A Review of the State of the Art Control Techniques for Wind Energy Conversion System

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Abstract- Alternative energy sources have become a necessity for the socio-economic growth of a country; fossil fuels are declining and by increasing the power demand, the world is on the edge of a global energy crisis. Furthermore, due to the widespread use of traditional energy sources, this creates pollution and global warming effects on the environment. In the light of this, renewable energy such as the wind and solar energy are highly significant and viable solution in order to fulfil power demand, due to its low operating costs and available in bulk quantities which make it exploitation beneficial for the development of any country. Besides that, for over the past decades, the researchers have been working on this enormous challenge. In this review article, we put forward a wide-ranging and significant research conducted on the state of the art control methodologies for wind energy systems. Therefore, author's main aim is to ensure up-to-date knowledge of wind energy control techniques for the research community and can be considered for future directions. In the available literature, we have summarized numerous wind turbine control techniques with their performance. Furthermore, prospective future advancements and gaps have also been examined comprehensively, and omissions of other researchers are purely unintentional.

Keywords: Controller technique, wind energy conversion systems, wind turbine generators.

Nomenclature

NN	Neural Network	FOFC	Fuzzy Output Feedback Controller	FOC-PI	Field Oriented Control-Proportional Integrator
PID	Proportional Integrator Derivatives	LMI	Linear Matrix Inequalities	Z-SI	Z-Source Inverter
PI	Proportional Integrator	BMI	Bi-linear Matrix Inequalities	ANN & DSP	Artificial Neural Network & Digital Signal Processing
FA	Firing Angle	FOC	Field Oriented Control	JR-CANN	Jordan Re-current Artificial Neural Network
NMPC	Nonlinear Model Predictive Control	VSC	Voltage Source converter	DSPANN	Digital Signal Processing Artificial Neural Network
NN	Neural Network	MSFL	Master Slave Fuzzy Logic	QNN	Quantum Neural Network
HCS	Hill Climbing Searching	TS-F	Tagaki Sugino-Fuzzy	MPNN	Multi-layer Neural Network

R CNN	Re- current Neural Network	QTS	Quasi Tagaki Sugino	SCIG	Squirrel Cage Induction Generator
FL	Fuzzy Logic	FESS	Fly Wheel Energy storage	BDFRG	Brushless Doubly-Fed Reluctance Generator
LPV	Linear Parameter Varying	DSTATCOM	Distributed Static Compensator	MATLAB	Matrix Laboratory
KF	Kalman Filter	BB -PW M VSC	Back-Back Pulse Width Modulation Voltage Source Converter	PS I M	Physic al Security Information Management
FFT	Fast Fourier Transform	BIC PWM	Boost Inverter Converter Pulse Width Modulation	FP GA	Field -Programmable Gate Array
VCPWM	Vector Control Pulse Width Modulation	SEIG	Self-Excited Induction Generator	DGA	Differential Geometric Approach
LQ	Linear Quadrant	SG	Synchronous Generator	CC	Cyclo-Converter
HCC/VC	Hysteresis Current Control/Vector Control	WRIG	Wound Rotor Induction Generator	IG	Induction Generator
BC	Boost Converter	DOIG	Double Output Induction Generator	MC & SFOC	Matrix Converter & Stator Flux Oriented Control
DDBC	DC -DC Bidirectional Converter	PM SG	Permanent Magnet Synchronous Generator	HOSM	Higher Order Sliding Mode
IVS/VSI	Integral Variable Structure/Variable Structure Integral	PMRG	Permanent Magnet Reluctance Generator		

1. Introduction

The rapid growth in world's population, expected to be about 9.6-billion by the end of 2050, raises the need for growth in energy demand, and it is predicted by the end of the year 2040 energy consumption would have increased by 56 percent [1-2]. Attributable to the massive energy potential known as natural free of cost sources, known as fossil fuels which are at the edge of depletion. These fossil fuels are environmentally friendly and their depletion is caused by the global climate. According to various researchers and scientists in developed and developing states, these effects create an unfavorable situation. It is pointed out here to the readers that globally, nuclear and renewable energies are the most rapidly growing energy resources growing at a rate of about 2.5 percent/year. To the best of our knowledge that the nuclear energy is more efficient and reliable, even though its capital cost is higher, but it has various human health drawbacks because of radioactive waste, which directly affects newborn births and much more [3-7]. In regards to the current energy and environment scenario, globally there has been a great concentration of renewable energy such as wind energy rapidly growing sources which are free of cost, clean, physically available for the power production and have minimum impact on the environment [8-13] i.e. low carbon dioxide emissions. It is indicated here to the readers that some researchers specify that the United States emits a large quantity of carbon dioxide in the atmosphere, as illustrated in Fig. 1. However, globally the installed wind energy capacities by the end of F.Y 2005 were extended at about 30% per year [29]. Afterward, at the end of 2013 installed capacity was about 35GW and slightly lower increment than 2012 [30]. It has been found that F.Y 2014 was a momentous year for wind turbine system industries, in which only after a year 51GW was installed. At that time nobody anticipated that the Chinese would install about 23GW in only one year. Globally, the yearly and cumulative installed wind energy capacity for the period of 1997-2014, as illustrated in Fig. 2 [31-34]. According to the law of principle, wind turbine systems can be used by directly or indirectly converting wind energy into electricity. The first wind turbine was launched early in the 20th century. Subsequently, the advancement of wind turbine design components, including power electronics topologies, electrical generators and gear systems have allowed gearless turbine designs [35-36]. Besides that, the wind turbine system has two most prominent components such as maximum extracting power and minimum cost for the development of continuous research study. Modern wind turbine systems can be divided into two types according to the turbine blade axes: (a) horizontal axis and (b) vertical axis. The horizontal-axis wind turbine is more reliable, which rules the majority of the wind industry due to its efficiency on the output side in comparison to vertical axis wind turbine systems [37-38]. In order to get equal output from the horizontal axis, the vertical axis requires more materials. Afterward, it is concluded that horizontal-axis wind turbine system is more applicable for the small scale wind applications [37 & 39-42]. However, a wind energy conversion system usually consists of these primary components such as blades, a tower, an alternator, a rotor, and a gearbox [43].

Tower: Amount of wind speed increases with the increment altitude. It is utilized to keep the rotor at a higher level in order to extract more wind power [44].

Rotor: It contains large blades resembling an airplane wing. As the moving air goes via wind turbine blades, the rotor rotates and accordingly draws up a mechanical power [44].

Nacelle: Referring to [45], it is situated on the crest of the turbine tower, and involved in the turbine rotor, which consists of the mechanical components i.e. rotor shaft, gearbox, and generator. The nacelle is in a position to rotate with respect to the wind direction in order to capture maximum wind power.

Gearbox: Typically rotor has a less than 100 rpm (revolution speed per minutes) speed; besides those most electrical generators require 1000 rpm to 3600 rpm to produce power. Consequently, the gearbox has the ability to convert low turbine rotor speed to maximum speeds in order to make the generator operation [46].

Alternator: The alternator directly converts mechanical energy of wind potential into electricity. However, at the present time, there are various most important varieties of wind turbine generators available on the marketplace described in detail [47-67 & 182-183] the squirrel cage induction machine (SCIM) is well known among all other electrical machines used for constant wind turbines speed. It is connected to the rotor of the wind turbine and stator is directly connected to the grid with a capacitor bank. This type of machine has some drawbacks such as: during energy conversion system, it has low efficiency, needs higher gearbox maintenance, the minimal capability to control active and reactive power, and SCIMs have higher mechanical stress. Similarly, doubly fed induction machine (DFIM) [184-186] is one of the most widely used machines for wind turbine applications with about 50 % of installed wind turbine system using these machines for variable speed technology, resulting in the reduction of the drive train mechanical stress and power oscillation; it also increases the mechanically captured power. At higher wind velocity in case of DFIM when compared to SCIM the power captured by wind energy can be restricted via pitch control. The DFIM have numerous advantages such as it reduces mechanical stress, more ability of maximum power point tracking (MPPT) for speed controller techniques, and more flexibility to control active and reactive power. However, doubly-fed induction machines use brushes, as it has been emphasized that the use of brush minimizes the robustness and requires extra maintenance than SCIMs for wind energy conversion system. To some extent, direct-drive synchronous machines (DDSM) are similar to doubly-fed induction machine; it has some advantages like DFIM except DDSMs can operate without the gearbox. The brushless doubly-fed induction machine (BDFIM) has emerged as a suitable alternative to the DFIMs for stand-alone applications. The main advantage of BDFIM is suitable for offshore applications and it is the lack of brushes with accordingly reduced maintenance, and stator windings have a separate pair of poles to avoid direct coupling.

