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ORIGINAL RESEARCH ARTICLE

Design analysis of intelligent controller to minimize harmonic distortion and power loss of wind energy conversion system (grid connected)

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ABSTRACT

The controlling of internal parametric variations in addition to the non-linearity of a large conversion system of wind energy (WECS) is prime challenges to make the most of the generated energy, with less power loss and secure the proficiency (η) integration conventional grid. An adjustable speed control structure of grid-connected conversion system of wind energy (WECS), with the help of a Permanent Magnet Type Synchronous Generator with intelligent controller minimizes the power loss. The control system incorporates a pair of controllers dedicated to the converters of both the generator and grid edge. The controller at the generator side has the main function is to optimize power that can be withdrawal from the wind by intelligently regulating the turbine's rotational speed. Meanwhile, the grid edge converter effectively manages active and reactive power by manipulating the d & q-axis current components, respectively. This paper discusses about the improvement in performance of the system when using Neuro-Fuzzy system as compared to Neural Network and Management of energy deliver system via direct control method. The findings reveal that the training time for Artificial Neural Networks (ANNs) is substantial, leading to the Neural Network-Direct Power Contol (NN-DPC) approach being the slowest option among the alternatives. Additionally, the NF-DPC system is less time-consuming than the NN-DPC, with a recorded duration of 24 seconds compared to the NN-DPC's observation of 8 min and 5 s. However, it is worth noting that the NF-DPC system is somewhat more time-intensive than Common-Direct Power Contol (C-DPC).

Keywords: wind energy conversion system (WECS); Permanent Magnet Type Synchronous Generator (PMSG) Neuro-fuzzy (NF); Neural Network (NN); Artificial Neural Networks (ANNs)

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1. Introduction

Review of controller design for Permanent Magnet Type Synchronous Generator (PMSG) based wind generator Permanent Magnet Type Synchronous Generator having variable speed Wind Turbine system (PMSG-VSWT) is premeditated to reach the maximum aerodynamic efficiency to produce maximum power and increase energy with nominal capture of wind. It will also decrease the mechanical stress which arise at the wind turbine system[1,2]. The power source can be unswervingly driven through a wind turbine without gear transmission system here, it may be with gear. Furthermore, the permanent magnet machines have flux linkage owing to large air gaps in between shaft and rotating part of the machine of wind energy conversion system. By which flux linkage reduces of the machine[3]. Nevertheless, such type of wind generator system has further byzantine controller system as compared to the different types. Here we are using filter circuit to reduce harmonics and make the system healthy.

The private sector is the main catalyst behind the surge in the Indian wind industry so far. However, the government's policy and financial support have provided the necessary impetus for the industry to take calculated risks, make progress, and attract investments across various states. When the 60 GW target was announced in 2015, the wind sector stepped up to the challenge of meeting it within the set timeframe. In 2016, a new record was set with the installation of over 3.6 GW of new capacity in a single year. According to the reporting timeline of the Indian fiscal year 2016–2017, the annual installations surpassed 5.4 GW by the end of March 2017, resulting a cumulative installed capacity that exceeds to 31 GW[4].

Some of the current issues related to harmonic distortion and power loss in grid-connected wind energy conversion systems are as follows:

(i) Harmonic Distortion: Wind turbines, being nonlinear power electronic devices, can introduce harmonic distortion into the electrical grid. This distortion can negatively impact the power quality by causing voltage and current waveforms to deviate from their ideal sinusoidal shape. It can lead to issues such as increased losses, reduced efficiency, interference with communication systems, and overheating of equipment.

(ii) Grid Synchronization: Maintaining proper synchronization between the wind turbine and the grid is vital for effectual power transfer. However, challenges emerge from the variable nature of wind energy, including fluctuations in wind speed and direction. Synchronization issues can result in power quality problems, including harmonics and voltage fluctuations, which can affect both the wind turbine and the grid.

(iii) Power Losses: Power losses occur at various stages in a wind energy conversion system. Conversion losses incurred during the energy conversion process from mechanical to electrical energy can reduce overall system efficiency. Additionally, transmission losses during power transmission from the wind turbine system to the grid can further contribute to energy losses. These losses not only decrease the overall power output but also impact the economic viability of wind energy systems.

(iv) Reactive Power Compensation: Wind turbines require reactive power compensation to uphold acceptable limits for power factor and voltage stability within acceptable limits. The fluctuation in the reactive power demand of wind turbines occurs due to variations in wind speed and load conditions. Inadequate compensation can result in voltage drops, increased losses, and reduced power quality.

(v) Control and Monitoring: The complex control and monitoring requirements of grid-connected wind energy systems pose technical challenges. Effective control algorithms are necessary to ensure optimal power generation, synchronization, and grid integration. Monitoring systems are also crucial for early fault detection, maintenance, and remote operation of wind turbines. Developing robust control and monitoring techniques is crucial to tackle the challenges associated with harmonic distortion and power loss.

The field of conversion systems of wind energy is evolving, and there may be advancements and new solutions to address these issues beyond my current knowledge cut-off.

2. Permanent Magnet Synchronous Generator (PMSG) with variable speed wind turbine system (VSWTS) modelling systems

In this paper block diagram of control system for PMSG-with VSWTS is depicted through the simulation diagram in **Figure 1**. The PMSG with VSWTS is comprise of the components mentioned below:

1) Direct drive PMSG.

2) Two-level back-to-back converters which consist of converter on the machine edge.
3) Converter which is on the grid side.
4) A Circuit consisting DC-link circuit and a capacitor (C_{dc}).
5) Controller on the grid side.
6) Controller on the stator side.

It is very meaningful that the Converter on machine side is connected to the stator side of the Permanent Magnet Synchronous Generator (PMSG), so that it alters the 3 phase AC generated voltage by PMSG to DC voltage which is a fixed value. The three-phase Current sensor and the voltage sensor are coupled at one side of the stator terminal of PMS Generator. Tachometer is attached to measure the speed. So, for the speed of rotor of PMSG a tachometer is connected on the rotor side of wind turbine. It is directly measured in rpm.

