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Review

A Comprehensive Review on Voltage Stability in Wind-Integrated Power Systems

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Abstract: The fast growth of the world's energy demand in the modernized world has stirred many countries around the globe to focus on power generation by abundantly available renewable energy resources. Among them, wind energy has attained significant attention owing to its environment-friendly nature along with other fabulous advantages. However, wind-integrated power systems experience numerous voltage instability complexities due to the sporadic nature of wind. This paper comprehensively reviews the problems of voltage instability in wind-integrated power systems, its causes, consequences, improvement techniques, and implication of grid codes to keep the operation of the network secure. Thorough understanding of the underlying issues related to voltage instability is necessary for the development of effective mitigation techniques in order to facilitate wind integration into power systems. Therefore, this review delves into the origin and consequences of voltage instability, emphasizing its adverse impacts on the performance and reliability of power systems. Moreover, it sheds light on the challenges of integrating wind energy with existing grids. This manuscript provides a comprehensive overview of the essential features required for critical analysis through a detailed examination of Voltage Stability Indices (VSIs). To address voltage stability issues in wind-integrated power systems, this review examines diverse techniques proposed by researchers, encompassing the tools utilized for assessment and mitigation. Therefore, in the field of power system operation and renewable energy integration, this manuscript serves as a valuable resource for researchers by comprehensively addressing the complexities and challenges associated with voltage instability in wind-integrated power systems.

Keywords: voltage stability; wind farm integration; wind penetration level; low voltage ride-through (LVRT); high voltage ride-through (HVRT); FACTS; voltage stability limit; voltage stability indices; weakest bus; weak grid

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Citation: Malik, F.H.; Khan, M.W.; Rahman, T.U.; Ehtisham, M.; Faheem, M.; Haider, Z.M.; Lehtonen, M. A Comprehensive Review on Voltage Stability in Wind-Integrated Power Systems. *Energies* **2024**, *17*, 644. https://doi.org/10.3390/en17030644

Academic Editors: Tek Tjing Lie, Saeed Sepasi and Quynh Thi Tu Tran

Received: 9 August 2023
Revised: 3 January 2024
Accepted: 24 January 2024
Published: 29 January 2024

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1. Introduction

The never-ending potential of renewable energy resources has made them a viable solution to get rid of costly fossil fuel-dependent energy generation portfolio and to cope with the ever-increasing demand of energy due to fast population growth and intense industrialization. Economic as well as eco-friendly attributes have nominated wind energy as an excellent resource over various other renewable energy resources. Government policies of many countries around the globe seem to be more inclined towards switching their power generation pathways to wind energy [1]. Power electronics have revamped the wind generation technology and altered the generation paradigm utterly to make it as one of the most attractive energy origins [2]. The heavily loaded systems and the increasing penetration of wind farms in the conventional power system have given rise

to the complexity in power systems. Because of this, power systems are operating at the verge of the stability limits that impose severe threats on the reliability of the system [3]. Many countries have published grid codes that are significant drivers for wind farm integration to ensure system stability, power quality, protection of equipment, and demand for interconnections and generation to the grid [4].

Multifarious factors like grid codes, Low Voltage Ride-Through (LVRT), High Voltage Ride-Through (HVRT), Doubly Fed Induction Generator (DFIG) role, and permissible penetration level of wind power need to be analyzed before proper wind power integration to avoid a voltage instability aftermath. Thus, multiple solutions are presented by different researchers to improve the power system stability that is mostly related to the voltage stability of wind turbines' generation and distribution systems. Many publications have proposed different methodologies to improve voltage stability by using DFIG, but most of them did not fully explore the crowbar circuit, which is a protecting circuit against high voltages during power supply malfunction or power surge operation [5]. In [6], the crowbar operation and its role during voltage dips are discussed; however, some of the disadvantages of crowbar like increasing mechanical stress, power oscillations, and consumption of more reactive power from the grid are not highlighted.