During this study, our focus is on surveying the latest advances in the wind energy conversion systems on consequent a sophisticated control approaches.

This manuscript is split up into six sections. The rest of the sections are presented as below. Prior literature review described in Section 2. The preceding literature review referred to in article 3. In Section 4, we have discussed the wind energy control techniques. The literature review trend investigation has been reported in Section 5. Finally, the conclusion and future directions are presented in section 6.

2. Prior Literature Review

A groundwork interrelated explore was carried out using exploring engine. IEEE Explore Digital Library [68], Google Scholar [69] and Research Gate [70]. The key terms searched on the web for ‘wind turbine control’ and ‘control methods. Furthermore, to the best of our knowledge all cited research articles were properly checked and the appropriate article included in the literature. All cited articles have been made in chronologically descending order for presenting a literature review for the control strategy of wind energy conversion systems. However, the major consideration has been given maximum power point tracking (MPPT), active and reactive power control techniques, efficiency, and overall wind turbine system performance.

3. Literature Review

Several researchers have previously published articles on wind energy conversion system control approaches. The authors *F. D. Bianchi et al.*, [71] introduced the dynamics modeling oriented control design of wind energy conversion systems. *P. Moriarty et al.*, [72] discussed the different wind turbine systems, categorization, and evaluation according to the generator types and angular speed. *Y. Z. Sun et al.*, [73] investigated wind turbine system stability and reliability, the power quality, wind turbine transmission systems and storage, etc. as referring to [74], the authors reviewed a wind energy conversion system control concept in various working zones and subsequent advanced and standard control techniques, which mainly include the multi-input/output and proportional integral derivatives (PID). *J. Yan et al.*, [75], reviews on the wind turbine system control founded on fuzzy logic and neural network concepts. As consulting to [76], the authors surveyed on controlling the frequency of the wind turbine system with wind power saturations. *J. H. Laks et al.*, [77], reviews focuses on the present, past and future trends of wind turbine power system control using individual horizontal wind turbine. Consulting [78] reviewed in (2012) and covered the comparison of the optimal power tracking system with doubly-fed induction machines of wind energy conversion system. N. Y. Murthy et al. [79], details surveyed on power electronic applications in a wind energy system. As referring to [80], the author concentrates on modeling and control of wind energy systems. *V. J. Kante et al.*, [81], reviewed wind turbine system modeling and control based on permanent magnet synchronous machines. In the preceding literature reviews, several features in this area may find a lack of systematic reviews of existing research and developments focusing on advanced control techniques for wind energy conversion systems based on different wind turbine machines. To the best of our knowledge, for each method, we have selected a certain number of research articles.

4. Wind Turbine Controller Techniques

The most advanced and sophisticated wind energy conversion systems control techniques are classified as below:

4.1 Proportional integrator differentiator controller

As referring to [82-84], a Proportional Integrator Differentiator (PID) Control Technique was proposed to optimize the performance and efficiency of wind turbine system based on the modern power converters placed between wind turbine generator and load (resistive) by silicon control rectifier techniques especially refer [82]. However, the controller is used to calculate the integrated error signal between reference maximum and the real output power, which is measured from the resistive load. In the above-mentioned references especially [83-84], focused on power electronics converter and inverter, which are operated by some desired firing degrees. Referring to [85], authors conducted a comparative analysis and studied the effects of the single and multi-rate system performance and reliability of the nonlinear dynamic wind turbine model based on proportional integrator controller techniques. Besides that, *S. Natarajan et al.* verified that the multi-assessment techniques have much better performance than single rate systems. *I. Tsoumas et al.* claim that to get optimal power at the output side, a proportional integrator is utilized to trigger the variations of load current firing angle. *J. W. Perng et al.* proposed and identified the optimum operating point for proportional integrator- differentiator of a wind energy conversion system. The authors introduces the graphical techniques and it was utilized to determine the 2D and 3D boundaries of the PID type controller space in closed loop systems. As referring to [86], the authors claim that pitch and drive train model of the wind turbine system can be controlled by with and without time delay approaches, respectively.

4.2 Predictive controller

The predictive control technique can manipulate nonlinear control issues with limitations reasonably well. M. Bayat et al. introduced the predictive control techniques for a power grid associated with a wind turbine system using doubly fed induction machines. The authors in reference [86], claims that the recommended controller design can effectively trace the wind turbine speed perturbations in order to control the active and reactive power. As referring to [87], the most advanced techniques were applied based on nonlinear model predictive control (NMPC) to obtain the maximum level of power to a large extent possible from the wind speed. D.Q Dang et al. claim and justify the NMPC algorithm performance and effectiveness, which is better with other conventional techniques such as linear quadratic Gaussian techniques, a linear parameter varying, proportional integration differentiator etc [88-91]. Besides that, the author’s [92], study and justify the proposed controller design technique is preferable to the linear proportional integrator (LPI) for achieving the regulation of dynamics wind energy conversion system parameters during optimal operation. *J. Novak et al.,* justify and compared with (PI) controller techniques, showed that the model based predictive control can be operated in regimes in a smooth way under the turbulence, wind circumstances and it has been proved that significant improvement has been obtained in the case of model-based predictive control concept and [93]. Similarly, referring to [94] justified those non-model based predictive control techniques for wind energy conversion system based on a doubly-fed machine plugged into the power grid is more accurate, simple and having better performances than other conventional algorithms. *L.Wang et al*., in detail (see [95]), justified the predictive controller performance of wind turbine system is better, the author discussed, a method based on multimodal modeling and predictive control is proposed for the optimal operation of the direct-drive wind turbine with permanent magnet synchronous generator in this paper.

4.3 Adaptive controller

It’s very difficult to construct an unknown nonlinear dynamic model of a wind turbine system, and then the adaptive control technique is taken into account. Due to extreme intrinsic nonlinear parameters, the adaptive control technique has been brought into operation for wind energy conversion system. *M. A. Mayosky et at.,* proposed direct adaptive control strategies have been focused. As referring to [96], author’s focused on two control procedures: a supervisory control technique, based on crude bounds of the nonlinearities of the wind turbine system and a radial system based on z-function controller methods, which operates the tracking error to zero with user dynamics of the wind energy conversion system. Similarly, referring to [97], author’s focused on direct adaptive control strategy, but different from [96], because in [96] the authors did not focus on wind speed tracking, but in [97] authors focused on optimum wind speed measurement tracking control to make the turbine speed follow the required output asymptotically stable. *M. Sedighizadeh et al.*, in reference [98], discussed and studied for self-tuning PID controller for wind turbine system for lyapunov method. The authors put forward this control strategy, where the impulse response filter was first trained to estimate and modernize the PID controller constraints of the dynamic wind turbine system. As referring to [99-100], the authors claimed that adaptive technique that is more suitable and is followed by the optimal response to a change of wind turbine systems than the self-regulated control strategy through Lyapunov concept. The authors, proposed a new adaptive controller design at the optimal point of the wind power in which employees new up to date approaches called a Hill Climbing Searching (HCS) combining two more ways operating point adjustment loop (OPAL) and change detection loop (CDL), to get maximum power points. Similarly, *K. Raza et al.,* in reference [101] improved this drawback which occurred in reference [100-101]. The authors not only estimate and prove the tracking wind turbine speed versus controller efficiency trade-off issues of HCS but provide sure about wind speed circumstances should not be in the wrong direction. In this strategy, the authors claimed that it does not require any kind of signal such as mechanical etc, but that it can operate with any types of wind energy conversion systems. As referring to [102], the HCS technique for maximum power point tracking method was proposed for wind turbine system, in this reference, the authors perform the self-tuning to manage with variable efficiencies of the wind turbine subsystem and actively operate under unreliable wind turbine speed. Besides that, the authors not only develop a smart speed sensor-less technique controller based on HCS to avoid the mechanical sensors but also keep in mind the cost and reliability of the wind turbine systems. *D. A. Haris et al.,* in reference (see [103]), discourage the authors *F. Karim et al.,* and proposed the latest control techniques to maximize the power of variable speed grid connected wind energy conversion system, and claims that the proposed approach, based on a recurrent neural network, allowed quick convergence and tracking system to do well against uncertain, noisy and disturbance circumstances to a nonlinear dynamic behavior of WECS.

