SVU-International Journal of Engineering Sciences and Applications (2023) 4(2): 269-278
Print ISSN 2785-9967| Online ISSN 2735-4571
DOI 10.21608/svusrc.2023.215683.1132

A Review of Intelligent Control Systems for Grid Tie Doubly Fed Induction Generator Based Wind Farm

I. Hamdan[1,], Marwa M. M. Youssef [1], Omar Noureldeen[1,2]

Abstract: This a review research focuses on various methods used in intelligent control systems for grid tie doubly fed induction generator (DFIG) Wind Farm. This paper reviews a controller using fuzzy coordinated PI suggested for improving the dynamic performance of supercapacitor (SC) coupled to DFIG through a buck-boost converter (DC-DC converter) during disturbances in large scale wind farm. Also, this research reviews a pitch angle control employed to regulate the angle of the wind turbine (WT) blade during different wind speeds to control power and operate WT safely. Implementation of artificial intelligent control (fuzzy approach) on pitch angle replaces the traditional control to enhance the system performance, fuzzy approach is used to auto tuning the conventional control parameters under various working conditions. Then, this paper reviews a developed control technique using an interval type-2 fuzzy logic control (FLC) tuned PI for optimum torque adjustment for WTs operated by DFIG. The suggested control regulates the error of the mechanical rotor speed and generates the optimum torque that achieves the maximum output power. On basis of the results obtained from the literature available, the integration of a SC to the dc-link of three-phase four-wire active power filter (APF) is introduced by using interfaced three level bidirectional buck-boost converter controlled by a fuzzy control approach.

Keywords: Intelligent Control Systems; Wind Energy; Power Electronic; Doubly-Fed Induction Generators; Maximum Power Tracking.

1 Introduction

One of the most rapidly expanding renewable energy sources is the wind energy. The electricity generation market is very interested in wind resources due to their inherent benefit of low marginal costs. Over the previous two decades, the installed capacity of wind power both offshore and onshore has expanded by a factor of roughly 75. The wind speed does, however, have a built-in variability that is related to mesoscale wind circulations as well as regional characteristics like topographic parameters like height, aspect, slope, surface quality, and temperature difference near water bodies. As a result, wind power exhibits a great deal of spatial and temporal variability [1].

Since the strategies are adaptable enough to keep up with developments and events, the renewable energy strategy has been modified to target 20% of the total energy produced in 2022 in light of the developments, events, and political developments that Egypt has seen over the past few years and their impact on the implementation of renewable energy projects in particular [2]. Then, the energy production sources in 2022 is illustrated in **Fig. 1.**

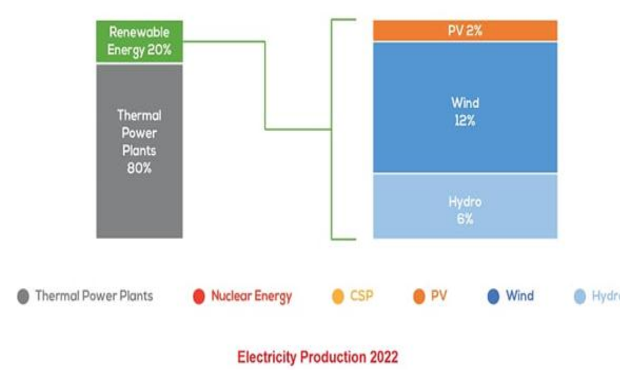

Fig. 1 Energy production sources in 2022 [2]

The wind energy conversion system must be able to harness as much energy from the wind as they can when it is present in order to be a reliable alternative energy source. Because of their unique aerodynamic profile, each wind turbine (WT) has an own power characteristic. According to the power characteristic, there must be a certain efficient turbine rotational speed for each type of wind that optimizes power absorption. There are numerous

Received: 5 June 2023/ Accepted: 11 July 2023
Corresponding Author:
I. Hamdan, IbrahimHamdan86@eng.svu.edu.eg
Other Authors:
Marwa M. M. Youssef, marwa.safi@eng.svu.edu.eg
Omar Noureldeen, omar_noureldeen@svu.edu.eg
1. Department of Electrical Engineering, Faculty of Engineering South Valley University, Qena 83523, Egypt
2. Department of Electrical Engineering, Faculty of Engineering, Al Baha University, Al Aqiq 65779-7738, Saudi Arabia

research studies that have presented different maximum power point tracking (MPPT) algorithms [3].

Because of the rising use of wind energy, its low voltage ride through (LVRT) capabilities is more important than ever. Nowadays, experimental voltage sags of various magnitudes and lengths are used to test the LVRT capability of wind machines [4]. Additionally, according to grid codes, WTs must remain connected to the grid throughout a fault for the duration of the LVRT curve, which changes from each country. Grid codes promote the protection of WTs against grid faults and disruptions; hence numerous techniques have been developed and improved to meet LVRT standards. Energy storage systems (ESS) are favored to be utilized as a protection approach to retain energy during fault situation in an effort to store energy loss rather than having it disperse. Pumped water and compressed air are the most often utilized ESSs for power grids because of their inexpensive capital costs, although they are inefficient and sluggish to react. Batteries and supercapacitors (SCs) are an effective way to increase response and efficiency [5]. Because SC has a longer lifespan than batteries, a wider temperature range, a wider voltage range, higher efficiency, and a larger power density than batteries, it is more useful in applications requiring high power ratings.

Different designs and control techniques have been researched from distinct viewpoints to improve the co-operation efficiency of wind with ESS. Using intelligent control techniques rather than traditional control are the main focus of this thesis. The performance of wind energy systems, control techniques, and fault detection systems may be significantly impacted by the uncertainties that are present during process operation if they are not taken into account during design. Due of this, scholars have given the issue of uncertainty quantification increasing interest over the past few decades. Due to their utility in representing a variety of processes as universal approximators, researchers have concentrated on building prediction intervals relying on the use of fuzzy systems and neural networks [6].

One of the difficulties that faces the wind energy electric systems is the nonlinear and unbalanced loads that damage the electrical system and other connected devices by drawing not only active current but also harmonic and reactive current from the AC network. Reactive power compensation and harmonic suppression have since drawn interest and undergone extensive research. Active power filters (APFs) are now one of the best instruments for reducing harmonics, and with the right control, they can also reduce reactive power usage.