The grid side controller establishes a connection with the grid via an Line Capacitor Line (LCL) filter, facilitated by a step-up transformer[5,6]. Sensors are installed on the grid side to monitor both the grid current and voltage. Alternatively, it can be stated that the sensors are connected to the converter side of the LCL filter which is at the grid side[7,8]. The constant value of the DC voltage (Vdc) is determined across the capacitor. The converter on the grid side utilizes a controlled reference voltage for modulation. These controllers are implemented specifically on the grid side[9].

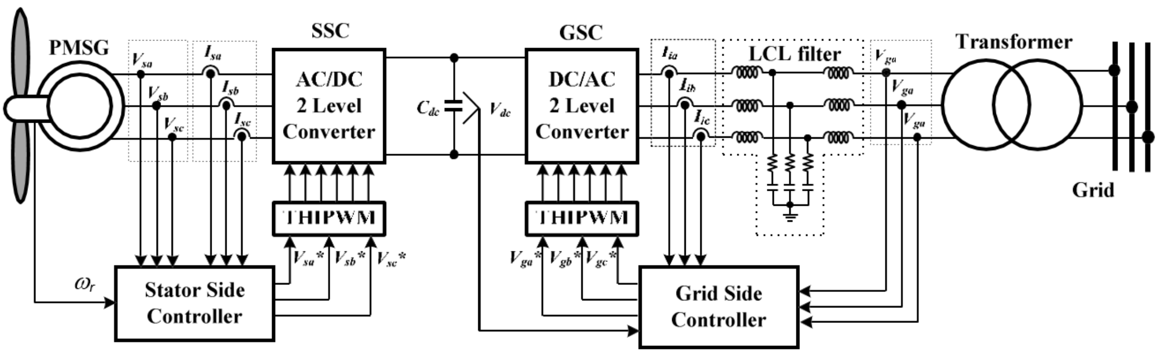

Figure 1. Model of VSWT-PMSG with control system.

Modulation technique is used here to reduce different harmonics, in this paper we use Third Harmonic Injection Pulse Wave Modulation (THIPWM) to do work[10]. With the help of utilizing the voltage reference in the output, ensuring avoidance of over modulation can be achieved by injecting the third harmonic and using it as a reference voltage. In contrast, the fundamental element of the output voltage can also be maximized with THIPWM[11].

The global installation of offshore wind has been gaining significance in driving the growth of the wind energy sector. In recent years, a new record was set with the installation of 6.1 GW of offshore wind, which accounted for a record-breaking 10 percent of new installations[12].

The speed of the rotor of the wind turbine system is represented by ω_r. In variable speed wind turbine system (VSWTS), measuring the rotor speed (ω_r) of a wind turbine enables the achievement of Maximum Power Point Tracking technique (MPPT). While accurately gauging the wind speed we can stance a challenge, it is still possible to determine the maximum power (MPPT) without directly measuring the wind speed. The reference power (Pref) is constrained solely by the generator’s rated power, serving as its limit.

$$P_{MPPT} = ½ (\rho\pi R^2) (\omega_r R/\lambda opt)^3 Cp_{opt} \quad (1)$$

3. Modelling of controller of VSWT-PMSG

3.1. Controller at machine side

Controller at machine side system (MSC) utilized in this system is shown in **Figure 2**. The main objective of the machine-edge controller is to control the active and reactive (both) power output of the PMSG. With the help of the d-q rotating reference frame, the current control loop is evaluated, and the rotor angle position (θr) is essential for the transformation between *a-b-c* and *d* & *q* variables is determined based on the generator's rotor speed. The *d*-axis current (Isd) is responsible for measuring the active power (Ps), whereas the *q*-axis current (Isq) is used to measure the reactive power (Qs) of the generator[13].

The MPPT technique of the wind turbine characteristic determines the value of the active power reference (Pref). The reactive power reference (Q_s*, Q = VI sinφ) is zero. To compensate for the cross-couplings of $I_{sd}\omega_e L_{sd}$ and $I_{sq}\omega_e L_{sq}$ at the output level, current controllers are employed, owing to the power factor being unity. In order to enhance the tracking capability, various techniques are implemented. The transfer function 1/(R + L_ss) represents the controller constraints in the *d*/*q* current loop, and the fine tuning of the gain of the PI controller is adjusted using the pole placement method to optimize its performance.

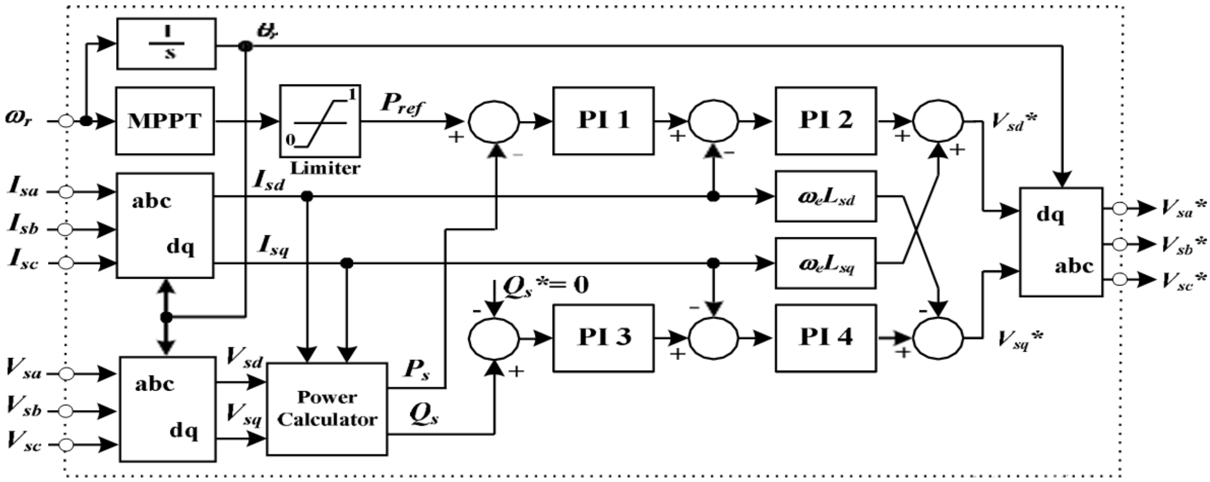

Figure 2. Stator side controller system.

