State-of-The-Art Techniques for LVRT Enhancement using Artificial Intelligence Methods

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Abstract

The stringent requirements demanded by grid codes worldwide have sparked immense research activity in applying new and enhanced methods in grid-connected wind generators to improve their Low Voltage Ride Through (LVRT) capability. Rapidly increasing wind energy penetration into the conventional grid has made it necessary to implement preventive control techniques to successfully detect voltage sags and compensate them before the system is disconnected from the grid. The various techniques available for LVRT enhancement are classified into control techniques and hardware technologies. Artificial intelligence-based algorithms help to enhance and accelerate the performance of conventional control techniques like PI controllers, hysteresis controllers, and sliding mode controllers. Machine learning, a subset of Artificial Intelligence (AI) can be successfully applied for power system fault detection and outage management. The role of various AI based optimization techniques like Genetic Algorithms, Artificial Neural Networks, and ANFIS Systems are compared. Also, the ability of different machine learning methods including supervised machine learning techniques like linear regression, decision trees, and reinforcement learning algorithms in augmenting the LVRT capability of various grid-integrated wind turbines were reviewed in this work. The application of various AI algorithms in improving the performance of controllers in FACTS devices during voltage sags are also reviewed.

Keywords: LVRT capability, Machine learning, preventive control techniques, grid-connected wind generators.

1. Introduction

Global warming, increasing greenhouse gas emissions, and rapidly depleting coal resources have prompted many countries to shift their focus to renewable energy sources like solar and wind. Among the various renewable energy sources, wind energy stands out due to its advantages like low environmental pollution, mature turbine technology and low operating cost. According to Global Wind Energy Council (GWEC)'s worldwide wind data, the installed capacity of wind power has increased by 906 GW, 742,689 GW, and 733 GW in the last three years, 2022, 2021and 2020 respectively(Hutchinson, 2023.) as shown in Figure 1.

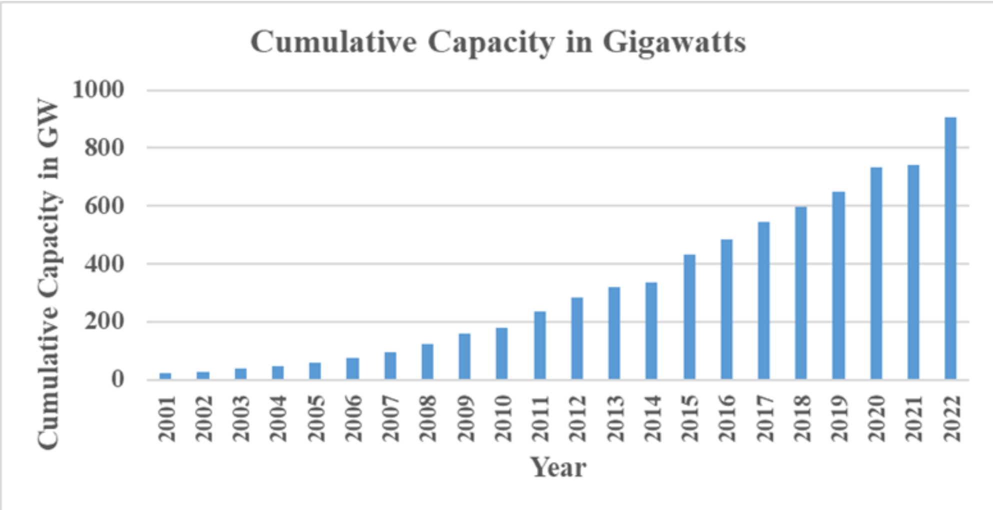

Figure (1): The Global Annual Installed Wind Power Capacity in Years 2001–2022.