4.4 Robust controller

As referring to [104-107], many authors designed a robust controller due to unpredicted wind speed disturbances of wind energy conversion systems in power systems. In above-mentioned references, the authors claimed that maximized power and reduction of load fluctuation can be calculated by considering feedback loop approaches. R. Rocha et al., [101], justify the effectiveness between H-infinity and H-2 controlled by considering the same constraints of wind energy conversion systems. It is observed that controller H-infinity grants more robust method and has the minimum response time as compared with H-2 control concepts. Finally the results, it is concluded that H-infinity controller is not suitable for variable wind turbine systems, and the H-2 controller is not suitable for constant wind turbine systems. Even though authors, *C. C. Hao et al*., in reference [108], justify and claim that H-infinity has more advantage such as it is simple, higher dynamic performance and can be used for variable wind turbine speed. As referring to [109-112], many researchers widely study the advanced control strategy. The power control techniques can take advantage of the internal structure of the wind turbine systems, and to render it simple. In reference [114], the author's shows the energy-based control strategy can thoroughly take benefit based on the Hamiltonian structure and ensure the L-2 system stability under systematic errors. We know that wind speed is an uncertain parameter and it varies from time to time in wind turbine systems. Based on these uncertain situations, the authors H. Tien et al., in reference [115], declare that linear time invariant function has been active interest for wind turbine systems that the robust synthesize a controller have the effective response regarding uncertain wind speed and also adjust the induction machine constraints. Many researchers [116-117], proposed the anemometer and Kalman Filter (KF) techniques for wind speed estimation respectively, in order to feed into gain scheduled controller, from wind turbine torque for the maximum operating points. In this proposed strategy, the proportional integrator is not able to compensate for the gain-scheduled controller through the LPV system model. W. Wang et al., justified the gain scheduling switching mechanism of H-infinity controller techniques using Lagrange interruption that has the better robust performance for optimal operating points instead of using a single PI controller, under the rated wind turbine speed of wind energy conversion systems [118]. As referring to [119], proposed the robust controller design of a wind turbine system coupled permanent magnet synchronous machine with direct current techniques. In this concept, the authors justify the unique approaches like iso-damping has better performance than the conventional approaches. In this concept, the fractional order control concept can be utilized for efficient control of dynamic wind turbine systems model with uncertain circumstances. Finally, H. Moradi et al., proved that H-infinity robust controllers have the ability for effective performance for large range of operating conditions, and in these approaches the wind turbine systems are implemented through μ-synthesis concept based on DK-iteration techniques then both output parameters such as angles and power will be a smaller amount of disturbances [120].

4.5 Optimal controller

In order to capture the optimal power of wind speed, many researchers suggested their ideas, but their approaches were not attractive enough for the optimal control strategy for wind turbine systems for uncertain wind conditions [121-122]. Subsequently authors *K. Tan et al.*, [123], have recommended the optimal control techniques for the maximum power point tracking (MPPT) using permanent magnet synchronous machines at fixed pitch of wind energy conversion systems. In this optimal control strategy, the authors combined the forecasted output maximum DC power versus DC voltage characteristics and the stator frequency of permanent magnet machines to operate the wind energy conversion system at the maximum power point level, and no need to utilize the other techniques except [123], for tracking of wind speed at the optimal power level of wind turbine system. Refereeing to [124], discourage *K. Tan et al.*, and claimed that the maximum power point can be obtained by using Fast Fourier Transform, between rotational speed and unit less power coefficient obtained from the estimated power. Referring to [125] introduces new and simple control strategy for direct drive of permanent magnet synchronous machines based on variable wind turbine speed. In this control concept, the authors discussed the maximum power point tracking system for small size wind turbine system under remote areas of the power supply using simple and less costly vector control ideas under constant and varying load conditions by regulating frequency and voltage at uncertain wind circumstances. According to the optimal power point of view, *A. Bratcu et al.*, [126], presents their ideas of fluctuating wind turbine speed for optimal power. In this article, the authors cover different techniques to wind turbine control issues, and focused on power optimization, particularly considering frequency separation control in managing multi optimization issues. Furthermore, referring [127], the authors introduced the linear state space MW wind turbine system models to obtain the optimal power conditions, which employed an optimal feedback controller-linear quadrant regulator approaches in order to regulate wind turbine pitch system. The model was implemented in real wind farm house and it was observed that the linear quadrant regulator controller proves more effective compared with conventional controller concepts. As referring to [128], the authors more sophisticated method was presented by using successfully effectual conventional PI controller in order to maximize their gains with respect to going beyond and error tracking quality. Afterward, a simple sensor-less variable speed control concept based on permanent magnet synchronous machines has been put forward for wind turbine systems [129], in this manuscript, controller design strategy is distinct from other researchers. The authors justify that the controller can capture the power at the maximum level at uncertain wind speed to the power grid. In this concept, the permanent magnet synchronous machines are combining to connect switch mode and 3-phase source inverter mode. So, the maximum power point could be achieved, in which power grid voltage inverter uses a hysteresis current controller to supply power at unity power factor into the power grid. More recently, *M.M. Hussein et al.*, [130], proposed a controller design concept for optimal wind turbine system conditions as unreliable wind speed, and their ideas was different from other literature. Furthermore, *M. M. Hussein et al.*, modify the manuscript [129 & 132], and uses DC-link voltage to maintain at a constant level and supply surplus power at the time of load shedding at the load side, and during the low wind turbine speed, the chopper buck-boost converter controls it, which is coupled with DC link voltage. The complex vector control ideas control by regulating amplitude and frequency. Latest ideas have been put in place to develop maximum power point techniques for permanent magnet synchronous machine wind energy conversion system by *S. Faqirzay et al.,* [131], with this concept for maximum power point tracking system, initially synchronous machine speed control is coupled with simple rectifier and then a boost converter to control the amplitude and speed to get optimal conditions. It is seen that the authors justify the simulated results having the effective accuracy and can be utilized for small wind turbine system.