2 Wind Energy Conversion Systems

Induction generators (IGs), permanent magnet synchronous generators (PMSG), and wound rotor synchronous generators are the three main types of commercially accessible WT generators today. The IGs are appropriate for operating WTs since wind speed is an uncontrollable natural property. The two most common types of WTs utilized today are variable-speed WTs (VSWT) with doubly fed IGs (DFIG) and fixed-speed WTs (FSWT) with squirrel cage IGs. The DFIG for VSWT concept offers the capability for regulating both reactive and active power, which is a big benefit when it comes to grid integration. The capabilities of DFIG WTs to provide power at a fixed voltage and frequency during fluctuations in the rotor speed are its key advantage. While the rotor windings are coupled via a partial size back-to-back converter, the stator windings are linked directly to the electrical network. The back-to-back converter is composed of a grid-side converter (GSC) and a rotor-side converter (RSC) with a DC-link capacitor. The electric configuration of the DFIG is illustrated in **Fig. 2.**

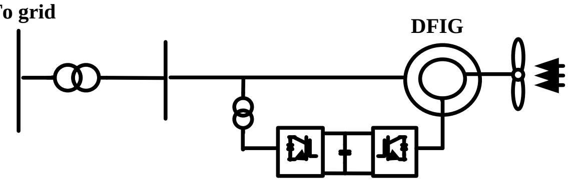

Fig. 2 DFIG electric configuration

The relationship between wind speed (V_w) and the power the turbine recovers from the kinetic energy of the wind (P_m) is shown in the following equation [7]:

$$P_m = 0.5\rho\pi R^2 V_w^3 C_p \tag{1}$$

where R is the WT blade's length and C_p is the power coefficient represented by the tip speed ratio λ, which is determined by:

$$\lambda = \frac{R\Omega_t}{V_W} \tag{2}$$

where Ω_t is the angular rotational speed of turbine. Theoretically, C_p can have a maximum value of 0.593. The recovered power is divided by the turbine's rotational speed to calculate the rotor torque [7]:

$$T_t = \frac{P_m}{\Omega_t} = \frac{\rho\pi R^3 V_W^2}{2\lambda} C_p \tag{3}$$

The drive train can be described by a two-mass model with soft connection between the two inertia portions, which are represented by the damping and stiffness coefficients (D_{tm} and K_{tm}). J_t is the masses inertia on the turbine side whereas J_m is the masses inertia on the generator side. An expression for the dynamic equations is as follows:

$$J_t \frac{d\Omega_{t\_ar}}{dt} = T_{t\_ar} - D_t \Omega_{t\_ar} - T_{em} \tag{4}$$

$$J_m \frac{d\Omega_m}{dt} = T_{em} - D_m \Omega_m + T_{em} \quad (5)$$

$$\frac{dT_{em}}{dt} = K_{tm}(\Omega_{t\_ar} - \Omega_m) + D_{tm}\left(\frac{d\Omega_{t\_ar}}{dt} - \frac{d\Omega_m}{dt}\right) \quad (6)$$

where the variables T_{t_ar}, Ω_{t_ar} in the fast shaft represent the turbine driving torque and rotational speed, respectively. The friction coefficients D_t and D_m for the WT and machine are specified. The generator's driving torque is T_{em}.

To create the DFIG mathematical dynamic model, voltage and flux equations are reformed in direct and quadrature (*d*-*q*) rotating frames as follows.

$$V_{sd} = R_s i_{sd} + \frac{d\varphi_{sd}}{dt} - \omega_s \varphi_{sq} \quad (7)$$

$$V_{sq} = R_s i_{sq} + \frac{d\varphi_{sq}}{dt} + \omega_s \varphi_{sd} \quad (8)$$

$$V_{rd} = R_r i_{rd} + \frac{d\varphi_{rd}}{dt} - \omega_r \varphi_{rq} \quad (9)$$

$$V_{rq} = R_r i_{rq} + \frac{d\varphi_{rq}}{dt} + \omega_r \varphi_{rd} \quad (10)$$

$$\varphi_{sd} = L_s i_{sd} + L_m i_{rd} \quad (11)$$

$$\varphi_{sq} = L_s i_{sq} + L_m i_{rq} \quad (12)$$

$$\varphi_{rd} = L_r i_{rd} + L_m i_{sd} \quad (13)$$

$$\varphi_{rq} = L_r i_{rq} + L_m i_{sq} \quad (14)$$

where magnetic fluxes, current, voltage, and inductance are represented by φ, I, V, and L. The mutual inductance is represented by L_m, whereas the subscripts *r* and *s* refer to the rotor and stator, respectively. The stator and rotor windings' respective voltage angular frequencies are denoted by the letters *s* and *r*, respectively.

3 Intelligent Control Techniques

The reality is that there are control problems nowadays that cannot be articulated and studied using "normal (or traditional) control" approaches that were created in previous decades to regulate dynamical system. In recent years, several techniques have been created that are collectively known as "intelligent control" strategies in order to solve these complicated difficulties in a methodical manner. A category of intelligent control techniques makes use of artificial intelligence numerical methods such as neural networks, reinforcement learning, fuzzy logic, machine learning, Bayesian probability, genetic algorithms, and evolutionary computation. Intelligent control is a computationally effective method of guiding a complicated system toward a given objective while operating under imperfect instructions, with insufficient representation, and in an uncertain environment. Planning and online error correction are generally combined in intelligent control, which also calls for learning about the system and its surroundings. The most significant point is that intelligent control typically uses generalization, focused attention, and combinatorial search as their major operator, which results in multiscale design.

Adaptive fuzzy control (AFC) approach is one of the most popular intelligent control methods used for wind energy application. The adaptive law of the AFC approach was created to reduce the tracking error to zero without taking the modelling error into account. A function that converts items in a domain of interest to the set's membership value defines a fuzzy set (FS). An alternate method of approaching a control or classification problem is offered by fuzzy logic. Fuzzy logic control (FLC) is essentially a multivalve logic that enables the definition of intermediate values between traditional evaluations like one/zero, true/false, etc. AFC scope of use is so broad that it may be used to manage any kind of task, including managing the tools and appliances we use every day. It eliminates the need for numerous computations and processes, and because the results are so precise, they can be used right away to complete a task. Engineers and researchers are very interested in fuzzy logic due to its effectiveness in a variety of applications. Fuzzy logic offers a more effective and creative approach to handling control systems. The theory of sets is among the most significant mathematical techniques. A group of items is fundamental to both everyday life and mathematics. Set theory is viewed as a tool for thinking. Sets are clarified groups of objects or groups of similar objects. Two sorts of sets can be distinguished by set theories: crisp set and FS. A characteristic function µA(x) that equals zero or one defines a classic or crisp set. A FS theory is a popular theory that defines FSs. According to this idea, a FS is a class of objects with a continuum of membership grades. In contrast to a sudden change, the shift from membership to non-membership in a subset of the reference set is gradual [8].