India stands at 4th position globally in terms of installed wind power generation capacity with 42.6 GW in 2023. Major challenges while inter-connecting wind power plants to the grid include Low Voltage Ride Through (LVRT) capability or Fault Ride Through Capability (FRT), frequency stability, real and reactive power flow, power quality issues, virtual inertia support, and Maximum Power Point Tracking. (MPPT). LVRT capability is one of the most important requisites for grid-connected wind farms due to its rapidly increasing wind penetration into the grid. (MacDowell et al., 2015)

With approximately 365.97 Gigawatts of installed wind generating capacity, China remains the world’s largest producer of wind energy. In Northern region of China, the increasing wind power penetration along with lack of LVRT capability in wind turbines have resulted in large scale tripping of wind farms during voltage dips, leading to severe cascading trip faults during the period 2011-2014(Niu et al., 2016; H. Yu et al., 2017).In

India, in 2015, a fault at 110 kV line in Udumalpet Substation Tamil Nadu (a state of India) caused a wind withdrawal of 860 MW, which affected the grid security significantly(Gounder et al., 2016). The reason for this failure is large scale tripping of wind farms due to lack of LVRT capability. Hence Transmission System Operators (TSOs) have made LVRT requirement mandatory for grid connected wind farms for smooth functioning of power grid(Amalorpavaraj et al., 2020). The LVRT requirement varies with each country based on the requirements of TSOs. Previous literature implies the importance of AI techniques in LVRT enhancement in wind farms(Lee & He, 2021; Y. Wang et al., 2020). Hence, a comprehensive review of the role of AI techniques in LVRT enhancement in grid-connected windfarms is done, which will help researchers in this field understand the research being done in this area.

1.1.Objectives of the study

To highlight the grid code requirements specified by TSO's of various countries

To identify the LVRT issues faced by windfarms employing fixed speed and variable speed wind turbines during grid interconnection

To classify and analyse the role of AI algorithms in enhancing the performance of LVRT techniques in fixed and variable speed wind farms.

1.2. Significance of the study

This study intends to give an in-depth analysis of cutting-edge AI approaches for hardware- and software-based LVRT techniques in grid-connected wind farms, which will be very beneficial to academics working on improved LVRT technologies for grid farms to meet the grid code criteria.

2. Materials and Methods

This paper shows a detailed review of various articles over the past five years which are bibliometrically analysed from Scopus database in February 2023.Figure 2 shows the steps involved in doing the bibliometric analysis using VOSviewer software(Y. Yu et al., 2020). This software can be used to visualise and explore maps made from network data.

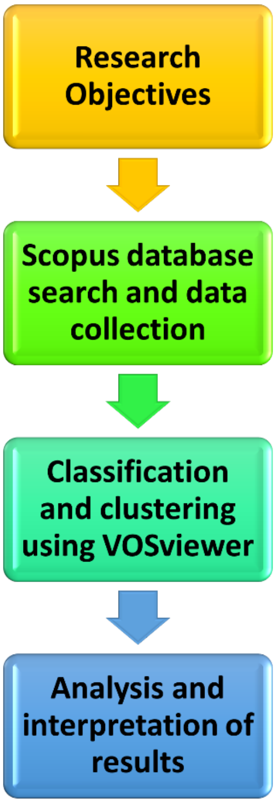

Figure (2): Steps in Bibliometric analysis

In this database, the Keywords used for extracting the data are "LVRT enhancement, Fault Ride Through and LVRT enhancement using Artificial Intelligence and machine learning. The data was taken from Scopus database in February 2023. A total of 1597 documents were taken from the Scopus databases to cluster into certain categories over the past five years because a sharp increase in papers utilizing AI and machine learning methods is seen from 2019. The bibliometric analysis of keywords related to LVRT and AI is shown in Figure 3. The size of nodes shows the frequency of occurrence. The most frequent keyword is Artificial Intelligence followed by Artificial Intelligent Techniques and asynchronous generators. Bibliometric analysis was done based on journals with largest number of publications in this area and with highest number of citations. The highest-ranking journal was Renewable and Sustainable Energy Reviews with a cite score of 28.5 followed by Applied Energy with a cite score of 20.4. The journals with maximum number of papers in this area is IEEE Access followed by Energies and IET Renewable Power Generation. The 79 papers that were deemed to be the most pertinent out of 1597 were chosen and will be thoroughly examined in this paper.