Reference [7] addressed a bunch of plus points about DFIG-based wind turbine systems, and the structure of DFIG with the interconnection between Rotor Side Converter (RSC) and Grid Side Converter (GSC) in terms of reactive power support was also discussed; however, they did not talk about the reactive power limitation by these generators. In the last few decades, most of the research work have highlighted and presented various methods and techniques to improve the performance of wind-integrated power systems, but some of its problems need more research. For example, extensive research has been performed on LVRT. However, the researchers did not fully illustrate the emerging HVRT behavior of Doubly Fed Induction Generators (DFIGs) [8–10].

High-Wind Speed Shut Down is also an essential consideration in wind farm integration, which few researchers have taken into account [11]. For voltage stability improvement, most of the researchers have just focused on FACTS devices [12,13], even though other tools like D-SMES (Distributed Superconducting Magnetic Energy Storage) for voltage stability improvement exist, as has been discussed by [14]. Monitoring and measurement of the power system are generally performed by SCADA, which is a sophisticated supervisory system, but real-time tracking with any system changes makes the WAMS technology a remarkable choice. There is vast research present on the SCADA system, while researchers should focus on the WAMS technology [15–17].

In wind-integrated power systems, one of the major reasons for voltage instability is the reduction in system inertia due to the reliance on energy conversion from wind, unlike the rotational inertia of the conventional synchronous generators. Therefore, during faults, the power grid is more susceptible to voltage and frequency fluctuations. Furthermore, reactive power deficit and weak grid connections are also major concerns to the maintenance of voltage stability. Wind turbines might not be able to provide sufficient reactive power support owing to the technology employed and the limited capacity of the grid to transmit power, leading to voltage instability. In addition, the intermittent nature of wind power and the limited fault response also contribute to voltage and system instability. The reduced contribution of wind turbines in fault current compared to conventional generators makes it difficult to clear faults, potentially causing system instability and cascading effects. To address these challenges, researchers have proposed different approaches to enhance voltage and system stability, which includes upgradation of transmission and distribution infrastructure and deployment of FACTS devices. Moreover, some studies have suggested boosting the grid resilience with energy storage technology and demand side management techniques. However, stress on the utility grid can be further relived by integrating advanced forecasting tools, efficient monitoring systems, and hybrid power systems.

This paper is compiled in two sections (2 and 3). Section 2 highlights issues related to voltage stability of a power system and the techniques for their prevention. Section 3

covers the wind farms' evolution and the integration of wind farms with conventional grids. Lastly, penetration levels and the optimal location for wind farm integration are also studied.

2. Overview of Voltage Stability

Voltage stability has become the most vital concern for today's complex electrical networks. It refers to the ability of a power system to maintain constant voltages at all buses in the system after being subjected to a disturbance from a given initial operating condition [18]. Multifarious causes are at the back-end that lay the foundation for voltage instability. Some of the top-listed reasons include intensive use of capacitor banks for reactive power compensation, voltage-insensitive loads, low system voltages, and over-stressing the system with heavy loads [19,20]. M Johnson in [21] prescribed the slow voltage instability phenomenon, and through mathematical computation, he manifested that there is a fundamental relationship between system voltage (V) and reactive power (Q) and thereby confirmed that limitations of the reactive power transfer across the transmission lines are the prime cause of voltage instability that in turn gives rise to voltage collapse.

The load characteristic is one of the significant factors responsible for dynamic voltage instability [22]. P W Sauer et al. explained the relationship between loading characteristics and voltage stability [23]. Bradley R. Williams et al. in [24] presented that stalled air conditioner compressors delay the voltage recovery following the fault. High Voltage Direct Current (HVDC) link, induction motor load, and air conditioner loads affect the short-term voltage stability, while long-term voltage stability is affected by thermostatic loads, distributed voltage regulation, and tap changing of transformers [25,26]. Voltage stability may also stem from rotor angle or frequency instability. In [27], Thierry Van Cutsem illustrated two aspects of voltage instability. Firstly, voltage stability is distressed by the tripping of generation or transmission equipment and secondly by a maximum loading power attempt beyond its limits. The greatest threat to a power system is "blackout" that is the complete outage of power. Deplorable voltage profile of any power system causes blackouts that typically arise due to voltage collapse [28,29]. In case if any line trips, the rest of the lines go on carrying the power, resulting in more reactive power consumption, and thus, the voltage profile decays further [30]. Weak grids, climatic effects, abrupt load changes, heavily loaded systems, and human errors are the factors because of which a system encounters blackout [31–33]. Because of this, people suffer from communication and traffic interruptions, and the countries have to face a considerable decline in the economy and stock markets [32].