The FSs, in which the uncertainty is addressed by defining it with numbers, typically in range (0,1), can be used to handle some of this uncertainty. Additionally, they are highly helpful in absorbing uncertainties when membership functions for a FS can be precisely specified by a single numerical value. However, in more complicated circumstances, it can be very challenging to determine the exact numerical value of an entity's membership or to provide a specific membership value for any ambiguous entity. Since the knowledge needed to create the rules for fuzzy systems is unpredictable, creating the rules is itself a challenging undertaking. As a result, membership functions may also experience uncertainty due to improperly formed fuzzy rules. Therefore, it is safe to say that, despite type-1 fuzzy logic's utility in some applications, there are many issues for which type-1 is insufficient to attain the appropriate level of accuracy or reliability. The necessity for various tools and methodologies that can represent larger levels of uncertainty results from this. A significant level of modelling inaccuracy can be provided by type-2 fuzzy logic, which is an expanded form or generalization of type-1 fuzzy logic. Type-2 fuzzy logic may therefore address linguistic-related uncertainties by accounting for the unreliability and ambiguity of data [9].

4 Literature Survey

There have been numerous studies that have developed and used the ESS with wind energy applications. In [10], A multiple stage hybrid ESS wind farm dispatching approach that is market-oriented is suggested. The first stage ESS is intended to increase the profitability of wind generation through day-ahead market operations, the second stage ESS, which is based on real-time market activity, is targeted at reducing day-ahead forecasting errors and minimizing wind power fluctuation, and the backup stage ESS is connected to them to offer ancillary services. In [11], A direct control technique is suggested to track the variance of the wind power plan in order to enhance the overall economy of the wind-energy storage power station. The control technique in this work may alter the charge and discharge power of energy storage in real-time according to the deviation of wind power and the state of charge, in contrast to the conventional strategy for mitigating wind power fluctuation. The research in [12] suggests a coordinated operation method for microgrids between a wind generator and a hybrid energy storage (HES) system. Additionally, efforts have been made to increase the capacity of the SC and provide high-quality communication infrastructures with little delay in order to enhance the microgrid's inertia reaction. The cost of the installed SC and the quality of the communication services are what this paper refers to as the operation cost. In [13], Magnetic ESS with a superconducting fault current limiter has been created. One superconducting coil is used to smooth out wind power output and improve LVRT capability of WTs. A wind farm in China's northwest has installed and started using this developed technique. The research in [14] examines the wind power's fluctuating feature. Output is examined in the frequency and temporal domains, and the fluctuation degree is extracted and displayed as index of quantization (QI), the wind is based on QI clustering. The worst-case scenario is the one with the biggest power fluctuation. In [15] the joint planning that takes into account the wind power installed capacity and location, the transmission network expansion, and the placing and sizing of ESS is taken into consideration in order to increase the wind power accommodation and load acceptance level. Additionally included are the charging-discharging strategy of energy storage devices and the generation-side operation process. In [16], authors took into account three operational scenarios, calculated the ESS sizes, and suggested the optimum one based on operational costs. While Scenario 3 is a freestanding microgrid supported by diesel generators, Scenarios 1 and 2 are grid-connected configurations. The ideal operation cost of the microgrids is used to create the optimization problem in each scenario. A novel converter system appropriate for driving high-power medium-voltage WTs is presented in [17]. It features a modular multilayer structure and decentralized energy storage integration. This converter has significant structural and control features that make it simple to integrate an ESS, enabling the WT to operate with great levels of flexibility. The study in [18] investigates the dynamic and transient performances of a battery ESS connected with the output of a wind system. This article [19] examines how utility grid operation can be improved by electric vehicles integration strategies. The suggested analysis takes into account the targeted energy storage devices put on utility grids supplied by renewable energy. In order to cost-effectively smooth wind power oscillations, the research in [20] suggests a hybrid ESS sizing and control method based on probabilistic forecasting. In a framework of scenario-based stochastic programming, a day-ahead scheduling model for IES with wind power and multiple types of energy storage is proposed in [21]. In [22], This study demonstrates how the wind farm layout determines not only the total amount of energy captured but also the degree of power fluctuation. This in turn influences the amount of battery ESS capacity that is necessary to reduce the natural power fluctuation of wind farms. Given that the capacity of battery ESS and the amount of gathered energy both directly affect the owner's profit. The studies in [23-29] presents other techniques of ESS integrated with wind energy.