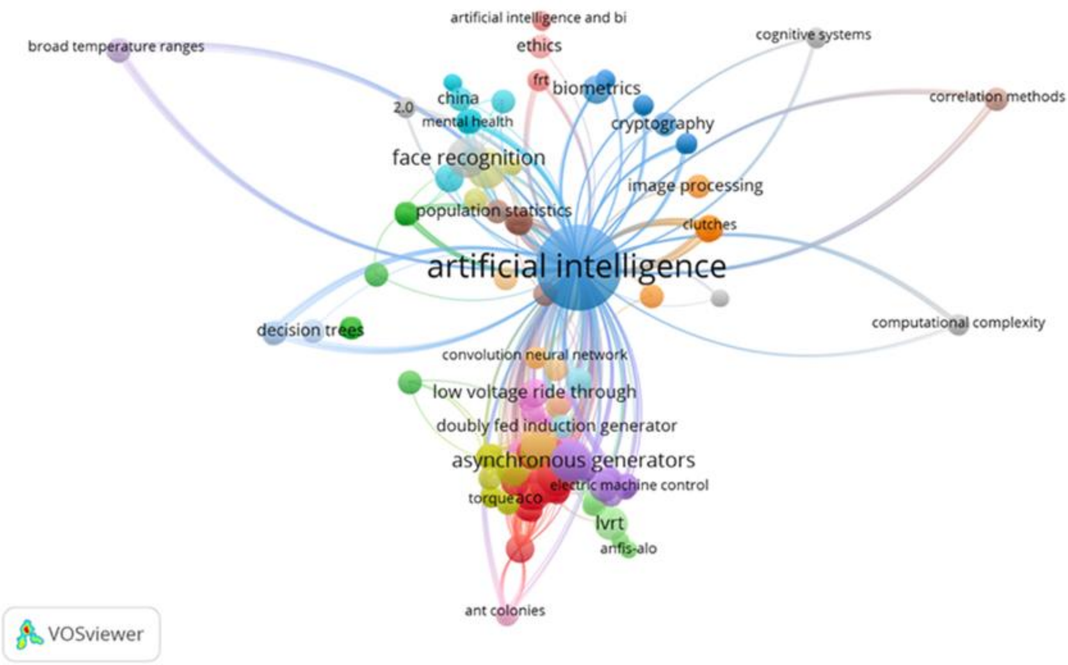

Figure (3). Bibliometric analysis of the keywords in publications

3. Literature Review

3.1 Grid code requirements

Earlier, most of the power sources were traditional fossil fuel power stations using synchronous generators with high rotational inertia, which helped in ensuring frequency stability, voltage regulation and maintaining grid stability during disturbances(Gao et al., 2016). Due to the fluctuating nature of wind and the different technical characteristic of wind generators, wind power plants were allowed to disconnect from the grid and absorb reactive power during faults(Wood, 2020). But the rapidly increasing wind penetration have caused problems in grid stability, prompting authorities to modify grid codes which insist that wind power plants should contribute to grid support during faults by remaining connected to grid for a period specified by Transmission System Operators (TSO) and provide active and reactive power regulation(Basit et al., 2012; Gidwani & Pareek, 2016; Tsili & Papathanassiou, 2009). Figure 4 shows the comparison of LVRT requirements specified by TSOs of different countries(Jin et al., 2020; Liu et al., 2020; Shafiullah et al., 2013(Ann Jerin, 2017.; Mohseni & Islam, 2012). WECS are required to remain connected to the grid as long as the voltage at PCC remains above the curve shown in Figure 4(Ma et al., 2023). Once the voltage falls below the curve, the wind turbines are permitted to disconnect from the grid till the fault is cleared. V_{min} is the minimum voltage and T_{min} is minimum time during fault for the turbine to remain connected to the grid to prevent disconnection(Gidwani & Pareek, 2016; Mohseni & Islam, 2012). . .