3.2. Grid side controller

The design of the grid-side controller plays a crucial role in enhancing the performance of a VSWT-PMSG system connected to the grid. It leads to notable improvements in the output grid voltage and effectively reduces harmonics, resulting in enhanced system performance overall. Below are the objectives of controlling Voltage Source Converters (VSC),

1) Uphold the voltage of the DC link circuit.
2) The aim is to accomplish the exchange of reactive power with the grid system and sustain a power factor of unity[14] to achieve maximum AC power.

Figure 3 illustrates a block diagram depicting the grid-side control system. The implementation of the control strategy for this system we use *d-q* rotating reference frame, that can align its rotational speed with that of the grid voltage[15]. The *d-q* transformation is accomplished through the utilization of a Phase Locked Loop (PLL)[16]. By altering the grid voltages to the *d-q* reference frame from the existing stationary reference frame, a constant Vgd and zero Vgq are achieved. Consequently, the active power and reactive power transmitted to autonomously regulate the grid using the d-axis current (Iid) and q-axis current (Iiq), separately[17].

To enable active power exchange amongst the PMSG and the grid, the voltage of the DC-link capacitor (Vdc) is maintained at a fixed level[18]. As a result, the reference signal for the d-axis current (Iid*) is derived out of the DC voltage controller's output. Additionally, to reach unity power factor action, the reference signal for the q-axis current (Iiq*) is kept zero. To enhance the tracking ability of the control system, the term (scross-coupling) can be removed by integrating ωLtot into the output of the current controllers, where Ltot signifies the net series inductances of the filter along with the transformer. The output i.e., (current controller output) (Vgd* and Vgq*) is then transformed into the stationary reference frame (Vga*, Vgb*, Vgc*), which can aid the pulse width modulation of the reference signal.

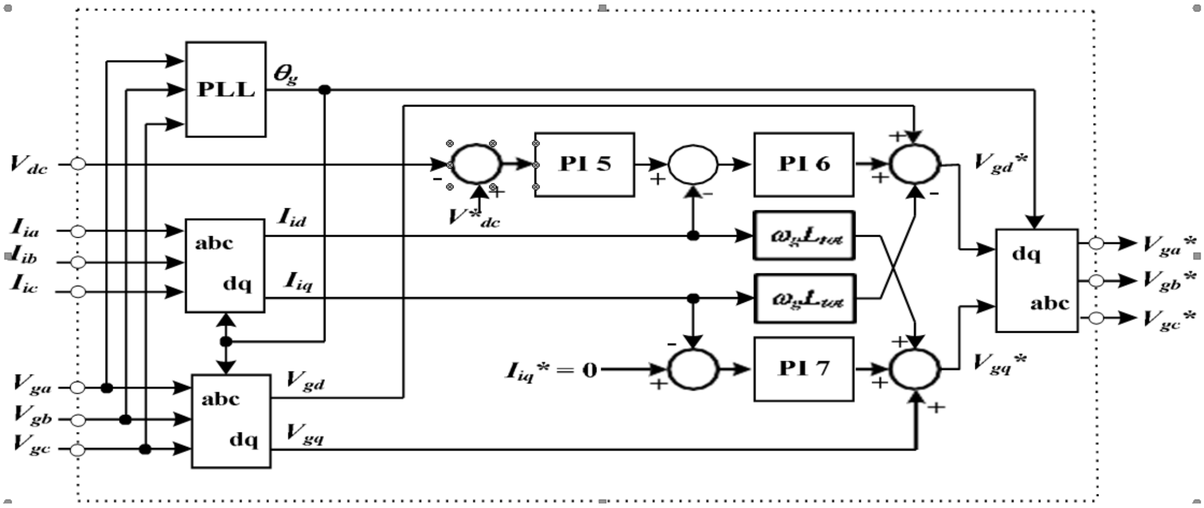

Figure 3. Grid side controller system.

The research indicates that injecting overexcited reactive power from the grid-side converter results in reduced annual energy losses when compared to the utilizing of the overexcited reactive power from the rotor-edge converter. Moreover, by optimizing the filter, the annual energy loss can be further reduced, resulting in increased energy production for the wind turbine[19]. In the study, the authors proposed method, which is based on the equivalent phase voltage, is more precise in comparison with the conventional H.C.C i.e., harmonic current calculation method that relies on the phase voltage[20].

4. Wind energy conversion system

Wind Energy Conversion System(WECS) consists of a three-phase (3-φ) PMSG. A Back To Back (BTB) Converter is also coupled with the PMSG and grid. System is shown in **Figure 4**. The machine side converter (MSC) utilizes the model predictive control (MPC) to excerpt maximum power from wind by means of addition of the active power into the grid for unity power factor operation for the maximum power[21].

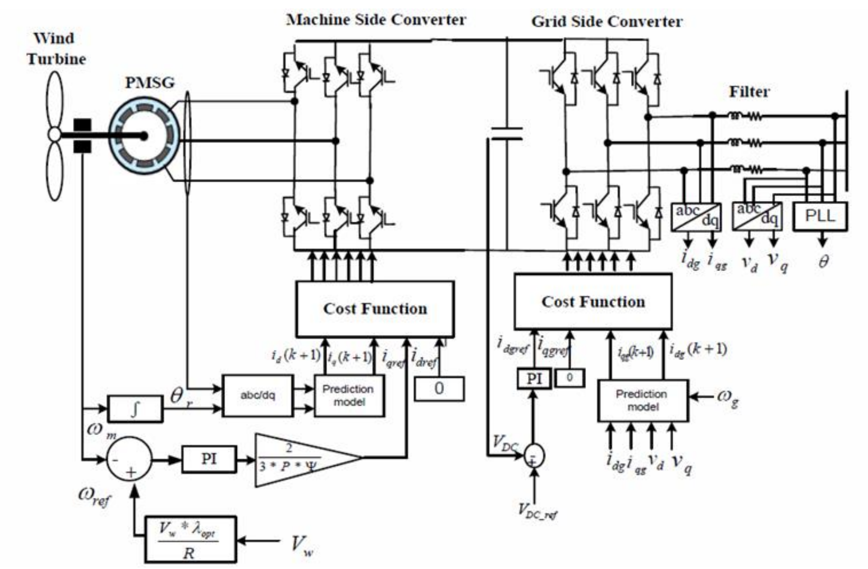

Figure 4. PMSG wind energy conversion system configuration.