The second topic discussed in this work is the pitch control methods techniques. In [30], The systemic design for a revolutionary tidal pitch system presented in this work is based on a hydraulic servo and a bevel-geared transmission. This system's triangular and compact structural features make it simple to install in a small turbine hub. In [31], The work's major objective is to put forth an intelligent WT system control method that does not require model identification. To achieve this, a unique model-independent nonsingular terminal sliding-mode control is created for non-linear WT pitch angle control. It combines the single input interval type-2 FLC with the fundamental ideas of the ultra-local model. In [32], to deal with the issues of high order nonlinearity, noise, and friction interference when tracking the pitch angles of WT hydraulic pitch systems, a unique finite-time command filtered back stepping control algorithm is suggested. In [33], VSWT systems operating in high-speed regions are approached with the use of artificial intelligence and intelligent control approaches. Utilizing an online data stream, the real-time information of effective wind speed is retrieved and predicted using support vector regression. In [34], a back-propagation (BP) neural network and PID neural network-based variable pitch controller is developed. The BP neural network with self-learning and weighting coefficient correction capabilities is utilized to change the PID parameters online and further to obtain the ideal combination of the PID parameters by real-time detecting the deviation of the rotor speeds. In the research [35] a reliable load mitigation method for individual WT blade pitch angle adjustment in the presence of blade pitch actuator faults is proposed. This method is referred to as "fault-tolerant individual pitch control". The proposed plan includes a system for defect detection and diagnosis as well as a collective pitch control enhanced by an individual pitch control. In [36], a robust adaptive dynamic programming (ADP) WT controller is suggested based on reinforcement learning and system state information. The ADP algorithm, which combines the Temporal-Difference algorithm and actor-critic structure, can ensure that the rotor speed is stable around the rated value, allowing for the real-time, online adjustment of the wind energy utilization coefficient by altering the pitch angle in high-wind areas. In [37], using neuro-estimators of the effective wind, this work proposes a unique pitch neuro-control architecture. A lookup table, a neuro-estimator, a virtual sensor, and PID controller make up the control system. The neuro-estimator is utilized to calculate the floating offshore WT's effective wind and predict its future value. In [38], a small pitch-controlled WT model with a 0.8 m rotor diameter was designed, built, and tested in the wind tunnel for the current investigation. A DC servomotor was employed as the actuator in a linkage mechanism to control the pitch angle; this proved to be effective and practical for small WTs, and it performed flawlessly. In [39], analysis is done on the performance of the S-wind-induced vertical axis WT's rotation with various fixed pitching angles and blade counts. In order to do this, both the starting stage and stable rotation stage of the turbine have been examined, and a numerical coupling model has been developed and validated to simulate the interaction between the wind flow and the induced turbine rotation. In [40], Based on dynamic experimental data, this study determines the ideal blade angle of attack in the upwind and downwind zones with the goal of maximizing the tangential force coefficient. The vertical axis WT's complicated flow field's influence on the amplitude and direction of induced velocity change. In [41], based on the WT's boundary analysis, a hybrid fast frequency response optimized power point tracking method and pitch angle control technique is suggested to extend the service life of the WT. The control approach can greatly lower the WT pitch angle's adjustment frequency and range. The suggested approach is tested in a micro-grid that combines modest thermal and wind production sources. In [42], for pitch angle management, a fractional order fuzzy-PID controller is suggested in order to maintain the rated output power of a 2 MW direct-drive wind energy system in dynamic wind conditions. In contrast to existing methods, the research in [43] suggests using a fuzzy based model-predictive controller for pitch angle control to limit power output and rotor speed to their rated values and minimize the loading effect on WTs. When the non-linearity of the system is encountered, the fuzzy logic controller functions extremely well, and the model predictive controller aids in making the system more reliable and effective. In [44], for WT generator power variations, a new electro-hydraulic servo pitch system is presented to improve pitch angle control capabilities. The basic components of the pitch system are a hydraulic motor, a variable-speed hydraulic pump, and a pitch gear set. In [45], An adaptive neuro-fuzzy inference system (ANFIS) type-2 structure with unsupervised clustering is handled by passive reinforcement learning solved by particle swarm optimization (PSO) policy for managing the pitch angle of a real WT. The rotor speed is kept at its rated value while the output power is smoothed using the suggested control technique, which is based on a gain-scheduled reinforcement learning recurrent ANFIS type 2 pitch angle controller. In [46], in order to maintain stable output power and generator speed in the presence of turbulent wind conditions, a unique L1 adaptive controller is created for wind energy conversion systems (WECS) blade pitch management. In [47], The purpose of this study is to develop and use a pitch angle control method at the blade's outer part using a distinct pitch control at the blade tip. This article in [48] suggests a reliable analysis of the pitch control system of large WTs with fractional order PID controller and communication time delay. Pitch angle control uses a fractional order PID controller. A real-time feedback blade pitch control system is created in [49] through an extensive aerodynamic analysis between the performance of vertical-axis WTs and the blade pitch. This system is based on the actual flow velocity around the blade. Other pitch angle control techniques are developed and presented in [50-56].

The third topic discussed in this work is the speed regulation and optimum torque estimation techniques used with WECS. There is a lot of published material in the areas of optimal torque production and speed control. For their simplicity, traditional controllers like PI, PD, and PID control were used in early investigations. But due to their restricted working range and high sensitivity to changes in system parameters, these common controllers are unreliable for nonlinear complex systems. There have been several nonlinear controllers presented, including sliding mode control methods, passivity-based controllers, linear averaged controllers, feedback linearizing controllers, and others. The major challenges for these techniques are the complexity of the system, the difficulty of making accurate claims, and the difficulty of drawing general conclusions about its behavior [57].

On the other hand, artificial intelligence techniques, including FLC, are now widely used to address the robust control of ambiguous, complex, and dynamic systems. A key benefit of these controllers is that they do not require any knowledge of the mathematical design model or familiarity with the system issues. A variety of dynamic uncertainties and non-linearity that appear in tracking mistakes are represented by the interval type-2 adaptive fuzzy approach, which is an enlarged version of type-1 fuzzy logic.

There are many studies on the subject of speed regulation to create reference torque, for example: The maximum power tracking approach is utilized to adapt an ideal rotor speed reference based on PI controller in [58]. The research in [59] evaluates the efficacy of two predictive control systems for controlling the speed of IGs; one of these controllers employs a finite control set-model strategy, and the other employs a continuous control set-model method in conjunction with space vector-pulse width modulation.

In [60], a speed controller for WT based on DFIG is suggested using the fuzzy approach with inputs of rotor speed and wind speed, and the PSO algorithm is used to fine-tune the controller settings. The study in [61] presents a trustworthy control method for the WT's optimal torque determination based on super-twisting technology (STW), which is preferred over the conventional sliding mode algorithm. The results are compared with PI controllers to determine the effectiveness of the proposed control on enhancing dynamic system performance.

According to [62], a robust, non-linear STW sliding mode controller with fractional order computation is suggested to control speed in order to generate reference torque. The outcomes of this control are compared with PI control. In [63], the authors offer a simple link weight modification neural network controller for speed adjustment that takes system parameter resilience into account. In [64], the fuzzy PI approach is used to control speed, and the scheme's outcomes are comparable to those of traditional PI control. In order to control PMSG, a brand-new direct-speed control (DSC) prediction approach utilizing the double-cost function with an altered duty ratio is described in [65].

A fuzzy PI solution for speed control is presented by the authors in [66] with a new switching function in a PMSG to produce reference q-axis current equivalent to the best torque. In [67], the rotor speed, which is calculated using a model reference adaptive system, is altered to change the optimum torque.

The use of APF topologies for harmonic suppression and reactive power compensation constitutes the fourth topic covered in this paper. Shunt APF, series APF, and hybrid APF are different types of the topologies for APF that have been presented in [68-73]. The voltage source inverter (VSI) with a dc-link attached to a large capacitor—which is exactly what the shunt APF is—is said to be a tried-and-true technique for lowering the current harmonics down to the recommended standards constraints [74]. A unique control for a three-phase half bridge interleaved buck shunt APF is discussed in study [75]. A fractional-order sliding mode methodology based on a double-hidden-layer recurrent neural network is suggested in [76] for a single-phase shunt APF.

A novel artificial neural-network control for APF employing the Genetic-Algorithm technique is suggested by the research in [77]. The PI control settings are modified for the DC-voltage regulation of the APF by using an optimization technique. The authors of [78] construct a universal APF using an adaptive filtering method based on the least mean mixed-norm to effectively remove reactive currents and harmonics. Recent works have concentrated on changing the way that APF is used. An improved modulated carrier control with on-time double that eliminates harmonic and reactive currents drawn by nonlinear low-frequency is presented for the single-phase shunt APF in [79].