4.6 Sliding mode controller

In this section, a sliding mode controller design technique will be examined bit by bit. Basically, the sliding mode controller design techniques have the capability to handle nonlinear systems with intelligent robust responses to the unreliable systems [133]. Referring to [134-135], the authors presented a sliding mode controller design technique for wind turbine systems using a double-output induction generator that is directly connected to the power grid by the stator and a static converter of the rotor of machines. In detail *H. De Battista et al.,* developed a simple and easy sliding mode controller in which static converter regulates the torque of the generator, which is interpolated between stator and rotor. In this way, damping produced in the system may eliminate the substantial reduction of generator torque and power fluctuation. The feedback dynamics system is totally robust to uncertainties of the generator constraints and AC-power grid voltage interruptions. Furthermore, *H. De Battista et al.,* [135], discussed the firing angle and generator torque parameters by commanding different switching meanings consequent to work provisions. The simulation outcomes demonstrate the complete robustness of power grid disturbances and uncertainties in the electrical constraints. To avoid chattering issues, *R. Pena et al.,* [136] presented two integral algorithms for small wind energy conversion systems to address above mentioned issues. The authors justify that both controllers such as integral variable structure (IVSC) and variable structure integral (VSCI) techniques showed the effective performance in the maximum point level of wind turbine generator speed. Although it was important to note that VSCI, have slightly better performance than the other mentioned method because it does not require an approximation of sign function in the control function like in IVSC techniques. That’s why such control strategy needs a precise estimation of wind energy conversion systems. *F. Valenciaga et al.,* [137], investigated a sliding mode control concept for the variable structure system model. This control technique founded on the differential geometric approach to nonlinear systems affine in the control of uncertainties and disturbances. The author’s main purposes of the proposed sliding mode control are the reduction of chattering, simplicity, robustness, minimizes disturbances and reaching mode control. Referring to [138], effectively introduced a multiple-input multiple out (MIMO) combines the variable structure controller and Lyapunov’s techniques for wind energy conversion systems based on brushless doubly-fed reluctance machine. In this way, the robustness to chatter reduction and bounded interruptions is achieved. *S. F. Pinto et al.,* [139] introduced a doubly-fed wind turbine system based on directly controlled matrix converter by means of sliding mode control approaches instead of using static converters. The author’s main aim is to capture maximum power from the uncertain wind speed in order to control the rotor currents, guaranteeing the necessary torque to capture the maximum power. As referring to [140], proposed a simple control method called sliding mode control by using a 1.5MW wind turbine systems simulated to evaluate the system parameter performances. In this technique, the authors justify that the control strategy is effective in terms of power regulations. Furthermore, the authors arranged a control strategy, to minimize chatter in the generated torque that could lead to maximizing the mechanical stress due to strong uncertain torque variations. *I. Munteanu et al.,* [141], proposed an energy reliability of wind energy conversion systems by sliding mode control based on off-line and real time simulations; afterward, dedicated experimental work shifted upon the hardware in the loop simulation approaches, in order to gain maximum power point tracking (MPPT). In this manuscript, the effective result performance is achieved, which are quite satisfactory. Even though some physical constraints and certain estimations were still needed in such control techniques. As referring to [142-143], the authors introduced higher order control schemes based on a wind energy conversion system in order to focus the chattering issues. *F. Valenciaga et al.,* introduced higher order wind energy conversion system based on permanent magnet synchronous machines in a hybrid power generation system. For power optimization and power regulation modes, the manuscript deals with the design of two different sliding mode controller, which ensures the better performances. The main objective of the designed controller was simple, robust and free from chattering with respect to external disturbances and non-modeled dynamics. Moreover, *X. Zheng et al.,* specify that higher order sliding mode controller dynamics is estimated by a linear combination of the tracking error and its 1st derivatives, and it is able to stabilize the system. In this work, it is considered that by reducing the rotor current variations of 15% potential dip. Talking about [144] deals with the higher order control techniques of a (PMSM) based on the marine current turbine. In this paper, the authors studied to run off 7.5kW wind turbines, the main objective was the chattering free response, a finite reaching time, and robustness with respect to external interruptions. Finally, it is concluded that outcomes are satisfactory and very encouraging. *D. Kairous et al.,* [145] studied and focused on two control techniques such as sliding mode control and PI control for wind turbine systems based doubly fed induction machines. In this paper, both stator and rotor currents of DFIM and power over and under sag are observed. The sliding mode controller performance is better than PI controller. Referring to [146], focus on a comparative study of both sliding mode and PI controller based on field oriented control techniques in order to optimize the power of uncertainty low and medium wind speed of the wind turbine system for permanent magnet synchronous machines. It was noted that the sliding mode control strategy for wind energy conversion system is more effective than the PI controller having good tracking error performance and robustness in the occurrence of turbulence substitute on the system. *Y. Errami et al.,* [147], proposed a new control algorithm of a wind energy conversion system based on grid connected permanent magnet synchronous machine. This control scheme is built on the sliding control technique in order to optimize the wind power at maximum power point tracking (MPPT). In this strategy of two control method, one on the grid side converter and grid side have been introduced. The sliding mode nonlinear control schemes are utilized to maintain the DC-bus voltage and regulate the grid side power factor. In this paper, the focus was not confined to extract the maximum power, but also it controls the frequency and voltage with unity power factor and low interruptions. *E. Rajendran et al.,* [148], proposed a novel sliding control technique for permanent magnet synchronous generator with Z-source inverter in order to capture maximum power at low wind speed of the wind energy conversion systems. In this paper, the wind turbine network consists of buck-boost capabilities through LC-DC-link network in between the DC source and inverter, with the help of these schemes the disturbance is reduced and enhanced voltage level is achieved owing to the uncertainty of wind speed. Referring to [149], the authors proposed sliding mode control schemes for optimal tracking systems which are low cost and can be deployed in real time data applications using the digital signal processor based on Lyapunov theory concepts. In this paper, authors show the effective and robust results with respect to the uncertainties of the system constraints which usually occur in real time applications. Furthermore, as referring to [150] overcomes the deficiency in order to get (MPPT) from wind turbine system based on permanent magnet synchronous machines and it is intended for a variable speed. In this control system, the outcomes involve a variation of system constraints, reduction of chattering, and comparison with other techniques which need the further recommendation.

4.7 Neural network controller

As referring to [151], the authors describe neural network principles and implemented for a small wind turbine system. In this paper, the authors claim that while implementing artificial neural network maximum power can be traced to both conditions such as steady state and dynamic, also wind speed tracking system is more quickly compared with an anemometer. The neural network based concept is presented to pay compensation for the probable drift of wind turbine coefficient. This technique can be made to implement hardware, and in this case, no need to pay the extra cost for a digital controller. Similarly, *Y. Ren et al.,* [152] introduced a new control strategy for a wind turbine system based on neural network. In this paper, authors used an artificial neural network in order to predict the optimal wind speed rotation due to uncertain wind speed circumstances for maximum power point tracking (MPPT). Finally, obtained outcome performs quite well and verify via simulation in which the system minimizes the system failure probability. Owing to wind speed variations, the wind turbine systems have greater nonlinear characteristics, and it is extremely difficult to construct a wind turbine system model to justify the issues. Similarly, *J. Thongam et al.,* [153] recommended an artificial neural network based on Jordan recurrent concept making up of four input signals such as output power, rotor speed, wind speed, and optimal power to estimate the reference tracking speed of the rotor. Furthermore, author's discussed that the output of the artificial neural circuit is feedback via a holdup entity, and is back to dissemination. Finally, it is concluded the ANN control scheme was satisfactorily applied to wind energy conversion systems based on permanent magnet synchronous machines. In this way, as referring to [153]. Authors designed a wind energy conversion system model based on Markov schemes approaches using neural network techniques in order to optimize the output of the wind turbine system. In this paper, the output results justified and compared with the supervisory control system, and shown that the proposed techniques reduce generator speed fluctuations, besides that the wind turbine system improved safety/protection and captures more power from uncertain wind speed. As referring to [155], in this paper authors described a maximum power point tracking of a permanent magnet synchronous generator used in a wind energy conversion system based on the artificial neural network. The control strategy analyzed experimental and simulation-based where the maximum power tracking error was about 0.17 percentages. *S. Ganjefar et al.,* [156]), proposed a quantum neural network (QNN) control was utilized to enhance the efficiency and optimize the wind energy conversion system. In this concept, a direct and indirect control structure was implemented via QNN in optimized torque and tip speed ratio MPPT techniques. Furthermore, authors showed the operative results, which were evaluated via battery charging windmill system connected with permanent magnet synchronous machines and finally compared to other conventional methods. Recently, another technique which was introduced by *E. Assareh et al.,* [157], in this approaches the torque control in wind turbine system is adjusted via the proportional integral controller in such a way at minimum wind speed level, the power is maximized through the generator. By the way, the controller designs through a multilayer perception neural network. Finally, the outcomes indicate the appropriate and being effective in performance compared with above-mentioned results referring to [151-156].