When wind is harnessed by the turbine, the resulting mechanical power is transferred to the generator's rotor. For a variable speed wind turbine, the output mechanical power and torque can be mathematically expressed as follows:

$$P_m = 1/2\rho A C_p(\lambda, \beta)V^3_w \quad (2)$$

$$T_m = P_m/\omega_m \quad (3)$$

where:

ω_m: Turbine's Mechanical angular speed (in rad/s),

P_m: output power of Turbine (in Watts),

ρ: Density of Air (in kg/m^3),

A: Area swept through the turbine blades (in m^2),

T_m: Turbine's Mechanical torque (in Nm),

V_w: Wind velocity (in m/s),

C_p: Turbine power coefficient (dimensionless).

Turbine power coefficients: The given equation signifies the efficiency of power extraction of the wind turbine (WT), which is a non-linear function dependent on both the tip speed ratio (λ) and the blade pitch angle (β). The tip speed ratio (λ) is a parameter that quantifies the ratio between the linear speed of the blade tip and the rotational speed of the wind turbine (WT). It is defined by the following equation:

$$\lambda = (R/V_w).\omega_m \quad (4)$$

The equation for the coefficient of power (Cp) is dependent on various factors and can be represented by different equations. In this system, Cp is determined using Equations (5) and (6) as shown below:

$$C_p(\lambda, \beta) = C_1 (C_2/\lambda_1 - C_3\beta - C_4)\, e^{-C5/\lambda 1} + C_6\, \lambda \quad (5)$$

$$1/\lambda_1 = 1/(\lambda + 0.08\, \beta) - 0.035/\, (1 + \beta^2) \quad (6)$$

The relation between C_p and λ when β is equals to zero degree is shown in **Figure 5**.

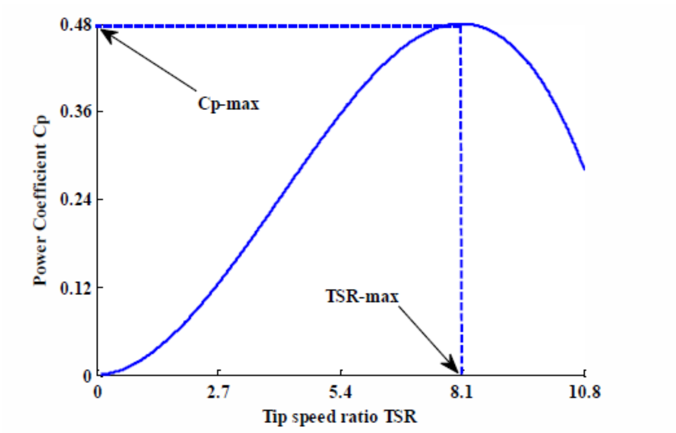

Figure 5. Power Coefficient (Cp) vs. Tip Speed Ratio (TSR/λ).

By implementing MPPT control, we can effectively harness the maximum wind energy to generate a higher amount of electrical energy. Alongside, we carefully utilize vector control. Our observations indicate that direct power regulation control is a straightforward implementation approach but not the most efficient one. Alternatively, in the indirect control, regulating the currents in contrast, it involves a slightly more intricate implementation. but ensures better adherence to instructions and optimal system performance[22,23]. In a related study[24], the author highlights the effectiveness of adaptive backstepping control in achieving high dynamic performance for tracking references, particularly in scenarios involving real wind profiles. Furthermore, this control method maintains optimal energy conversion and offers a practical solution addresses robustness and dynamics concerns within the structure of the Field-oriented control (FOC) command.

In order to address oscillations, the sequence domain control (SDC), which is an advanced control technique, is being assessed. This approach involves the implementation of separate regulators in the positive and negative sequence domains, leading to equilibrium of the dc link voltage during a disturbance. However, this method is slower compared to the conventional control. An alternative control technique called direct power control (DPC) is being investigated as well. DPC replaces the conventional current control loops with straightforward active and reactive power control variables, leading to stable regulation of both active and reactive power[25].

J.O.O. i.e., joint operations optimization technique was proposed for the determination of optimal Proportional integral derivative (PID) controller constraints in PMSG-based Wind Energy Conversion Systems (WECS). The objective of their study was to enhance the performance of Maximum Power Point Tracking (MPPT) for different wind speed profiles.

Application of grey wolf optimization to fine-tune the optimal gain of eight PI controllers. These controllers were employed the control of generator-side and grid-side converters, with the aim of enhancing Maximum Power Point Tracking (MPPT), Low Voltage Ride Through (LVRT) capability, and steady-state operation. The objective was to minimize the integral-squared error of real power, DC voltage, and terminal voltage errors in the grid and PMSG.

A novel Multilevel control strategy built on the Adaptive Neuro-Fuzzy Inference System-Genetic Algorithm (ANFIS-GA) for PMSG-based grid-connected Wind Energy Conversion Systems (WECS). The strategy involved utilizing the genetic algorithm to adapt the parameters of the ANFIS and regulate both the grid-side and generator-side converters.