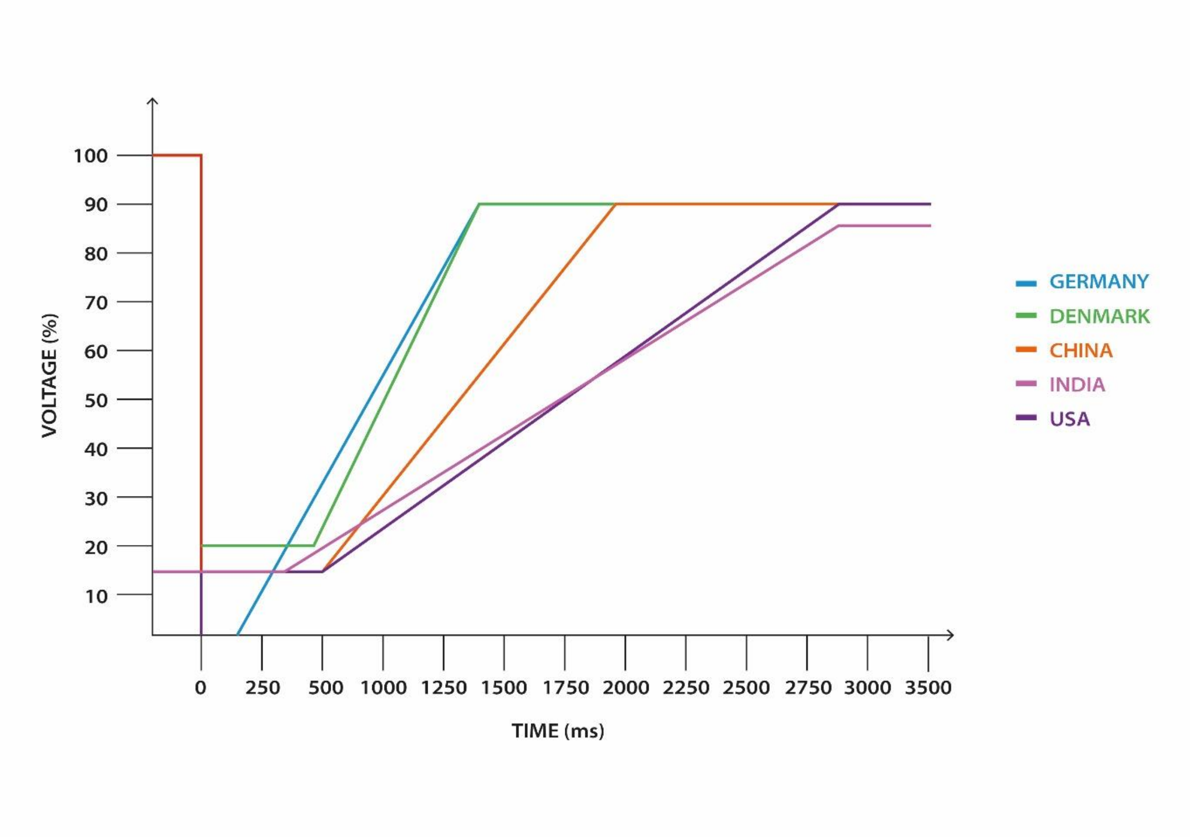

Figure (4): Grid code requirements of different countries

3.2 LVRT issues of different Wind Energy Conversion Systems

The wind energy conversion system (WECS) converts the energy contained in wind into electrical energy. The components of a WECS include wind turbine rotor, gearbox, electrical generator, power electronic converters (PEC) and control circuitry as shown in Figure 5.