4.8 Fuzzy logic controller

Comprehension-based control schemes for wind energy conversion systems have been interested. To the best of our knowledge, we just try to focus up to the most recent study of fuzzy logic control presented in wind turbine systems. Referring to [158], authors described a concept for capturing the optimal power tracking system from the wind energy conversion systems based on fuzzy logic control schemes in order to track wind turbine speed via cyclo-converter concept. In this paper, designed schemes were tested on real metrological data. *M. M. Prats et al.,* [159], the author has introduced a fuzzy logic controller for extracting the optimal level of the wind speed and control of uncertain wind speed and blade pitch wind turbine. In this paper the main goal of authors, replacing linear control of fuzzy logic in order to improve the speed control and to extract the power of the MADE AE-52 wind turbine model. It is noted from the outcomes of proposed fuzzy design that the fuzzy controller performance can improve the performance at low, rated and maximum wind turbine speed by using authentic 800kW wind turbine system. Referring to [160], proposed a fuzzy state closed loop and fuzzy observer techniques are used together to resolve the practical issues of regulating the constraints of wind energy conversion systems. The authors employed a Takagi-Sugeno fuzzy system to improve the performance of the nonlinear wind turbine system model to guarantee the fuzzy controller performance. Furthermore, this concept is quite simple and more accurate than the conventional one. It is shown that this proposed controller can reduce the disturbance, which usually occurs in wind turbine systems owing to the uncertain wind speed conditions based on Linear Matrix Inequality approaches. Furthermore, referring to [161], authors designed a fuzzy controller based on H-infinity ways using bilinear matrix inequalities (BMIs). In this class of controller, it reduces the two-step method of LMIs which can be evaluated efficiently by using convex optimization concept. Finally, authors rejected previous concepts as discussed in [160]. However, in order to prevent the wind turbine system, constructing models referring to [162-164], designed a fuzzy logic controller for below and above the rated wind speed. The original controller has two input signals for capturing at an optimal wind power level such as error between tip speed and actual tip speed ratio, the derivative of this error, and one output of the generator voltage. The second controller, which operates in stabilizing output power, has the exact same dynamic structure. However, in this case, the error is between the assessed and actual output power, and the output is the pitch angle of wind turbine blades. Both authors designed controllers for maximum power point level tracking slightest disturbances of generator speed and output power. Besides that, *C. Amendola et al.,* [165] introduced a same fuzzy controller design like [162-164], except one of the input signals of the fuzzy controllers, is the discrepancy of the error signal instead, and the fuzzy controller traces the turbine reference rotational speed. Furthermore, the author's main aim is to control the power flow between the wind turbine generator and the power grid. At the same time referring to [166], authors proposed a same fuzzy controller like [165], but designed two controllers for two power electronic topologies in order to control the active power and balance it between DC-link and the power grid. Furthermore, an efficient and effective control system is necessary for maximum capturing wind power from wind energy conversion systems. As referring to [167], the authors proposed effective fuzzy control strategy techniques based on Takagi-Sugeno-Kang (TSK) in order to obtain the optimal wind power level. In the same way, in order to estimate the optimal power point tracking techniques, a fuzzy logic combines with Hill Climbing Searching (HCS) controller for variable wind energy conversion system to maintain the DC-link voltage at DC reference voltage consequent from the HCS maximization proposed by authors *Q. L. Zeng et al.,* [168]. In this paper, the proposed controller is not obliged to have physical dimensions of angular rotor and wind turbine speed. Finally, it is concluded that the authors demonstrated the MPPT technique in order to validate the operational performance through both field and simulation tests without wind turbine speed detection. Referring to [169], presented a fuzzy controller for an induction machine based on the wind turbine system in order to monitor the active and reactive power. In these methods, the voltage regulations have been obtained while compensating the static capacitor banks. A pitch angle is set to obtain an effective performance as uncertain wind speed conditions. Similarly, *L. Jerbi et al.,* [170], proposed a wind energy conversion system based on a doubly-fed generator at uncertain wind speed. In this way, the author's study and design a fuzzy logic controller to control the rotor side through the converter and improve the performance of active and reactive power through flywheel storage techniques. As consulting to [171], proposed and devised a fuzzy logic controller based on master slave concept for maximum power point tracking approaches for wind turbine systems. A master-slave fuzzy controller is in charge of sensing an uncertain wind speed, and later producing optimal rotational speed routes. Afterward the system is governed by a master-slave fuzzy logic controller in order to track the generated maximum angular speed. In the same way, *X. Yunqi et al.,* [172] introduced a similar technique like [171], except master-slave technique. Furthermore, it also minimizes the reactive power, as the system reaches at steady state circumstances in order to estimate the minimum reactive power reference points. Talking about [173], authors deliberately implemented the Tagaki-Sugino (TS) fuzzy logic controller for the dynamic power and DC link voltage control of DFIG based on wind energy conversion system. In this paper, the proposed controller has better and effective performance regarding fault-ride-through potential than the conventional PI controllers. This oscillation not only minimizes the mechanical stresses on the rotor side converter and grid-side-converter, but it would need to be able to employ a suitable designing protection system for the secure operation of a wind turbine system based on a doubly fed induction machine. Consulting [174-175], introduced a fuzzy logic controller in stabilizing wind energy systems. Exacting in [174], comparative study on two fuzzy controllers and deduced that the superconductivity magnetic energy storage (SMES) and pitch systems have capabilities to become stable under overall 3-phase-ground fault. It is noteworthy from the outcomes that the controllers can protect the systems during fault conditions. The SMES based controllers have more effective performance than the fuzzy logic control pitch. *Z. Huo et al.,* [175]; used fuzzy logic controller based on Quasi-Tagaki-Sugino (QTS) for wind energy systems while taking uncertain constraints into account. In this paper, based on parallel distribution compensation methods, a fuzzy logic controller concept was synthesized, and it was proven to stabilize the TS fuzzy controller functions. *B. Farid et al.,* [176], studied the overall operation of the wind turbine generator to provide an indefinite and constant power to the end users. In this paper, a Flywheel Energy Storage System (FESS) technique based on power electronics topologies was implemented. The FESS is used for control by a reference power obtained as a function of the generated power and sent to end network. Referring to [177], studied fuzzy logic controller based on DSTATCOM concept, in this approach DSTATCOM enhances the load voltage through VAR compensation leading to the results that the overall power factor improved damping of inductive type load. Furthermore, the proposed control theory concept based on instantaneous power balance and precise voltage control, and results conducted using simulation software MATLAB. *A. Boukadoum et al.,* [178], proposed a wind turbine system is built on DFIG and power electronic topologies an associated RL-load, in these approaches the authors' main goal is to make exact output waveforms like input. In this way, a conventional pulse width modulation and venturing techniques with fuzzy logic control approaches can be used for controlling the matrix converter. Notice towards outcomes is to restrain the total harmonic disturbances. Referring to [179], focuses on variable wind speed control schemes for grid coupled with a wind turbine system using permanent magnet machines with optimal power point tracking conditions. In this article, a fuzzy logic control concept via back-back pulse width modulation static voltage compensator methods employs for optimal power conditions. In this approach, two controllers were introduced, in which one for optimal power tracking known as generator side converter controller and other active and reactive power controller has been achieved by adjusting dq-axis current constraints respectively, known as grid side converter controller. Referring to [180], a fuzzy logic based controller is introduced for variable wind turbine speed for doubly-fed induction machines. In these techniques, the author's main goal is to extract maximum power at maximum rotor speed. It is observed from the results that proposed conceptual design for the fuzzy logic system is much effective and results in higher performance than the conventional strategy. Referring to [181], the authors proposed a wind turbine system with permanent magnet synchronous machine (PMSM) connected with separate load through a boost converter/inverter. PMSM output constraints such as electrical frequency and voltage are varied due to uncertainty of wind speed. This means a fuzzy logic controller is designed to maintain a DC link voltage at constant. Finally, the authors claim that the fuzzy controller performance has a significant advantage than the other practices.