In another study[26], Qais et al. proposed an optimal design of multi-Sugeno Fuzzy Logic Controllers (FLCs) via the whale optimization technique. The objective of this research was to augment the Fault Ride Through (FRT) capability of grid-connected PMSG-based Wind Energy Conversion Systems (WECS) under conditions of both unbalanced and balanced grid faults. A grasshopper optimization technique-based PI controller was proposed by Amin et al.[27] to improve transient stability performance of grid-connected PMSG-based WECS. The method of optimization is used with the integration of square error criterion as the objective function.

A novel transient search optimizer was achieve optimal design of PI controllers employed in generator-side and grid-side controllers, aiming to enhance the Low Voltage Ride Through (LVRT) capability in grid-connected Permanent Magnet Synchronous Generator (PMSG)-based Wind Energy Conversion Systems (WECS). The effectiveness of the proposed method was compared with a recent grey wolf optimization under various instabilities of the grid.

In their research[28], Amin et al. acquainted with a fusion control method combining the cuckoo search technique and grey wolf optimization for enhancing the dynamic stability of grid-connected PMSG-based Wind Energy Conversion Systems (WECS). An optimal PI controller was utilized for both the grid-side and generator-side converters with the objective of maximizing power extraction from the PMSG while maintaining unity Power Factor (PF).

In their study[29], Shutari et al. presented an innovative approach utilizing the sine cosine technique. Their objective was to determine the optimal proportional-integral (PI) gains for achieving maximum wind power extraction and enhancing the overall performance of Wind Energy Conversion Systems (WECS) in the face of random wind speed variations and severe grid disturbances. The proposed method focused on minimizing the cumulative integral squared errors of the 12 PI controllers employed in the control strategies concurrently.

5. Steps for implementation of Neural Network-Based Direct Power Control (NN-DPC) and Neuro fuzzy-Direct Power Control (NF-DPC) control of grid-connected wind energy conversion system

The methodology for implementing NN-DPC and NF-DPC control in a grid-connected wind energy conversion system to minimize harmonic distortion and power loss involves the following steps:

1) System modeling: Develop a mathematical model of the grid-connected wind energy conversion system, considering the dynamics of the wind turbine, generator, power electronics converters, and the grid. The model should accurately represent the system's behavior and interactions, including the harmonic distortion and power loss mechanisms.

2) Data collection: Collect real-world data of wind speed, wind turbine parameters, grid conditions, and system performance metrics. This data will be used for training and validation of the neural network models.

3) Neural network training: For NN-DPC, design and train a neural network model using the collected data. The neural network should be capable of mapping the input variables (e.g., wind speed, grid voltage) to the optimal control actions that minimize harmonic distortion and power loss. Use appropriate training algorithms and techniques to ensure the neural network learns the desired control behavior.

4) Neural Network-Based Direct Power Control (NN-DPC): Implement the trained neural network model in the control system architecture of the wind energy conversion system. The neural network takes the system's input variables as input and outputs the control signals for the power electronics converters. The control signals should be optimized to minimize harmonic distortion and power loss while ensuring stable and efficient operation.

5) NF-DPC design: Design the NF-DPC controller based on system modeling and analysis. Develop a control algorithm that utilizes a set of control rules based on fuzzy logic to determine the control actions of the power electronics converters. Define the fuzzy membership functions, rules, and inference mechanism based on system requirements and objectives of minimizing harmonic distortion and power loss.

6) NF-DPC implementation: Integrate the NF-DPC controller into the wind energy conversion system's control architecture. The fuzzy logic controller takes the system's input variables and applies the fuzzy rules to compute the control signals for the power electronics converters. The control signals should be optimized to minimize harmonic distortion and power loss while maintaining stable and efficient system operation.

7) Performance evaluation: Evaluate the performance of both NN-DPC and NF-DPC controllers by conducting simulation studies and/or experimental tests. Assess the system's ability to minimize harmonic distortion and power loss under various operating conditions, wind speed profiles, and grid conditions. Compare the performance of both controllers in terms of power quality, efficiency, and system stability.

8) Optimization and fine-tuning: Fine-tune the NN-DPC and NF-DPC controllers based on the performance evaluation results. Use optimization techniques, such as genetic algorithms or particle swarm optimization, to further optimize the control parameters and improve the control performance in minimizing harmonic distortion and power loss.

9) Validation and verification: Validate the optimized NN-DPC and NF-DPC controllers through extensive simulation studies and experimental tests. Verify their effectiveness in minimizing harmonic distortion and power loss under various operating scenarios and grid conditions.

10) Performance comparison: Compare the performance of the NN-DPC and NF-DPC controllers in terms of their ability to minimize harmonic distortion and power loss. Analyze their advantages, limitations, and trade-offs, considering factors such as computational complexity, robustness, and practical implementation considerations.

By following this methodology, we can develop and implement effective NN-DPC and NF-DPC control strategies for grid-connected wind energy conversion systems, aiming to minimize harmonic distortion and power loss while ensuring stable and efficient operation.

6. Artificial neural network

An Artificial Neural Network (ANN) is composed of interconnected units known as artificial neurons or perceptron's, which function similarly to the cells in the nervous system of vertebrates. A mathematical model is created, which is inspired by human behaviour and the functioning of the human brain. Each individual point of connection between two cells is called a weight and behaves as a synapse, which acts as the primary element of interaction between neurons.

Neural networks (ANNs) are composed of diverse architectures and multiple layers of interconnected neural units. The mathematical representation of a neuron in the *p*-th layer involves a summation of two variables, depicted as follows:

$$Y_j^p = \sum_i^{nl}.\,(W_{ji}{}^p + b_j{}^p) \tag{7}$$

The input vector, *Xi*, is attained either from the outputs of various neurons or from sensors. The synaptic weights of neuron *j* in layer p are represented by $W^p{}_{ji}$. Its primary role is to mimic the synaptic weights by assigning a weight to individually input neuron. The weights in the network can be adjusted through the learning process, and the bias input (*bj*) typically takes on the values of either +1 or −1. It allows for flexibility in the network by enabling the regulation of weights and biases during learning, which can alter the activation threshold of the neuron. A machine operates using a Multi-Layer Perceptron (MLP) network which includes multiple layers. The initial column serves as the input layer where sensors provide measures of various parameters. The neurons in the intermediate layer are hidden between the input and output layers.