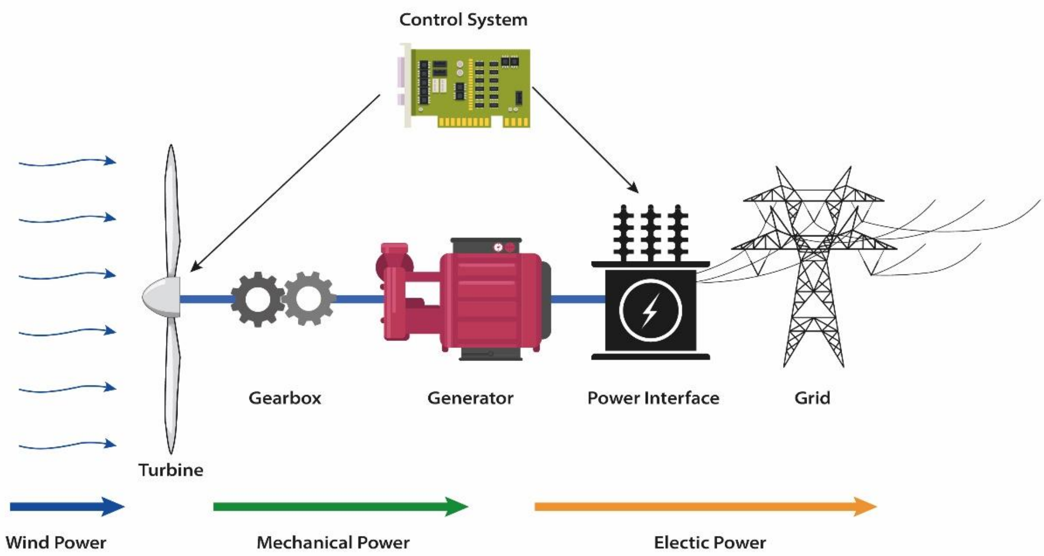

Figure (5): Wind Energy Conversion System

They can be broadly classified into fixed speed WECS and variable speed WECS as shown in Figure 6. In constant-speed WECS, the wind turbine rotates at a constant speed, which is determined by the frequency of the supply grid, the gear ratio, and the generator design. (Mahela & Shaik, 2016). Fixed speed wind turbines are coupled to squirrel cage induction generator (SCIG) and directly coupled to grid(Apata & Oyedokun, 2020). The variable speed WECS employ variable speed wind turbines which can achieve maximum aerodynamic efficiency over a wide range of wind speeds. The variable speed WECS are divided into two types: WECS employing doubly fed induction generator (DFIG) with the rotor connected to grid through a partial scale PEC and the stator of DFIG directly connected to grid. The second type is WECS employing permanent magnet synchronous generator (PMSG) or SCIG connected to grid through a full-scale PEC(R. A. Ibrahim et al., 2012; Jain et al., 2015; Wu et al., 2023).

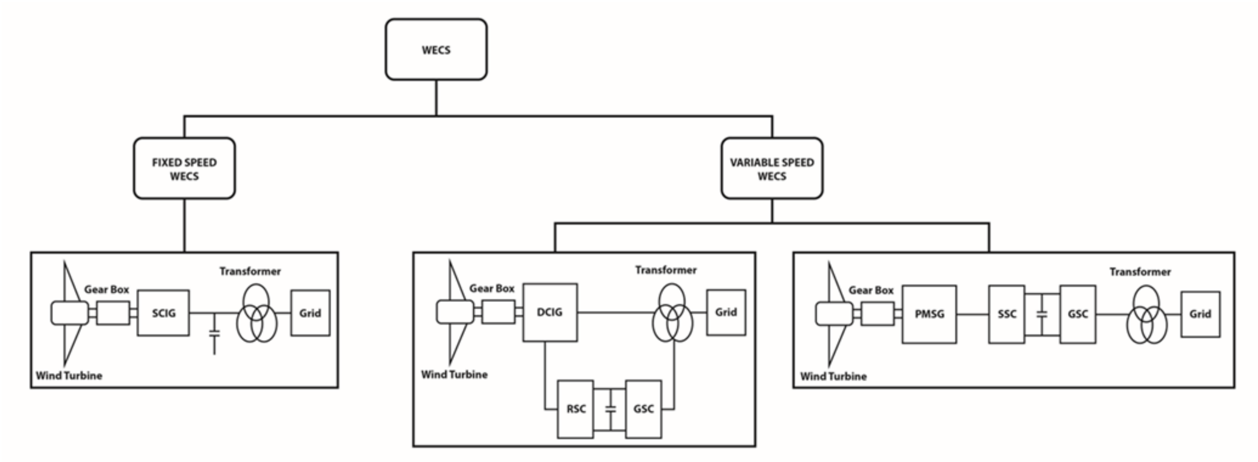

Figure (6): Classification of WECS

The configuration and control methods for the most common types of WECs, FSWT with SCIG, VSWT with DFIG and VSWT with PMSG/SCIG are different and hence the reasons leading to disconnection during faults are different.

In FSWT with SCIG, voltage sag causes due to wind turbine disconnection due to rotor acceleration to a very high value prompting disconnection of wind turbine. This increase in rotor speed rises the reactive power consumption of SCIG, worsening the voltage sag condition(Molinas et al., 2008; Mostafa et al., 2023a).

In VSWT with DFIG, during grid faults, the voltage dip at PCC result in large stator current transients and consequently cause large rotor currents to flow(Din et al., 2021; Mosayyebi et al., 2022). This increased current raises the dc link voltage which can damage the converters and also the wind turbines(Hete et al., 2022; Wei et al., 2018). Hence the DFIG is tripped from the grid during voltage dips(Islam et al., 2019; Qin et al., 2020).