5 Literature review trend investigation

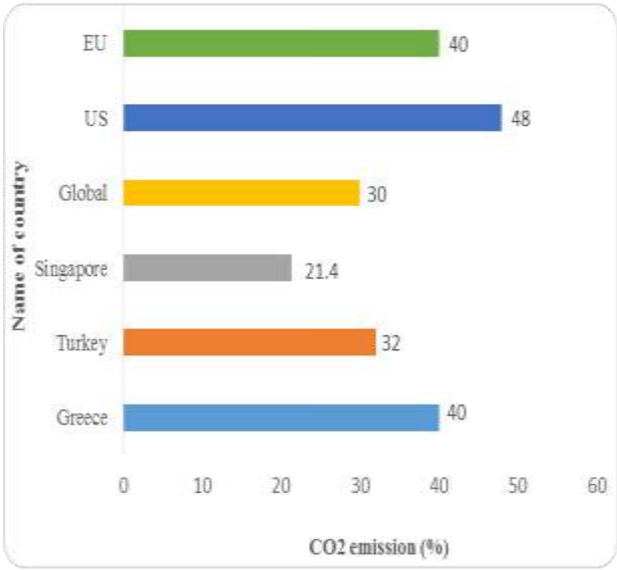
According to the collected literature in Table 1, the graphical review trend investigation is illustrated in Fig. 3. Numerous research authors use various constraints, techniques, concepts, algorithms with the different control strategy. Consequently, all mentioned literature study was not the same thing for all the section figures of Fig. 3. The notable enhancement in the area featuring controller design techniques has been observed in a wind energy conversion system for over a decade. Controller design techniques have been the main objective for our survey: whereas other objectives in terms of controller algorithm, tools, type of machines and MPPT techniques. The major controller was employed Fuzzy logic that was found at 28 % in the literature. Sliding mode constituted 15 %, Adaptive was at 11 %, Robust and Neural Network both were at 9 % only as illustrated in Fig. 3 (a). However, the remaining controller techniques, like PI, PID, Predictive, and Optimal control strategies have converted obsolete. Fuzzy and sliding mode controller becomes more popular among scientists and researchers due to their capabilities. The controller algorithm techniques which have been employed in controller design are shown in Fig. 3 (b) in which H-infinity become more popular than others and is getting the attention of scientists/ researchers. Whereas tools used for simulation purpose of wind energy conversion systems in an algorithm is Matlab at 72%, and others are depicted in Fig. 3 (c). The types of the machine were employed for the wind energy conversion systems in which. PMSG was found at 42% in the literature, and the remaining is depicted in Fig. 3 (d). Countries publishing their research with journals and conferences are shown in Fig. 3 (e) and Fig. 3 (f) respectively, which focuses the researchers have targeted research objectives with wind turbine energy conversion systems. However, according the literature survey. Fig. 3 (g) illustrated the publication timeline for the journals/conferences. Wind energy control sectors encountered in the literature survey constituted 74% of the MPPT (maximum power point tracking) and 26% of the others such as stability as shown in Fig. 3 (h).

Table 1. Short survey of the work that focused on wind energy conversion system controller design techniques.

S. #	Ref	Year	Controller Techniques	Controller Algorithms	Type of Machines	Tools	MPPT	Journals	Conferences
1	[82]	1981	PID	FA	-	ACS	-		IEEE
2	[83]	1991	PI	FA	SEIG	Hardware	-		ACC
3	[84]	2003	PID	FA	SG	MATLAB	√		ICEMS
4	[87]	2008	Predictive	NMPC	-	Hardware	-		IEEE
5	[96]	1999	Adaptive	Z-function (Gaussian)	WRIG	MATLAB	-	IEEE	
6	[97]	2008	PID	LPV	DOIG	-	-	-	-
7	[98]	2004	PID	NN RASPI	DOIG	-	√		IEEE
8	[99]	2008	Adaptive	HCS	PMSG	PSIM / C++	√		IEEE
9	[100]	2008	Adaptive	HCS	PMSG	PSIM	√		IEEE
10	[101]	2008	Adaptive	HCS	PMRG	FPGA/ Experimental	√		IEEE
11	[102]	2011	Adaptive	HCS	PMSG	MATLAB	√		ICME
12	[103]	2014	Adaptive	RCNN	DOIG	MATLAB	√	IJTPE	
13	[104]	1999	Robust	FL	IG	-	-		IEEE

14	[105]	2001	-	H-∞	-	MATLAB	√		IEEE
15	[106]	2003	-	H-∞	-	MATLAB	√		IEEE
16	[107]	2005	Optimal	H-∞ & H-2	-	-	√		IEEE
17	[108]	2011-12	-	H-∞	DFIG	MATLAB	-	CJSSM	
18	[114]	2009	Robust	H-2	-	MATLAB	-		SUPERGEN
19	[115]	2007	Robust	LPV	DFIG	MATLAB	√		European
20	[116]	2009	Sliding	KF	IG	MATLAB	-		UPEC
21	[117]	2010	PI	LPV		MATLAB	√		ICNSC
22	[118]	2010	Robust	H-∞	PMSG	MATLAB	√		IEEE
23	[120]	2015	Robust/PID	DK-Iteration	-	MATLAB	√	EJ	
24	[124]	2007	Optimal	FFT	SCIG	MATLAB	√		CC-EUROCON
25	[125]	2008	PI	VCPWM	PMSG	MATLAB	√	IEEE	
26	[127]	2008	Optimal	LQ	-	-	√		MCCA
27	[129]	2012	-	HCC/VC	PMSG	MATLAB	√	IJRSE	
28	[131]	2015	-	BC	PMSG	MATLAB	√	IJIREEICE	
29	[132]	2012	PI	DDBC	PMSG	MATLAB	√		ICRERA
30	[135]	2000	Sliding	FA	DOIG	-	√	IEEE	
31	[136]	1999	Optimal	IVS/VSI	IG	-	√		IEEE
32	[137]	2004	Sliding	DGA	PMSG	Computer/ Simulation	-	IEEE	
33	[138]	2007	Robust	Lyponov	BDFRG	MATLAB	√	IEEE	
34	[139]	2007	Sliding	MC & SFOC	DFIG	-	√		PEEED
35	[144]	2009	Sliding	HOSM	PMSG	Experimental	√		IEEE
36	[146]	2011	Sliding	FOC-PI	PMSG	Hardware	√		IEEE
37	[148]	2013	Sliding	Z-SI	PMSG	MATLAB	√	IJEST	
38	[149]	2014	Sliding	Lyponov	PMSG	Experimental	√	Energies	
39	[151]	2005	NN	ANN & DSP or Microprocessor	PMSG	Experimental / MATLAB	√	IEEE	
40	[153]	2009	NN	JR-CANN	PMSG	MATLAB	√	IEEE	
41	[155]	2014	NN	DSPANN	PMSG	MATLAB	√	TJEECS	
42	[156]	2014	NN	QNN	PMSG	MATLAB	√	EJ	
43	[157]	2015	NN	MPNN	DFIG	MATLAB	√	IETE	
44	[158]	2001	Fuzzy	CC	SG	MATLAB	√	RE	
45	[160]	2006	Fuzzy	FOFC	SEIG	MATLAB	√		IEEE
46	[161]	2007	Fuzzy	LMI & H-∞ BMI	-	-	-	IET	
47	[165]	2007	Fuzzy	FOC	DFIG	MATLAB	√		ICISDA
48	[166]	2006	Fuzzy	VSC	SCIG	-	-		ICECE
49	[170]	2009	Fuzzy	FESS	DFIG	MATLAB	√	EPSR	
50	[171]	2010	Fuzzy	MSFL	PMSG	PSIM	√		INTELEC
51	[172]	2010	Fuzzy	PI	DFIG	MATLAB	√		IEEE
52	[173]	2009	Fuzzy	TS-F	DFIG	MATLAB	-		IEEE
53	[175]	2009	Fuzzy	QTS/LMI	SCIG	-	-		SUPERGEN
54	[176]	2012	Fuzzy	FESS	SCIG	-	√	IJRER	
55	[177]	2012	Fuzzy	DSTATCOM	SCIG	MATLAB	√		IEEE
56	[178]	2013	Fuzzy	PWM & Venturing	DFIG	MATLAB	-	IJRES	