The layers in the neural controller are arranged in a specific manner to cater to the requirements in a feed-forward fashion, devoid of any feedback connections or backward paths. The ultimate layer acts as the output layer, delivering the desired outputs.

The proposed MPPT neural controller takes the form of a static Multilayer Perceptron (MLP), with an architectural structure illustrated in **Figure 6**. This MLP comprises an input layer with neurons which indicates wind speed and mechanical speed, two hidden layers, and an output layer featuring a single neuron denoting the electromagnetic reference torque. The activation functions employed for the hidden layers are hyperbolic sigmoid neurons, as described by the equation, while a linear activation function is chosen for the output neuron[30].

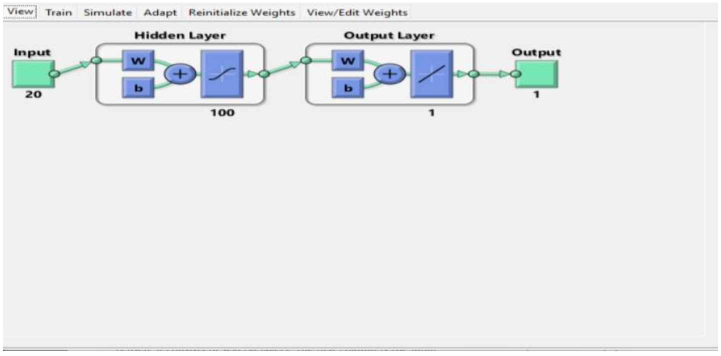

Figure 6. Structure of multilayer perceptron.

The amplitude of torque pulsation can approach its nominal value depending on the voltage imbalance level and the applied control strategy. In the event of a voltage imbalance condition, the torque signal's pulsation has a double frequency of the stator voltage. If not compensated, this pulsation could potentially cause mechanical and/or electrical harm to Doubly fed induction generator (DFIG)[31]. The optimization of wind energy efficiency is achieved through the application of Maximum Power Point Tracking (MPPT) system in addition with the pitch angle control, that are dependent on the operating zone of the wind turbine. The projected Enhanced direct power control (EDPC) strategy has been validated through simulation tests using Matrix Laboratory (MATALB)/Simulink, and the results indicate robustness and high performance, with low Total Harmonic Distortion (THD) of the generated currents[32]. In the study[33], the author has stated that the regulation of both rotor and grid side converters (RGSCs) is achieved through the combined Direct Torque Control-Field-Oriented Control (DTC-FOC) approach. The tasks of controlling the generator speed, torque, and rotor flux are assigned to Direct Torque Control (DTC), while Field-Oriented Control (FOC) is responsible for regulating the capacitor link voltage and maintaining power quality during Low Voltage Ride Through (LVRT) and Voltage Dip (VD) conditions. However, traditional linear controllers struggle to handle the nonlinearities present in the system dynamics over time. To address this limitation, Hybrid Maximum Power Point Tracking (MPPT) algorithms have emerged, offering the benefits of conventional methods while simultaneously overcoming their drawbacks[34].

Figure 7 depicts the training process for the Multilayer perceptron (MLP), which was accomplished using the Levenberg Marquardt algorithm. This algorithm was selected for its ability to facilitate fast convergence and its robustness properties[35]. The number of iterations was fixed at 1000 to reduce computation time, as observed during the preliminary examination. It was found that the use of additional iterations did not result in significant improvements in the results. As illustrated in **Figure 8**, the proposed structure rapidly converges to the optimal solution, with convergence occurring as early as the 8th iteration.

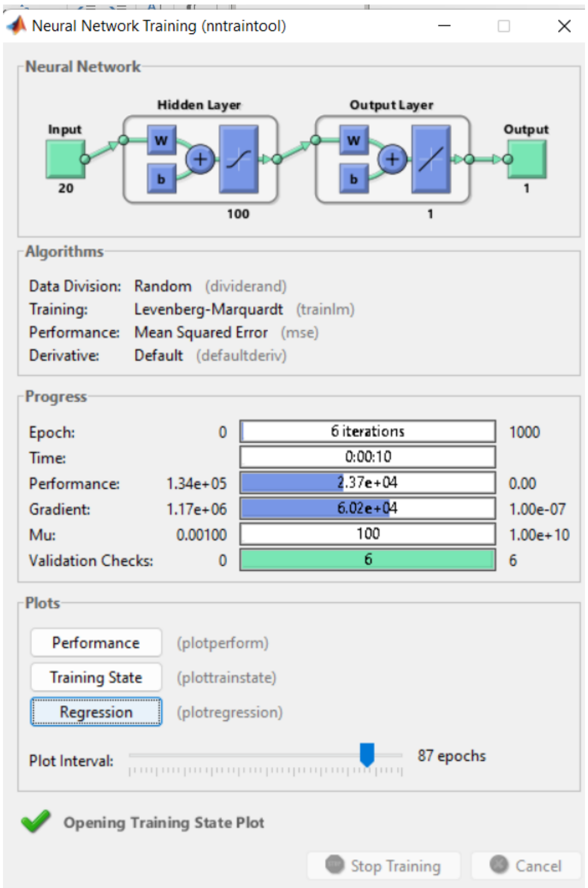

Figure 7. Training process of ANN.