A deficiency of reactive power results in blackouts each year all around the world. A glance over the globe in terms of significant outages over the past few decades highlights the Tokyo blackout in 1987 [34], the S/SE Brazilian system blackout in 1997 [35], the US and Canadian blackout in 2003, the Athen's blackout in 2004, the Pakistan blackout in 2006, which are among the significant blackouts. According to engineers and operators, the root of these blackouts was voltage instability that originated because of inadequate reactive power supply between generation and load points [30,36]. While discussing voltage stability of a power system, voltage stability limit is considered to be a worthy mentioning aspect that renders an insight about the range of load increment on a particular bus of a power system before it undergoes voltage instability. Load increment necessitates the determination of the voltage stability limit to restrict a power system operation within the permissible limits and stability margin [37–39]. Many researchers have shown their interest in developing different methods to estimate the voltage stability limit in an efficient, precise, and easy way. Some of the commonly utilized methods have been addressed here.

- PV and QV curves are commonly used to find out the voltage stability limit, which is not an effective method because one has to generate a family of the curves using simulation tools to determine the ceiling [37,38,40].
- Voltage stability index can be found using the static voltage stability index in terms of the minimum singular value of the power flow Jacobian matrix [38,41,42].

- Conventional load flow solution method and non-linear optimization technique can also be utilized to find the voltage stability limit [43–45].

When a power system is equipped with Static Var Compensator (SVC), the voltage stability limit of the system can be efficiently determined. M.H. Haque has verified it through tests on a two-bus system and IEEE 14-bus system [37]. An Energy Storage System (ESS) application is addressed in [46] for voltage stability enhancement, and the smallest eigenvalue is exploited to evaluate the lower voltage stability limit. With a view on the voltage stability limit, Chaisit Wannoi et al. suggested a repeated power flow-based technique for better installing positions of renewable power generation units that are integrated into a power system [47]. To cope with the need of maximizing the voltage stability limit, M. Tripathy et al. exploited the Bacteria Foraging Algorithm (BFA) in [39,48] for the proper allocation of transformer taps and the injection of reactive power at specific buses. Furthermore, the authors proclaimed the superiority of the BFA through MATLAB simulation based on the Interior-Point Successive Linearization Program (IPSLP) technique. Simulation-based comparison between the Real-Coded Genetic Algorithm (RCGA) and the Firefly Algorithm (FA) testifies the better efficiency of the latter to uplift the voltage stability limit [49]. The load flow equations concerning the minimum modulus eigenvalue have convergent behavior; therefore, a new approach is discussed in [50] for determining the static voltage limit and identifying the weak bus. The On-load Tap Changer (OLTC) having dynamic characteristics influences the system voltage stability, and therefore, it describes the static voltage limit and the maximum transmission power by adjusting its variable ratio properly [51].

During contingency and the standard operating scenario, an optimization-based strategy is used for controlling the reactive power. From the solutions of mixed integer programming problems and the backward–forward search approach with linear complexity, magnitude and location of reactive power control can be determined [52]. The physical and electrical characteristics like the thermal, voltage, and stability boundary decide the limit for the maximum power transfer of an interconnected power system [53]. For the calculation of the maximum power transfer limit, the static security constraints are considered because the transient and dynamic constraints are very hard for online applications [54,55]. A predictor–corrector framework is presented in [56] to obtain a fast estimation of the maximum power transfer limit for the load increase model with a common scaling factor and to derive a particular outline of the impedance matching state for the maximum power transfer.