In VSWT with PMSG/SCIG, when a dip in grid voltage occurs, the wind turbine's maximum active power output is lowered in direct proportion to the terminal voltage drop. The inverting converter's controller instantly reduces the output power(Dey et al., 2018; Errami et al., 2013). The input power taken from the wind turbine blades, however, cannot be decreased as quickly. Hence this unbalance in power causes an uncontrollable increase in DC Link voltage prompting protective devices to disconnect the wind turbine from the grid to prevent damage to converter(Conroy & Watson, 2007; Domínguez-García et al., 2012).

3.3 LVRT Schemes of various WECS

The LVRT enhancement techniques employed are classified broadly into hardware techniques and software techniques(Gandoman et al., 2018; Hamdan & Noureldeen, 2021; Mostafa et al., 2023b; Shan et al., 2021). The detailed classification is shown in Figure 7. The protection-based devices include Braking chopper(Noureldeen & Hamdan, 2018), Crowbar circuit, various types of fault current limiters (FCL) including solid-state, resonant circuit, transformer coupled bridge-type fault current limiter (BFCL), and superconducting fault current limiter (SFCL)(Gerbaud et al., 2021a; Heydari & Shahgholian, 2020a; Mahela & Shaik, 2016; Moghadasi et al., 2016; Nasiri et al., 2015; Qin et al., 2020).FACTS devices are power electronic based devices which can be used for fast voltage regulation and power control(Mallick & Mukherjee, 2019). They include shunt connected devices like STATCOM and SVC, series connected devices including SSSC, DVR and hybrid device like UPFC(Howlader & Senjyu, 2016; Mahela et al., 2019).

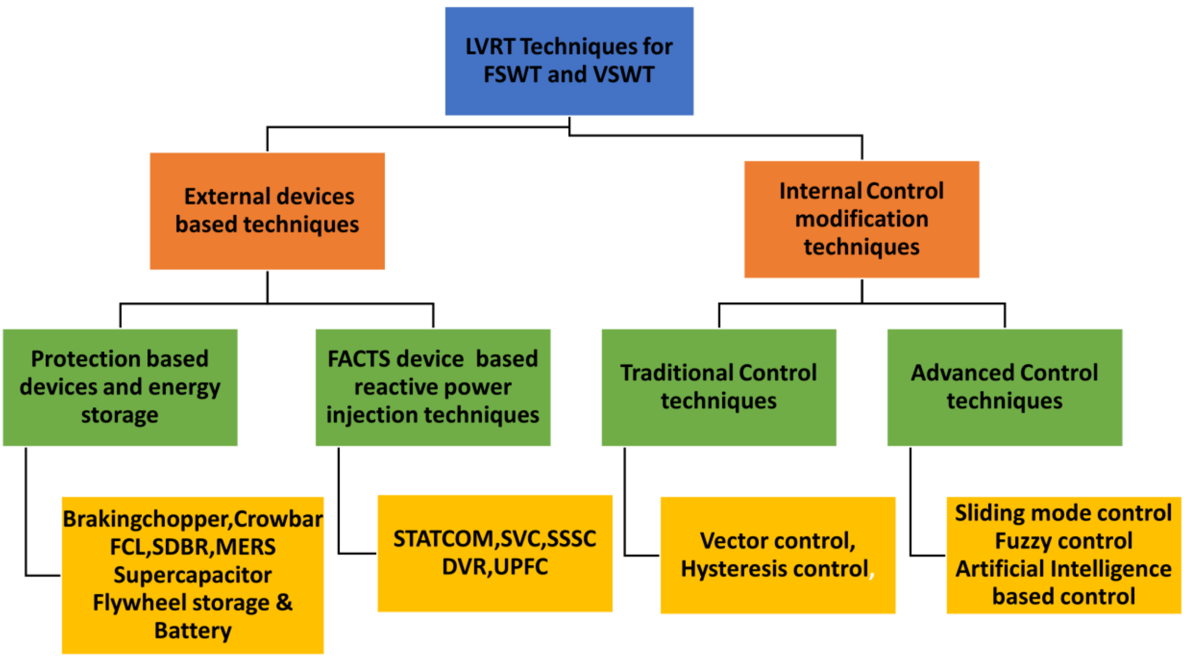

Figure (7): Classification of LVRT techniques

3.4 Advantages of AI algorithms in LVRT enhancement

Artificial Intelligence (AI) is defined as the simulation of human intelligence on a machine so as to make the machine efficient to identify and use the right piece of knowledge at a given step of solving a problem(Konar, 2000.).AI alternatively may be stated as a subject dealing with computational models that can think and act rationally(Entezari et al., 2023). The areas coming under the term AI algorithms can be broadly classified as ANN, Machine learning, Deep learning, Fuzzy logic and evolutionary algorithms as given in Figure 8.