It is suggested in [80] to use a novel deadbeat-based DPC technique to generate reference current and control APF. A single source of power delivered to a multilayer inverter with three transformers, where fewer transformers are required, is how the idea for a shunt APF is put forth in [81]. A new four-switch two-leg VSI design for a three-phase shunt APF is devised in [82] to reduce the total size and cost. According to [83], the current reference control method for shunt APF under unbalanced conditions makes use of both the symmetrical-component method and the Kalman filter to identify the source voltage's fundamental sequence component.

To increase the dependability of multicellular converters, the authors in [84] propose fault-tolerant control, which combines multicellular topology and two-level topology. According to the study in [85], a predictive power-control could be used to lessen APF DC-voltage fluctuations. A 3-level H-bridge APF with a direct connection to the distribution network is modified by the authors in [86]. Other recent works of literature explore strategies to improve APFs through the invention of novel controller designs or topologies [87–96].

5 Conclusion

In this work, the topic of power generation from wind-based renewable energy systems using intelligent control is introduced. Firstly, this research reviews the fuzzy coordinated PI controller to control ESS for large-scale wind farms and investigated the recommended control for applications of power fluctuation suppression and dynamic performance enhancement during faults. Then, a fuzzy adaptive PI control is designed and implemented in the pitch compensation control loop which is part of the pitch angle control system in DFIG and applied on a large-scale wind farm. Also, this research reviews a suggestion to use an interval type-2 FLC adaptive PI controller to manage rotor speed and produce reference optimal torque for power extraction. Then, a proposed methodology is presented that provides the integration of a three-phase, four-wire APF with an ESS made up of a SC and a three-level buck-boost converter with FLC.

References

[1] C. Wu, X.-P. Zhang, and M. Sterling, "Wind power generation variations and aggregations," CSEE Journal of Power and Energy Systems, vol. 8, pp. 17-38, 2021.

[2] "http://www.nrea.gov.eg/," ed.

[3] J. C. Hui, A. Bakhshai, and P. K. Jain, "An energy management scheme with power limit capability and an adaptive maximum power point tracking for small standalone PMSG wind energy systems," IEEE Transactions on Power Electronics, vol. 31, pp. 4861-4875, 2015.

[4] J. Ren, X. Xiao, Z. Zheng, Y. Wang, Z. Ma, and K. Liu, "Impact of Phase Angle Jump on DFIG Under LVRT Conditions: Challenges and Recommendations," IEEE Transactions on Power Delivery, vol. 36, pp. 3701-3713, 2020.

[5] Y.-W. Shen, D.-P. Ke, W. Qiao, Y.-Z. Sun, D. S. Kirschen, and C. Wei, "Transient reconfiguration and coordinated control for power converters to enhance the LVRT of a DFIG wind turbine with an energy storage device," IEEE Transactions on Energy conversion, vol. 30, pp. 1679-1690, 2015.

[6] O. Cartagena, S. Parra, D. Muñoz-Carpintero, L. G. Marín, and D. Sáez, "Review on fuzzy and neural prediction interval modelling for nonlinear dynamical systems," IEEE Access, vol. 9, pp. 23357-23384, 2021.

[7] G. Abad, J. Lopez, M. Rodriguez, L. Marroyo, and G. Iwanski, Doubly fed induction machine: modeling and control for wind energy generation vol. 85: John Wiley & Sons, 2011.

[8] M. Kumar, L. Misra, and G. Shekhar, "A Survey in Fuzzy Logic: An Introduction," International Journal for Scientific Research & Development(IJSRD), vol. 3, pp. 822-824, 2015.

[9] K. Mittal, A. Jain, K. S. Vaisla, O. Castillo, and J. Kacprzyk, "A comprehensive review on type 2 fuzzy logic applications: Past, present and future," Engineering Applications of Artificial Intelligence, vol. 95, pp. 1-12, 2020.

[10] Z. Zhang, Y. Zhang, Q. Huang, and W.-J. Lee, "Market-oriented optimal dispatching strategy for a wind farm with a multiple stage hybrid energy storage system," CSEE Journal of Power and Energy Systems, vol. 4, pp. 417-424, 2018.

[11] B. Li, X. Mo, and B. Chen, "Direct control strategy of real-time tracking power generation plan for wind power and battery energy storage combined system," IEEE Access, vol. 7, pp. 147169-147178, 2019.

[12] T. Rahimi, L. Ding, M. Kheshti, R. Faraji, J. M. Guerrero, and G. D. A. Tinajero, "Inertia response coordination strategy of wind generators and hybrid energy storage and operation cost-based multi-objective optimizing of frequency control parameters," IEEE Access, vol. 9, pp. 74684-74702, 2021.

[13] W. Guo, G. Zhang, J. Zhang, N. Song, Z. Gao, X. Xu, L. Jing, Y. Teng, Z. Zhu, and L. Xiao, "Development of a 1-MVA/1-MJ superconducting fault current limiter–magnetic energy storage system for LVRT capability enhancement and wind power smoothing," IEEE Transactions on Applied Superconductivity, vol. 28, pp. 1-5, 2018.

[14] J. Shi, W.-J. Lee, and X. Liu, "Generation scheduling optimization of wind-energy storage system based on wind power output fluctuation features," IEEE Transactions on Industry Applications, vol. 54, pp. 10-17, 2017.

[15] X. Wu and Y. Jiang, "Source-network-storage joint planning considering energy storage systems and wind power integration," IEEE Access, vol. 7, pp. 137330-137343, 2019.

[16] U. T. Salman, F. S. Al-Ismail, and M. Khalid, "Optimal sizing of battery energy storage for grid-connected and isolated wind-penetrated microgrid," IEEE Access, vol. 8, pp. 91129-91138, 2020.

[17] G. F. Gontijo, T. Kerekes, D. Sera, M. Ricco, L. Mathe, and R. Teodorescu, "Medium-voltage converter solution with modular multilevel structure and decentralized energy storage integration for high-power wind turbines," IEEE Transactions on Power Electronics, vol. 36, pp. 12954-12967, 2021.

[18] A. Sattar, A. Al-Durra, C. Caruana, M. Debouza, and S. Muyeen, "Testing the performance of battery energy storage in a wind energy conversion system," IEEE Transactions on Industry Applications, vol. 56, pp. 3196-3206, 2020.

[19] H. S. Salama, S. M. Said, M. Aly, I. Vokony, and B. Hartmann, "Studying impacts of electric vehicle functionalities in wind energy-powered utility grids with energy storage device," IEEE Access, vol. 9, pp. 45754-45769, 2021.

[20] L. Moser, S. Voigt, E. Schoepfer, and S. Palmer, "Multitemporal wetland monitoring in Sub-Saharan West-Africa using medium resolution optical satellite data," IEEE Journal of Selected Topics in Applied Earth Observations and Remote Sensing, vol. 7, pp. 3402-3415, 2014.