57	[179]	2013	Fuzzy	BB-PWM VSC	PMSG	MATLAB / PSIM	√	IJRER
58	[181]	2015	Fuzzy	BIC PWM	PMSG	MATLAB	√	IJIRSET



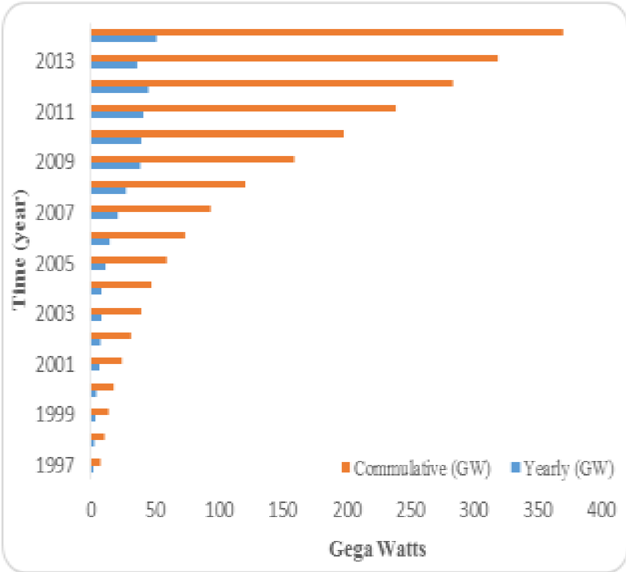
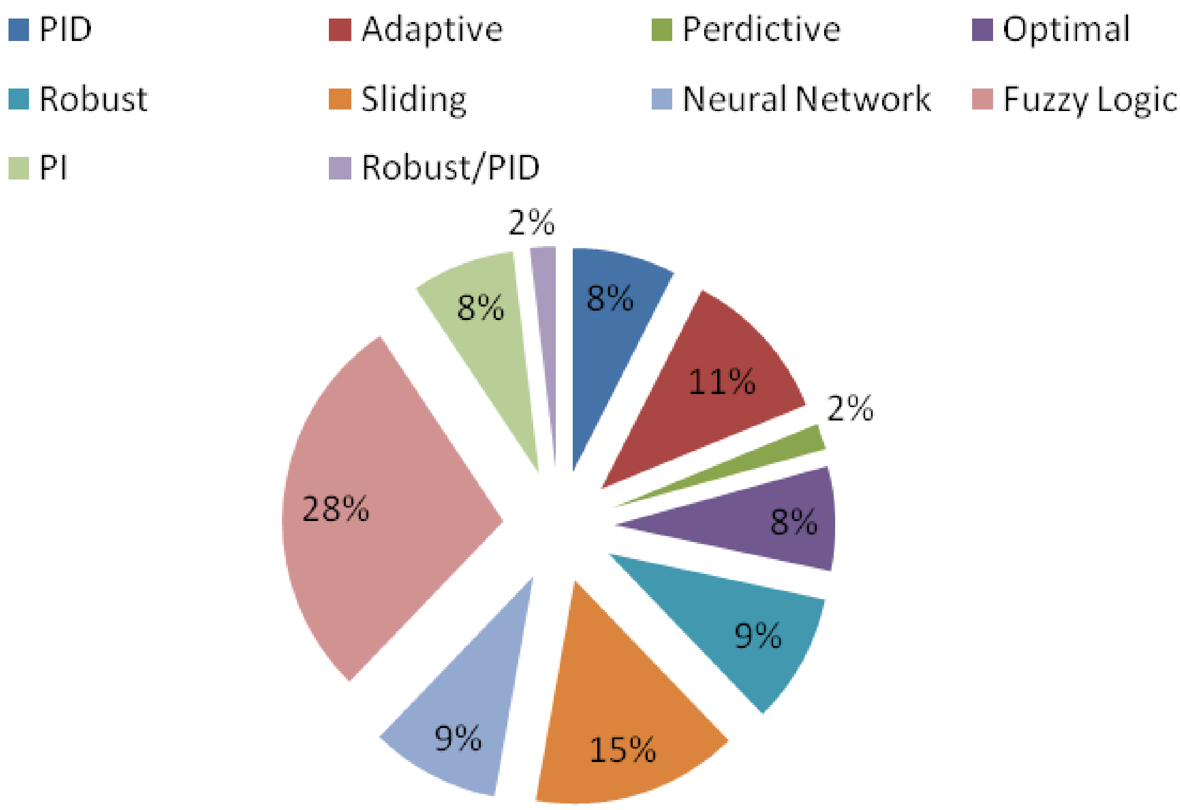
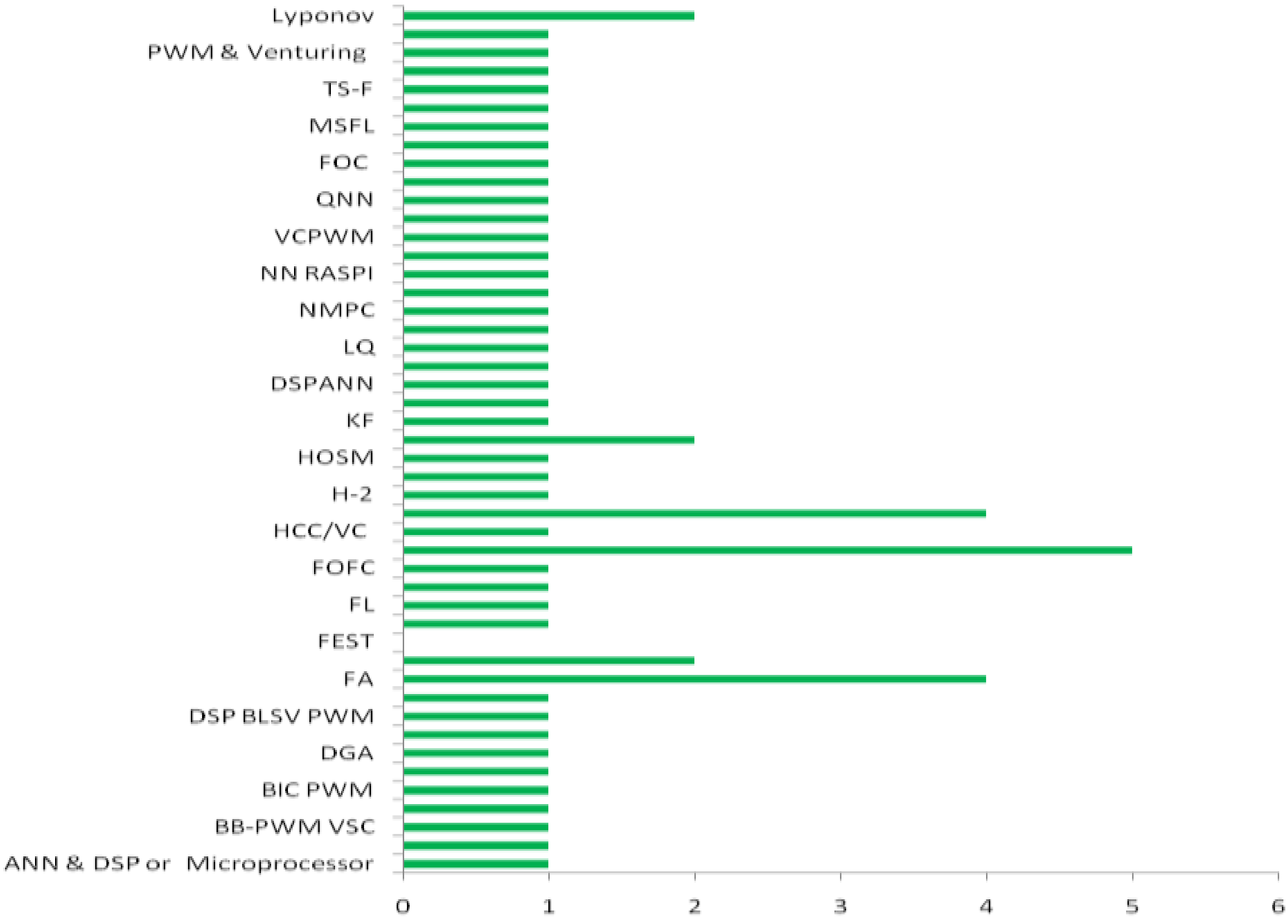


Fig 1. CO_2 emission (%) of selected countries and world [14-24]. **Fig 2.** Global, yearly and cumulative WT installation