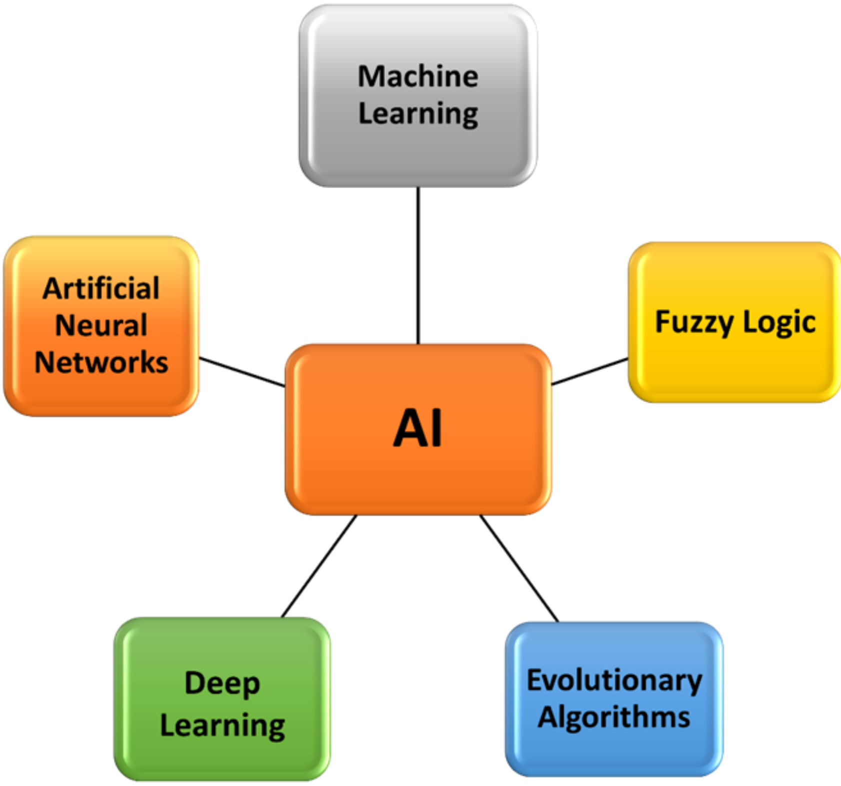

Figure (8): Components of AI

All the existing hardware and controller improvement methods for LVRT enhancement consists of a control part where usually traditional methods like PID controller and hysteresis controller, are used. But, the nonlinear nature of wind power generation makes it difficult for PID controller with static reference points to track accurately the rapidly varying error signal, especially under transient conditions(Abdelateef Mostafa et al., 2023).

AI methods excel at handling complex and nonlinear systems that might be challenging for traditional control methods. They can capture intricate relationships within data and make decisions based on patterns that might be difficult to model analytically.AI methods, such as Neural Networks, can approximate nonlinear relationships more effectively, enabling better control of such systems.AI techniques like reinforcement learning can continuously analyze data and adjust control parameters to achieve optimal performance, even when the system's behavior or external factors change(Entezari et al., 2023; Mosavi et al., 2019).AI algorithms like machine learning can predict voltage dips by analyzing historical data and patterns.AI-incorporated fault detection systems can rapidly detect the type and location of faults that cause voltage dips(Vieira et al., 2018). Machine learning models can analyze data from sensors and smart meters to differentiate between various fault types and determine whether they require LVRT activation(Khodayar et al., 2021). This helps in triggering the appropriate response strategy(Farrar et al., 2023).

3.5 Application of AI algorithms in LVRT techniques of various WECS

Table 1 explains the role of various AI algorithms in enhancing the LVRT capability of different types of retrofitting devices.