[21] R. Zhang, T. Jiang, G. Li, H. Chen, X. Li, L. Bai, and H. Cui, "Day-ahead scheduling of multi-carrier energy systems with multi-type energy storages and wind power," CSEE Journal of Power and Energy Systems, vol. 4, pp. 283-292, 2018.

[22] H. Kazari, H. Oraee, and B. C. Pal, "Assessing the effect of wind farm layout on energy storage requirement for power fluctuation mitigation," IEEE Transactions on Sustainable Energy, vol. 10, pp. 558-568, 2018.

[23] S. Bhattacharjee, R. Sioshansi, and H. Zareipour, "Benefits of strategically sizing wind-integrated energy storage and transmission," IEEE Transactions on Power Systems, vol. 36, pp. 1141-1151, 2020.

[24] K. Xie, S. Gaboury, and S. Hallé, "Real-Time Streaming Communication With Optical Codes," IEEE Access, vol. 4, pp. 284-298, 2016.

[25] B. S. Pali and S. Vadhera, "An innovative continuous power generation system comprising of wind energy along with

pumped-hydro storage and open well," IEEE Transactions on Sustainable Energy, vol. 11, pp. 145-153, 2018.

[26] I. N. Moghaddam, B. H. Chowdhury, and S. Mohajeryami, "Predictive operation and optimal sizing of battery energy storage with high wind energy penetration," IEEE Transactions on Industrial Electronics, vol. 65, pp. 6686-6695, 2017.

[27] Y. Wang, S. Lou, Y. Wu, and S. Wang, "Flexible operation of retrofitted coal-fired power plants to reduce wind curtailment considering thermal energy storage," IEEE Transactions on Power Systems, vol. 35, pp. 1178-1187, 2019.

[28] A. Nikoobakht, J. Aghaei, M. Shafie-Khah, and J. P. Catalão, "Minimizing wind power curtailment using a continuous-time risk-based model of generating units and bulk energy storage," IEEE Transactions on Smart Grid, vol. 11, pp. 4833-4846, 2020.

[29] Y. Yang, C. Qin, Y. Zeng, and C. Wang, "Optimal Coordinated Bidding Strategy of Wind and Solar System with Energy Storage in Day-ahead Market," Journal of Modern Power Systems and Clean Energy, vol. 10, pp. 192-203, 2021.

[30] X. Yin and X. Zhao, "Composite hierarchical pitch angle control for a tidal turbine based on the uncertainty and disturbance estimator," IEEE Transactions on Industrial Electronics, vol. 67, pp. 329-339, 2019.

[31] S. Abrazeh, A. Parvaresh, S.-R. Mohseni, M. J. Zeitouni, M. Gheisarnejad, and M. H. Khooban, "Nonsingular terminal sliding mode control with ultra-local model and single input interval type-2 fuzzy logic control for pitch control of wind turbines," IEEE/CAA Journal of Automatica Sinica, vol. 8, pp. 690-700, 2021.

[32] H. Ren, G. Deng, B. Hou, S. Wang, and G. Zhou, "Finite-time command filtered backstepping algorithm-based pitch angle tracking control for wind turbine hydraulic pitch systems," IEEE Access, vol. 7, pp. 135514-135524, 2019.

[33] X. Jiao, Q. Yang, and B. Xu, "Hybrid intelligent feedforward-feedback pitch control for VSWT with predicted wind speed," IEEE Transactions on Energy conversion, vol. 36, pp. 2770-2781, 2021.

[34] H. Ren, B. Hou, G. Zhou, L. Shen, C. Wei, and Q. Li, "Variable pitch active disturbance rejection control of wind turbines based on BP neural network PID," IEEE Access, vol. 8, pp. 71782-71797, 2020.

[35] H. Badihi, Y. Zhang, P. Pillay, and S. Rakheja, "Fault-tolerant individual pitch control for load mitigation in wind turbines with actuator faults," IEEE Transactions on Industrial Electronics, vol. 68, pp. 532-543, 2020.

[36] P. Chen, D. Han, F. Tan, and J. Wang, "Reinforcement-based robust variable pitch control of wind turbines," IEEE Access, vol. 8, pp. 20493-20502, 2020.

[37] J. E. Sierra-García and M. Santos, "Improving wind turbine pitch control by effective wind neuro-estimators," IEEE Access, vol. 9, pp. 10413-10425, 2021.

[38] M. E. Salem, H. M. El-Batsh, A. A. El-Betar, and A. M. Attia, "Application of neural network fitting for pitch angle control of small wind turbines," IFAC-PapersOnLine, vol. 54, pp. 185-190, 2021.

[39] X. Sun, J. Zhu, Z. Li, and G. Sun, "Rotation improvement of vertical axis wind turbine by offsetting pitching angles and changing blade numbers," Energy, vol. 215, p. 119177, 2021.

[40] L. Zhang, J. Gu, H. Zhu, K. Hu, X. Li, L. Jiao, J. Miao, J. Liu, and Z. Wang, "Rationality research of the adjustment law for the blade pitch angle of H-type vertical-axis wind turbines," Renewable Energy, vol. 167, pp. 484-496, 2021.

[41] X. Zhao, Z. Lin, B. Fu, and S. Gong, "Research on frequency control method for micro-grid with a hybrid approach of FFR-OPPT and pitch angle of wind turbine," International Journal of Electrical Power & Energy Systems, vol. 127, p. 106670, 2021.

[42] D. Pathak and P. Gaur, "A fractional order fuzzy-proportional-integral-derivative based pitch angle controller for a direct-drive wind energy system," Computers & Electrical Engineering, vol. 78, pp. 420-436, 2019.

[43] A. Iqbal, D. Ying, A. Saleem, M. A. Hayat, and K. Mehmood, "Efficacious pitch angle control of variable-speed wind turbine using fuzzy based predictive controller," Energy Reports, vol. 6, pp. 423-427, 2020.

[44] X. Yin, W. Zhang, Z. Jiang, and L. Pan, "Adaptive robust integral sliding mode pitch angle control of an electro-hydraulic servo pitch system for wind turbine," Mechanical Systems and Signal Processing, vol. 133, p. 105704, 2019.

[45] E. Hosseini, E. Aghadavoodi, and L. M. F. Ramírez, "Improving response of wind turbines by pitch angle controller based on gain-scheduled recurrent ANFIS type 2 with passive reinforcement learning," Renewable Energy, vol. 157, pp. 897-910, 2020.

[46] Q. Yang, X. Jiao, Q. Luo, Q. Chen, and Y. Sun, "L1 adaptive pitch angle controller of wind energy conversion systems," ISA transactions, vol. 103, pp. 28-36, 2020.