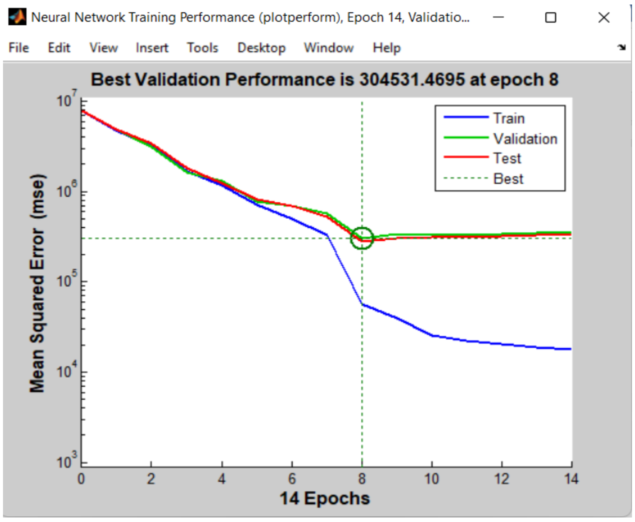

Figure 8. Performance curve.

7. Artificial Neuro-Fuzzy network

The ANN model, along with its values, was implemented using matrix laboratory (MATLAB)/Simulink. However, it was noted that the validation process using MATLAB's Neural Network Toolbox was not always effective, as it took a long time to complete. Instances were observed where the performance of the networks was in the order of 10^{-12}, yet the outcome still exhibited errors at the order of 10^{-5}. To enhance the efficiency of the wind energy conversion system, improve learning, and reduce the training time of the Simulink model, the solution has been redirected towards the exploration and enhancement of the Neuro-Fuzzy Network.

In this system, the regulation of the DC-link voltage is achieved by controlling the power flow to and from the battery bank through a bidirectional buck-boost converter. This converter ensures that the DC-link voltage remains at a constant reference value. Additionally, a dump load is incorporated to regulate the DC-link voltage by consuming excess power during periods of high wind conditions or when there is insufficient battery storage capacity[36]. Consequently, this arrangement enables the matching of the instantaneous three-phase resistive load demand with a constant voltage and frequency.

In this study, the MATLAB ANFIS Toolbox was employed to facilitate the determination of inputs, outputs, membership functions, efficiency, and fuzzy rules through matrix solving. The number of membership functions necessary for the fuzzification of inputs provided to the system was also calculated. Based on the Neuro-fuzzy network output, the system comprises a 6 × 1 matrix encompassing six inputs and one output. For each input, membership function members were assigned, and their corresponding numbers are provided in **Table 1** below:

Table 1. Membership functions for input signal.

S. No.	Particular	MFs member
1.	Temperature	4
2.	Humidity	3
3.	Sea level pressure	3
4.	Wind speed	4
5.	Wind direction	4
6.	Wind angle	4

Artificial neural networks were utilized to expedite the process of the system, improve efficiency, and enhance reliability, as ANN is capable of tracking the fuzzy rules introduced during the design stage. The ANFIS Toolbox from the library was used to construct and train the network. The proposed Neuro-Fuzzy network was trained using a hybrid optimization technique that combines the least squares method and the backpropagation gradient with data descent, as shown in the **Figure 9**.

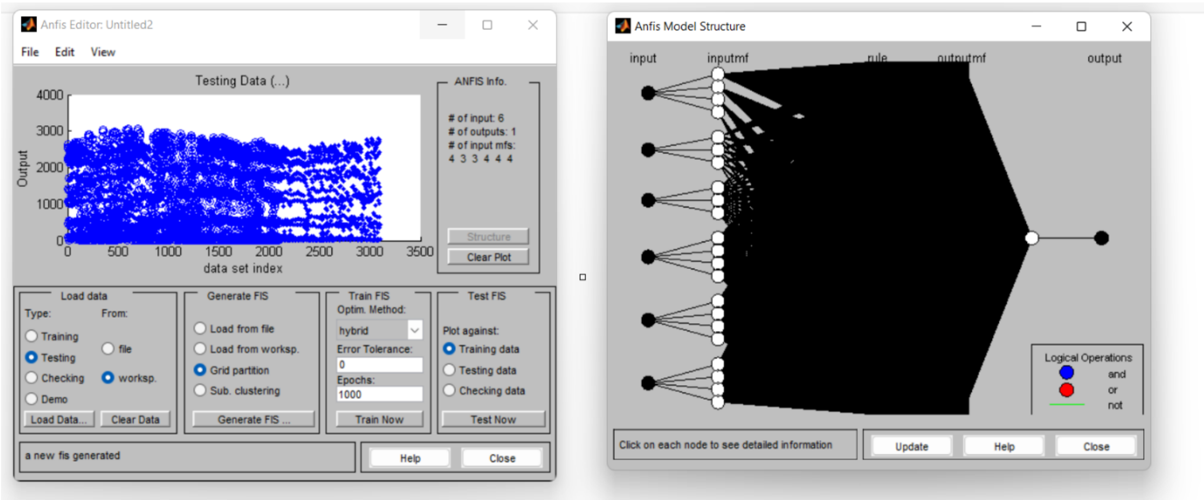

Figure 9. Structure of ANFIS system.

Historical data from the wind energy conversion system and the grid was utilized to train the ANFIS and establish the relationships between variables that impact power loss, including wind speed, angle, direction, temperature, pressure, humidity, etc. This enables the ANFIS to predict the ideal control settings for the system in real-time to minimize power loss.

The ANFIS system's fuzzy logic module is employed to make decisions based on ambiguous information, which is a prevalent occurrence in real-world systems. As a result, the neural network component enables the system to learn from experience and adapt its decisions based on new information[37].

We use this in adaptive DPC to obtain that as compared to other controls, (ADPC) results in lower power ripples and harmonic content in stator current[38].

Numerical simulation techniques are preferred for simulation tools such as Power electronics and motor drive simulations (Power-sim) (PSIM) and Simulink are widely used for modelling complex electrical power and power electronics-based systems. These tools offer flexibility, high processing rates, and the capability to parallelize numerical integration computations[39,40]. In the case of modelling a Wind Energy Conversion System (WECS), the power circuit is represented in PSIM, which includes the wind turbine connected to the utility grid through a back-to-back bidirectional PWM converter. The complete system control, encompassing both the generator side controller and the grid side controller, is executed using Simulink[41].

