sustainable energy production in Saudi Arabia according to Saudi Vision 2030; Current status and future prospects," *Journal of Cleaner Production*, vol. 247, Feb. 2020, Art. no. 119602, https://doi.org/10.1016/j.jclepro.2019.119602.

[4] A. I. Almulhim, "Understanding public awareness and attitudes toward renewable energy resources in Saudi Arabia," *Renewable Energy*, vol. 192, pp. 572–582, Jun. 2022, https://doi.org/10.1016/j.renene.2022.04.122.

[5] M. Alanazi, A. Alanazi, A. Almadhor, and H. T. Rauf, "An Improved Fick's Law Algorithm Based on Dynamic Lens-Imaging Learning Strategy for Planning a Hybrid Wind/Battery Energy System in Distribution Network," *Mathematics*, vol. 11, no. 5, Jan. 2023, Art. no. 1270, https://doi.org/10.3390/math11051270.

[6] S. Rajendran, M. Diaz, V. S. K. Devi, D. Jena, J. C. Travieso, and J. Rodriguez, "Wind Turbine Emulators—A Review," *Processes*, vol. 11, no. 3, Mar. 2023, Art. no. 747, https://doi.org/10.3390/pr11030747.

[7] G. Caraiman, C. Nichita, V. Mînzu, B. Dakyo, and C.-H. Jo, "Simulation Platform for Real Time Ocean Current Energy Emulator," *International Journal of Ocean System Engineering 2(1) (2012)*, vol. 2, Jan. 2012, Art. no. 2012.

[8] A. Ali, Z. Liu, A. Ali, G. Abbas, E. Touti, and W. Nureldeen, "Dynamic Multi-Objective Optimization of Grid-Connected Distributed Resources Along With Battery Energy Storage Management via Improved Bidirectional Coevolutionary Algorithm," *IEEE Access*, vol. 12, pp. 58972–58992, 2024, https://doi.org/10.1109/ACCESS.2024.3392911.

[9] A. Hafeez *et al.*, "Optimal site and size of FACTS devices with the integration of uncertain wind generation on a solution of stochastic multi-objective optimal power flow problem," *Frontiers in Energy Research*, vol. 11, Nov. 2023, https://doi.org/10.3389/fenrg.2023.1293870.

[10] A. Al Ameri, A. Ounissa, C. Nichita, and A. Djamal, "Power Loss Analysis for Wind Power Grid Integration Based on Weibull Distribution," *Energies*, vol. 10, no. 4, Apr. 2017, Art. no. 463, https://doi.org/10.3390/en10040463.

[11] C. Nichita, A. D. Diop, J. J. Belhache, B. Dakyo, and L. Protin, "Control Structures Analysis for a Real Time Wind System Simulator," *Wind Engineering*, vol. 22, no. 6, pp. 275–286, 1998.

[12] A. D. Diop, C. Nichita, J. J. Belhache, B. Dakyo, and E. Ceanga, "Error Evaluation for Models of Real Time Wind Turbine Simulators," *Wind Engineering*, vol. 24, no. 3, pp. 203–221, May 2000, https://doi.org/10.1260/0309524001495567.

[13] J. Tekobon, "Système multi physique de simulation pour l'étude de la production de l'énergie basée sur le couplage éolien offshore-hydrolien," Ph.D. dissertation, Université du Havre, Le Havre, France, 2016.

[14] M. O. Ashglaf, "Development of Hybridization concept for horizontal axis wind / tidal systems using functional similarities and advanced real-time emulation methods," phdthesis, Normandie Université, 2019.

[15] M. Masmali, M. I. Elimy, M. Fterich, E. Touti, and G. Abbas, "Comparative Studies on Load Frequency Control with Different Governors connected to Mini Hydro Power Plant via PSCAD Software," *Engineering, Technology & Applied Science Research*, vol. 14, no. 1, pp. 12975–12983, Feb. 2024, https://doi.org/10.48084/etasr.6722.