[47] R. Agarwala, "Development of a robust nonlinear pitch angle controller for a redesigned 5MW wind turbine blade tip," Energy Reports, vol. 5, pp. 136-144, 2019.

[48] H. Erol, "Stability analysis of pitch angle control of large wind turbines with fractional order PID controller," Sustainable Energy, Grids and Networks, vol. 26, p. 100430, 2021.

[49] L. Chen, Y. Yang, Y. Gao, Z. Gao, Y. Guo, and L. Sun, "A novel real-time feedback pitch angle control system for vertical-axis wind turbines," Journal of Wind Engineering and Industrial Aerodynamics, vol. 195, p. 104023, 2019.

[50] Z. Civelek, "Optimization of fuzzy logic (Takagi-Sugeno) blade pitch angle controller in wind turbines by genetic algorithm," Engineering Science and Technology, an International Journal, vol. 23, pp. 1-9, 2020.

[51] A. Rezaeiha, I. Kalkman, and B. Blocken, "Effect of pitch angle on power performance and aerodynamics of a vertical axis wind turbine," Applied energy, vol. 197, pp. 132-150, 2017.

[52] F. Golnary and K. T. Tse, "Novel sensorless fault-tolerant pitch control of a horizontal axis wind turbine with a new hybrid approach for effective wind velocity estimation," Renewable Energy, vol. 179, pp. 1291-1315, 2021.

[53] Y. Guo, X. Li, L. Sun, Y. Gao, Z. Gao, and L. Chen, "Aerodynamic analysis of a step adjustment method for blade pitch of a VAWT," Journal of Wind Engineering and Industrial Aerodynamics, vol. 188, pp. 90-101, 2019.

[54] A. El Hajjaji and A. Khamlichi, "Analysis of a RBF neural network based controller for pitch angle of variable-speed wind turbines," Procedia Engineering, vol. 181, pp. 552-559, 2017.

[55] L. Colombo, M. L. Corradini, G. Ippoliti, and G. Orlando, "Pitch angle control of a wind turbine operating above the rated wind speed: A sliding mode control approach," ISA transactions, vol. 96, pp. 95-102, 2020.
[56] Z. Civelek, M. Lüy, E. Çam, and H. Mamur, "A new fuzzy logic proportional controller approach applied to individual pitch angle for wind turbine load mitigation," Renewable Energy, vol. 111, pp. 708-717, 2017.
[57] B. Sujanarko, I. Syafrizal, S. Bachri, R. Gozali, S. Prasetyo, and T. Hardianto, "Performance Improvement of Buck-Boost Converter Using Fuzzy Logic Controller," International Journal of Engineering Research And Management (IJERM), vol. 4, pp. 22-27, 2017.
[58] A. Bakouri, A. Abbou, H. Mahmoudi, and K. Elyaalaoui, "Direct torque control of a doubly fed induction generator of wind turbine for maximum power extraction," in 2014 International Renewable and Sustainable Energy Conference (IRSEC), pp. 334-339.
[59] A. A. Ahmed, B. K. Koh, and Y. I. Lee, "A comparison of finite control set and continuous control set model predictive control schemes for speed control of induction motors," IEEE Transactions on Industrial Informatics, vol. 14, pp. 1334-1346, 2017.
[60] A. Ashouri-Zadeh, M. Toulabi, S. Bahrami, and A. M. Ranjbar, "Modification of DFIG's active power control loop for speed control enhancement and inertial frequency response," IEEE Transactions on Sustainable Energy, vol. 8, pp. 1772-1782, 2017.
[61] S. Boubzizi, H. Abid, and M. Chaabane, "Comparative study of three types of controllers for DFIG in wind energy conversion system," Protection and Control of Modern Power Systems, vol. 3, pp. 1-12, 2018.
[62] M. A. Soomro, Z. A. Memon, M. Kumar, and M. H. Baloch, "Wind energy integration: Dynamic modeling and control of DFIG based on super twisting fractional order terminal sliding mode controller," Energy Reports, vol. 7, pp. 6031-6043, 2021.
[63] K.-K. Shyu, H.-J. Shieh, and S.-S. Fu, "Model reference adaptive speed control for induction motor drive using neural networks," IEEE transactions on industrial electronics, vol. 45, pp. 180-182, 1998.
[64] M. Masiala, B. Vafakhah, J. Salmon, and A. M. Knight, "Fuzzy self-tuning speed control of an indirect field-oriented control induction motor drive," IEEE Transactions on Industry Applications, vol. 44, pp. 1732-1740, 2008.
[65] M. Liu, J. Hu, K. W. Chan, S. W. Or, S. L. Ho, W. Xu, and X. Zhang, "Dual cost function model predictive direct speed control with duty ratio optimization for PMSM drives," IEEE Access, vol. 8, pp. 126637-126647, 2020.
[66] A. V. Sant and K. Rajagopal, "PM synchronous motor speed control using hybrid fuzzy-PI with novel switching functions," IEEE Transactions on Magnetics, vol. 45, pp. 4672-4675, 2009.
[67] I. Benlaloui, S. Drid, L. Chrifi-Alaoui, and M. Ouriagli, "Implementation of a new MRAS speed sensorless vector control of induction machine," IEEE Transactions on Energy conversion, vol. 30, pp. 588-595, 2014.
[68] A. K. Dubey, J. P. Mishra, and A. Kumar, "Comparative Analysis of ROGI based Shunt Active Power Filter under Current Fed and Voltage Fed Type Non-Linear Loading Condition," IFAC-PapersOnLine, vol. 55, pp. 156-161, 2022.
[69] A. K. Mishra, S. R. Das, P. K. Ray, R. K. Mallick, A. Mohanty, and D. K. Mishra, "PSO-GWO optimized fractional order PID based hybrid shunt active power filter for power quality improvements," IEEE Access, vol. 8, pp. 74497-74512, 2020.
[70] T. Toumi, A. Allali, A. Meftouhi, O. Abdelkhalek, A. Benabdelkader, and M. Denai, "Robust control of series active power filters for power quality enhancement in distribution grids: Simulation and experimental validation," ISA transactions, vol. 107, pp. 350-359, 2020.
[71] G. da Silva Fischer, A. Mengatto, L. G. Kremer, and M. Mezaroba, "A control strategy for a series APF with critical-load-bus voltage feedback that avoids injection transformer saturation," IEEE Transactions on Industry Applications, vol. 55, pp. 2290-2299, 2018.
[72] L. Wang, C.-S. Lam, and M.-C. Wong, "Hybrid structure of static var compensator and hybrid active power filter (SVC//HAPF) for medium-voltage heavy loads compensation," IEEE Transactions on Industrial Electronics, vol. 65, pp. 4432-4442, 2017.
[73] Y. Han, L. Xu, M. M. Khan, C. Chen, G. Yao, and L.-D. Zhou, "Robust deadbeat control scheme for a hybrid APF with resetting filter and ADALINE-based harmonic estimation algorithm," IEEE Transactions on Industrial Electronics, vol. 58, pp. 3893-3904, 2010.
[74] L. R. Limongi, L. R. da Silva Filho, L. G. Genu, F. Bradaschia, and M. C. Cavalcanti, "Transformerless hybrid power filter based on a six-switch two-leg inverter for improved harmonic compensation performance," IEEE Transactions on Industrial Electronics, vol. 62, pp. 40-51, 2014.
[75] S. Echalih, A. Abouloifa, J. Janik, I. Lachkar, Z. Hekss, F. Chaoui, and F. Giri, "Hybrid controller with fuzzy logic technique for three phase half bridge interleaved buck shunt active power filter," IFAC-PapersOnLine, vol. 53, pp. 13418-13423, 2020.
[76] J. Fei, H. Wang, and M. Hua, "Double-Hidden-Layer Recurrent Neural Network Fractional-Order Sliding Mode Control of Shunt Active Power Filter," IFAC-PapersOnLine, vol. 53, pp. 6232-6237, 2020.
[77] S. Khalid, "Performance evaluation of Adaptive Tabu search and Genetic Algorithm optimized shunt active power filter using neural network control for aircraft power utility of 400 Hz," Journal of Electrical Systems and Information Technology, vol. 5, pp. 723-734, 2018.
[78] R. Chilipi, N. Al Sayari, and J. Y. Alsawalhi, "Control of single-phase solar power generation system with universal active power filter capabilities using least mean mixed-norm (LMMN)-based adaptive filtering method," IEEE Transactions on Sustainable Energy, vol. 11, pp. 879-893, 2019.
[79] G. Son, H.-J. Kim, and B.-H. Cho, "Improved modulated carrier control with on-time doubler for a single-phase shunt active power filter," IEEE Transactions on Power Electronics, vol. 33, pp. 1715-1723, 2017.
[80] M. Pichan, M. Seyyedhosseini, and H. Hafezi, "A New DeadBeat-Based Direct Power Control of Shunt Active Power Filter With Digital Implementation Delay Compensation," IEEE Access, vol. 10, pp. 72866-72878, 2022.