8. Result and conclusion

To minimize harmonics, a simulation-based module utilizing SIMULINK is proposed for the Wind Energy Conversion System (WECS). The WECS's power circuit is housed within the PMSG, while the control circuit is contained within MATLAB/SIMULINK. The integration between PMSG and SIMULINK is used to model the WECS, enabling the integrated system to be easily modified for future use. The interconnection of PMSG and SIMULINK also improves the simulation process in terms of speed and efficiency. The WT is connected to the grid through a back-to-back PWM-VSC. **Figure 10** below displays the regression plot for NN WES.

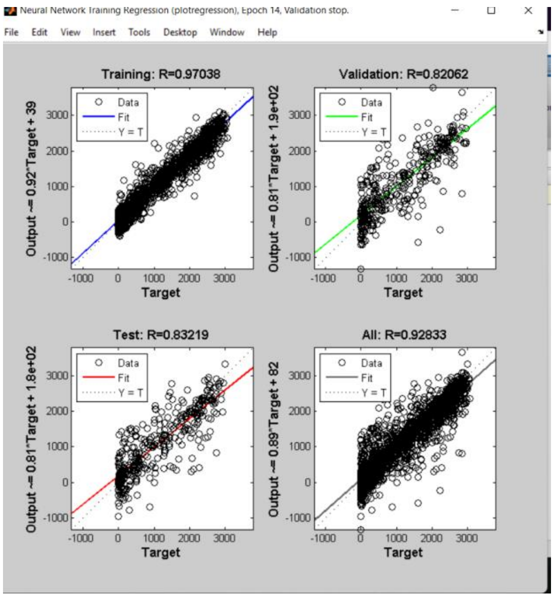

Figure 10. Regression plot for the NN system.

The SIMULINK model includes both the generator side controller and the grid side controller. The main objective of the generator side controller is to optimize power extraction from the wind by regulating the rotational speed of the turbine using the ANFIS controller. Therefore, the proposed algorithm for maximizing the output power of a grid-connected wind power generation system with a Permanent Magnet Synchronous Generator (PMSG) has been successfully implemented.

To assess the effectiveness of the proposed DPC in a Wind Turbine-Doubly fed induction generator (WT-DFIG) system, the wind speed is varied across a broad range (6–14 m/s) to accommodate various mechanical speeds, and the efficiency and harmonic reduction performance are evaluated. **Table 2** displays the three operating modes of the DFIG that can be achieved by varying the wind speed. These modes include the sub synchronous mode, super synchronous mode, and synchronous mode, which cover a wide range of mechanical speeds.

Table 2. Comparison between the control strategies.

Performance		Different types of operating modes		
		Sub synchronous mode of machine	Super synchronous mode of machine	Synchronous mode of machine
THD	DPC	8.87	6.72	6.69
	NN-DPC	2.91	2.49	2.19
	NF-DPC	2.72	2.31	2.08

The primary aim of the DPC control is to maintain the generated true power ($P = VI\cos\varphi$) equal to the power delivered by the wind turbine, while compensating for the reactive power ($P = VI\sin\varphi$). The reactive power compensation is accomplished through the use of a capacitor bank at the receiving end, with consideration given to the grid's demand.

The proposed methods for controlling the global system model and implementing ANN algorithms were carried out in MATLAB/Simulink. The system utilized an Intel Octa-core Ryzen5 processor of the 8th generation, with a minimum frequency of 1.8 GHz and a speed of 2400 MHz. The system also had 8 GB of double data rate fourth generation random-access memory (DDR4 RAM). **Table 3** shows a comparison of the computational costs of the system. It can be observed that the training time for ANNs is high, which makes the NN-DPC approach the slowest among the others. The NF-DPC system is less costly than the NN-DPC but somewhat more costly than C-DPC.

Table 3. Comparison of computational cost.

No Steps of proposed system	Run time (in s)		
	DPC	**NN-DPC**	**NF-DPC**
Time of ANNs training process	/	5 min 44 s	-
Time of NF network training process	/	25 s	8 s
Time (Simulation) of the global system	12	18 s	22 s
Total time	12	8 min 5 s	24 s

The system described in this paper deals with the continuous and sequential operation of the wind energy conversion system in three modes: sub-synchronous, super-synchronous, and synchronous modes. To optimize the generated power, an MPPT algorithm has been employed. The performance of the system has been evaluated through simulation using MATLAB with improved control strategies. The effectiveness and robustness of the proposed controls, NN- and NF-DPC, have been demonstrated and compared to conventional DPC. Results have shown that the proposed controls, especially NF-DPC, are capable of reference tracking and power ripple mitigation in all operating conditions or demands.

9. Future scope

Further exploration and development of advanced control techniques can contribute to reducing harmonic distortion and power loss. Techniques such as Model Predictive Control (MPC), Adaptive Control, and Advanced Optimization Algorithms can be investigated and applied to improve the performance of wind energy conversion systems. Utilizing intelligent optimization algorithms, such as Genetic Algorithms, Particle Swarm Optimization, or Machine Learning-based algorithms, can help optimize the parameters of the intelligent controller for minimizing harmonic distortion and power loss. These algorithms can efficiently explore the solution space and find optimal controller settings to improve system performance.

One of the key areas for researchers is to Investigate hybrid control approaches by combining multiple control strategies, such as fuzzy logic control, neural network control, and traditional control techniques, that can leverage the strengths of different approaches to achieve better control accuracy and system efficiency.

The performance can furthermore be improved by developing robust fault detection and diagnosis algorithms specific to wind energy conversion systems that can help identify and mitigate issues related to harmonic distortion and power loss promptly. Early detection of faults can enable timely corrective actions and prevent system degradation. Advancements in power electronics and converter design can also contribute to reducing harmonic distortion and power loss in wind energy conversion systems. Developing more efficient converter topologies, improving component selection, and optimizing the converter control strategies can be some research areas that can enhance overall system performance.

Author contributions

Conceptualization: CG and SS; methodology: JPP; software: VKM. All authors have read and agreed to the published version of the manuscript.

Conflict of interest

The authors declare no conflict of interest.

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