Application of AI algorithms in LVRT enhancement 1 Table

Methods	as Function LVRT device	AI algorithm used	Advantages
Braking chopper	Consumes active power during faults	Fuzzy logic PQ -GA, (FLC)controller coordinated controller (Nasiri & Arzani, 2022)	Improves LVRT capability and provides automatic braking
Crow bar	Short circuits the rotor converter during faults	ANFIS controller (Hamdan & Noureldeen, 2021; Nasiri et al., 2015)	demonstrates good efficiency in regulating active and reactive power and suppression of DC-link overvoltage during network faults
Fault current limiter	Reduces stator current	FLC ANFIS,controller(Naderi	ANFIS has better fault limiting

	rise and reduces voltage dip at generator terminals during faults	et al., 2018; Rashid & Ali, 2017)	characteristics
Energy-storage based technique (super capacitor, Fly wheel, super conducting magnetic energy storage, flow battery)	During faults, absorbs additional energy from DC link and prevents overvoltage	PSO ,FLC controller Optimized controller Adaptive ANN , ,controller SMAPA-based adaptive PIoptimized controller(Mahmoud et al., 2023)	ptimization O techniques help to select optimum parameters of controller and the capacity reduce of ESS
Series dynamic braking (SDBR)resistor	Reduces mechanical active power and limits stator current	Genetic algorithm for optimal control parameters(Heydari & Shahgholian, 2020b)	Increased FRT capability and reduced sub synchronous resonance
Magnetic energy recovery (MERS)switch	Stores energy during normal operating conditions and this stored energy can then be used to provide additional power during voltage sags .	Gradient optimization algorithm(Gerbaud et al., 2021b)	Low switching losses
Static var	Shunt	fuzzy grey ,FLC controller	oltage drop after V

(SVC)compensator	connected FACTS device which provides reactive power compensation during voltage sags	controller(Karami & Itami, 2017; Rezaie & Kazemi-Rahbar, 2019)	fault is fast ,decreased supply of reactive power
STATCOM	Shunt connected FACTS device which provides controllable reactive power and acts fast.	Reinforcement learning algorithm, Water Cycle Algorithm-Particle Swarm Optimization (PSO), Chaos orthogonal-PSO, ANN, Simulated Annealing optimization, FLC controller(Hong & Nguyen, 2020; Molinas et al., 2008; Muisyo et al., 2022; Ramirez et al., 2012; Rashad et al., 2019; Shehata et al., 2022; P. K. Wang et al., 2022; Zhou et al., 2020),	AI techniques
DVR	Series connected FACTS device injecting voltage in proportion to voltage sag	PSO,ANFIS,FLC-2-Type Genetic algorithm optimized Elman neural network control, Multi Objective Bees Algorithm (MOBA),Grasshopper optimization	Compensates balanced and unbalanced voltage sags and reactive power compensation with optimized control like grasshopper.

	and provides reactive power.	algorithm.(Amalorpavaraj et al., 2017; Darvish Falehi, 2020; Darvish Falehi & Rafiee, 2018; Farhadi-Kangarlu et al., 2017; Farooqi et al., 2022; A. O. Ibrahim et al., 2011; Priyavarthini et al., 2018; Ramirez et al., 2011; Rini Ann Jerin et al., 2017; Sitharthan et al., 2018)	
UPFC	Provides both shunt and series compensation	AVURPSO algorithm, Fractional Order Proportional–Integral–Derivative (FOPID) controller(Osama abed el-Raouf et al., 2023).	AI algorithms reduce active power absorption and size of DC link capacitor

4. Conclusion

This paper presents a comprehensive review of the various LVRT techniques used in fixed-speed and variable-speed wind turbines whose performance is enhanced using AI and machine-learning-based intelligent algorithms. AI algorithms successfully demonstrate their superior performance as compared to traditional control methods for enhancing LVRT capability. AI algorithms are able to successfully compensate for voltage dips and reduce the torque oscillations and rotor speed oscillations caused by voltage dips at PCC. AI methods can adapt in real-time to changing conditions, making them suitable for applications where the environment is dynamic and unpredictable. Further research is necessary to apply AI and machine learning algorithms to various LVRT techniques in windfarms to enhance their performance and satisfy the stringent requirements suggested by TSOs.

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