(a)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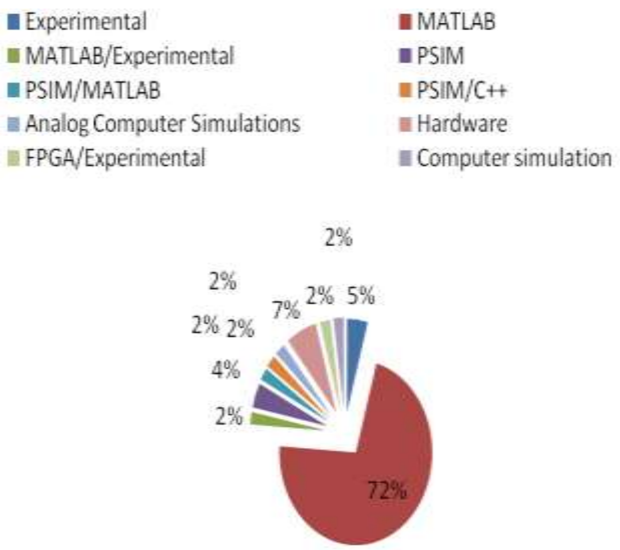
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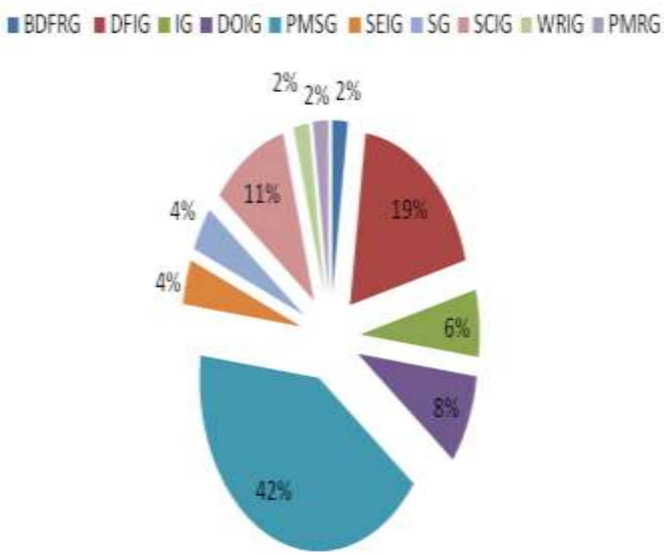
(c)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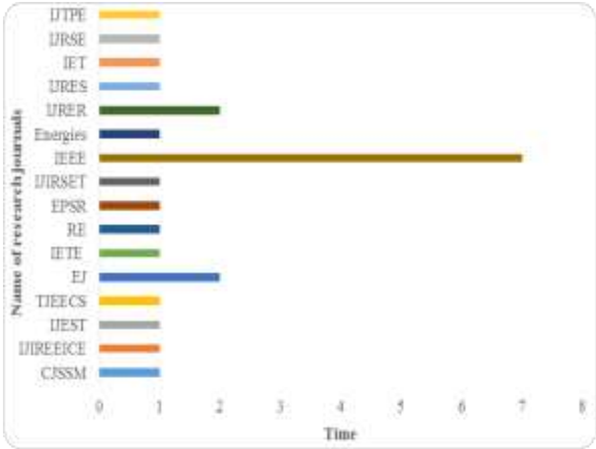
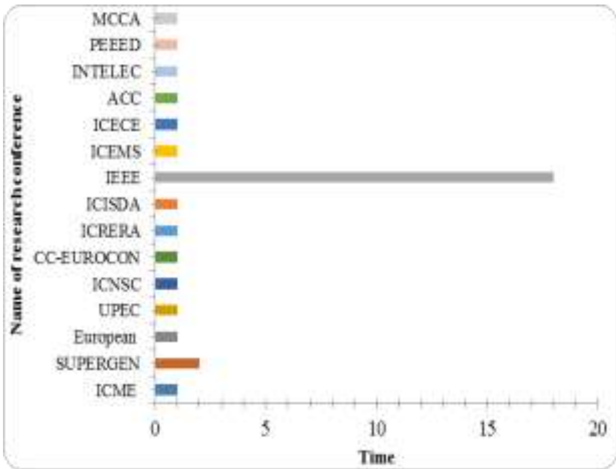
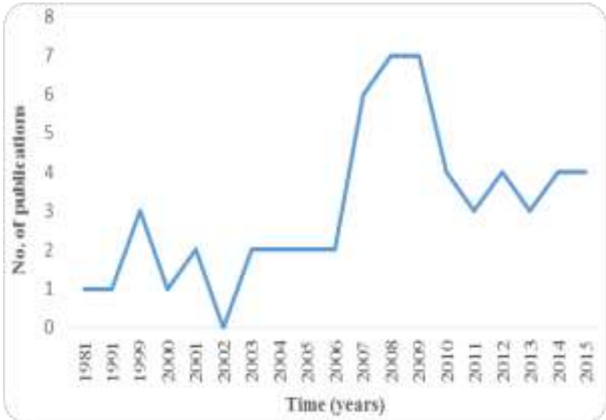


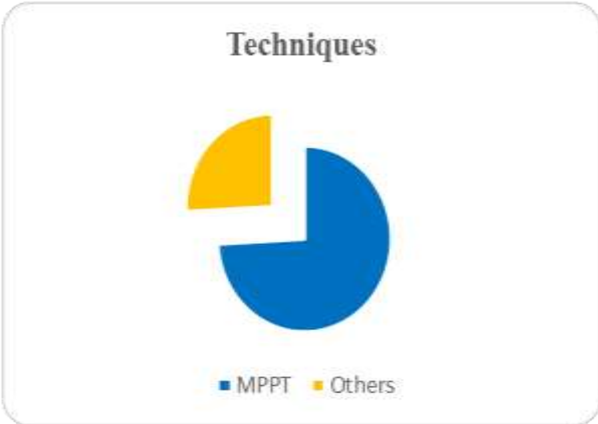
(e)



(f)



(g)



(h)

Fig 3. Short summary of the compiled research work (a) Controller design techniques. (b) Controller algorithms trends. (c) Simulation software tool trends. (d) Types of generator. (e) Journal timelines. (f) Conference timelines. (g) Publication timeline. (h) Techniques.

6 Conclusion survey findings and future prospective

Generally, global power demand is increasing day-by-day due to the rapid population growth. Renewable resources such as wind energy must be enhanced in order to fulfill the energy demand because it's clean and free of cost source with high global potential. This short survey brings the attention to the scientists, researchers and experts in the cost function optimization and control techniques of wind energy conversion systems. At present, it confirms that most of developed and developing regions are working to devise efficient and reliable control techniques for wind energy conversion systems. There has grown up to be an increasing trend towards wind turbine control systems and optimization approaches. Furthermore, various intelligent control systems have been added with frequent algorithms in order to maximize the efficiency of wind energy conversion systems due to unreliable wind conditions. This brief review of the state of art focuses on the control of wind energy conversion system techniques such as proportional integral derivatives (PID), predictive, adaptive, robust, optimal, sliding mode, neural network, and fuzzy logic. The review, in terms of all control strategies, indicated that the sliding mode controller design technique is more reliable, useful, accurate, and has the speedy action against wind turbine system disturbances. Furthermore, in recent times soft controller techniques such as: neural network, fuzzy logic, and genetic algorithms have significantly grown owing to their most attractive characteristics of nonlinear classification and control. Finally, it was investigated that above discussed controller concepts for wind energy conversion systems make it possible to exploit the greatest features of both hard and soft control methods.

Several parts acknowledged for the future prospects of wind energy conversion system are described as follows:

- More appropriate and precise physics base self-motivated, dynamic form of both constraints such as: lumped and distributed to existing future wind energy conversion systems.
- Most important future development of the research study must consist a prerequisite of the effective control strategy approaches for the evaluation of wind energy conversion systems.
- More significantly, various control systems should be developed for predicting the energy demands.
- More advanced controller techniques for robust, adaptive, optimal, analytical model, complex model, and with industry standard embedded

flexible control system for the integration of wind turbine systems.

- Various up-to-date controller algorithms are known as software based techniques such as fuzzy logic, genetic logic algorithm, computer programming, artificial neural network (ANN), and hybrid techniques, etc. probabilistic interpretation and much more need to be future research objectives.
- More advanced software tools for sculpting, drawing, development, analysis, testing and justification of the abilities and modularity of a wind energy conversion system integrated with AC-grid and the internet.
- Keeping in view, it is concluded that, all research study stated above needs to focus on the
- Significant concerns such as safety, cyber security, minimum cost, feasibility, compliance, and monitoring should be an objective for further research and analysis.

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