[81] B. N. Rao, Y. Suresh, A. K. Panda, B. S. Naik, and V. Jammala, "Development of cascaded multilevel inverter based active power filter with reduced transformers," CPSS Transactions on Power Electronics and Applications, vol. 5, pp. 147-157, 2020.

[82] W. U. K. Tareen and S. Mekhielf, "Three-phase transformerless shunt active power filter with reduced switch count for harmonic compensation in grid-connected applications," IEEE transactions on power electronics, vol. 33, pp. 4868-4881, 2017.

[83] X. Nie and J. Liu, "Current reference control for shunt active power filters under unbalanced and distorted supply voltage conditions," IEEE Access, vol. 7, pp. 177048-177055, 2019.

[84] B. Rouabah, H. Toubakh, and M. Sayed-Mouchaweh, "Fault tolerant control of multicellular converter used in shunt active power filter," Electric Power Systems Research, vol. 188, pp. 1-21, 2020.

[85] Y. Bekakra, L. Zellouma, and O. Malik, "Improved predictive direct power control of shunt active power filter using GWO and ALO–Simulation and experimental study," Ain Shams Engineering Journal, vol. 12, pp. 3859-3877, 2021.

[86] S. S. Patnaik and A. K. Panda, "Three-level H-bridge and three H-bridges-based three-phase four-wire shunt active power filter topologies for high voltage applications," International Journal of Electrical Power & Energy Systems, vol. 51, pp. 298-306, 2013.

[87] T. Gao, Y. Lin, D. Chen, and L. Xiao, "A novel active damping control based on grid-side current feedback for LCL-filter active power filter," Energy Reports, vol. 6, pp. 1318-1324, 2020.

[88] X. Sun, R. Han, H. Shen, B. Wang, Z. Lu, and Z. Chen, "A double-resistive active power filter system to attenuate harmonic voltages of a radial power distribution feeder," IEEE transactions on power electronics, vol. 31, pp. 6203-6216, 2015.

[89] J. Fang, G. Xiao, X. Yang, and Y. Tang, "Parameter design of a novel series-parallel-resonant LCL filter for single-phase half-bridge active power filters," IEEE transactions on power electronics, vol. 32, pp. 200-217, 2016.

[90] L. Wang, C.-S. Lam, and M.-C. Wong, "Unbalanced control strategy for a thyristor-controlled LC-coupling hybrid active power filter in three-phase three-wire systems," IEEE transactions on power electronics, vol. 32, pp. 1056-1069, 2016.

[91] D. Chen, L. Xiao, W. Yan, Y. Li, and Y. Guo, "A harmonics detection method based on triangle orthogonal principle for shunt active power filter," Energy Reports, vol. 7, pp. 98-104, 2021.

[92] D. Chen, L. Xiao, H. Lian, and Z. Xu, "A fault tolerance method based on switch redundancy for shunt active power filter," Energy Reports, vol. 7, pp. 449-457, 2021.

[93] I. Hamdan, , Marwa MM Youssef, and Omar Noureldeen. "Design of Fuzzy Coordinated PI Controller for Supercapacitor in Large Scale Wind Farm." 2021 22nd International Middle East Power Systems Conference (MEPCON). IEEE, 2021. https://doi.org/10.1109/MEPCON50283.2021.9686248

[94] S. AlGhamdi, I. Hamdan, Marwa M. M. Youssef, and O. Noureldeen, "Development and application of fuzzy proportional-integral control scheme in pitch angle compensation loop for wind turbines," Machines, vol. 9, p. 135, 2021. https://doi.org/10.3390/machines9070135

[95] I. Hamdan, Marwa M. M. Youssef, and O. Noureldeen, "Influence of interval type-2 fuzzy control approach for a grid-interconnected doubly-fed induction generator driven by wind energy turbines in variable-speed system," SN Applied Sciences, vol. 5, p. 25, 2023. https://doi.org/10.1007/s42452-022-05242-2

[96] I. Hamdan, Marwa M. M. Youssef, and O. Noureldeen, "A Proposed Supercapacitor Integrated with an Active Power Filter for Improving the Performance of a Wind Generation System under Nonlinear Unbalanced Loading and Faults," Journal of Electrical and Computer Engineering, vol. 2023, p. 17, 2023., https://doi.org/10.1155/2023/2863528