In the last few decades, researchers have been trying to develop various techniques to maximize the power transfer capability of a power system. In 1989, C.S. Indulkar et al. determined the maximum power transfer capability of transmission systems of 220–500 kV within stability limits by conducting tests on five different compensation schemes and concluded that by increasing the degree of series compensation, the extent of the maximum power transfer at the verge of stability could be enhanced. Moreover, the maximum power transfer limit is highest in the case of leading power factor loads [57]. The maximum power transfer expression bounded by voltage stability indicates that the point of the maximum power transfer is independent of the connected load type and changes only with the power factor of the load [51]. For different power factors, the PV and QV curves are used to estimate the parameters like the maximum power transfer value and reactive power transfer [58]. Maximum PowerPoint Tracking is highly essential in modern wind farms because it determines the operating point where maximum power can be extracted from wind streams. To achieve this economic benefit, four control strategies have been summarized in [59], namely, Optimal Torque (OT), Control Speed Ratio (TSR) Control, Perturbation and Observation (P&O) Control, and Power Signal Feedback (PSF) Control.

Xuan Wei and Joe H. Chow describe that, in the presence of Unified Power Flow Converters (UPFC), maximum power can be transferred at its conventional voltage within a rated capacity operation. FACTS devices improve the transfer capability of the power system, and they must operate at their rated limits (mega Volt-Ampere, voltage, current) to achieve maximum power transfer [60]. Static Synchronous Compensators (STATCOM)

are shunt controllers that improve voltage stability by providing reactive power, thus improving power transfer [61]. Reference [62] formulated the direct relationship between impedance matching (IM) and power injection sensitivities, and through this work, the Sensitivity Impedance Matching (SIM) tool is proposed to figure out the following: maximum power transfer point, maximum load ability point, and instability conditions. Reference [63] deals with the various loading characteristics on the maximum power transfer limit for the critical values of series and shunt compensators by examining these two different schemes. To quantify the amount of reactive power that could be added to the load end of an AC transmission line system for maximum power transfer, the controlled compensation scheme is addressed by [64] for different load models by neglecting the effect of line resistance and capacitance.

2.1. Types of Voltage Stability

Based on the magnitude of disturbance, voltage stability is mainly categorized as large disturbance and small disturbance. Each of these is further classified into short-term and long-term depending upon the period.

2.1.1. Large Disturbance Voltage Stability

Enormous disturbance voltage stability refers to the system's ability to maintain steady voltages following significant disturbances such as system faults, loss of generation, or circuit contingencies [18]. Large disturbance voltage instability usually arises due to long transmission lines or tripping of generators [65]. The voltages at the several bus nodes tend to decline by increasing the reactive power requirement during a massive disturbance voltage instability, thereby the operating point and steady-state operating points get apart from each other [66]. To shield the system from a failure, the large disturbance voltage instability needs to be uprooted as swiftly as possible. Phasor Measurement Units (PMUs) are very handy to deal with these circumstances [67]. It can lead the system to voltage instability or rotor angle stability depending on the magnitude of the load attached. For large loads, the system undergoes a voltage collapse point, while for lighter loads, the rotor angle instability becomes prominent [68].

Using simulations, R.B.L. Guedes et al. argues in [68] that the Extended Lyapunov Function can be utilized to determine the clearing time when a light load power system undergoes voltage instability due to a significant disturbance. Tang Yong et al. believes that load dynamics' characteristics have a significant impact on short-term substantial disturbance voltage stability and presented solutions for overcoming the short-term massive disturbance voltage instability by either of the following: appropriate load shedding in the under-voltage condition or running the system at high voltage and incorporating reactive power injection devices [69]. Based on the induction motor's electromechanical transients, Sun Huadong et al. established an improved criterion involving less simulative calculations for judging the short-term considerable disturbance voltage stability [70]. For the improvement of the substantial disturbance voltage stability, G Naveen Kumar et al. have suggested the appropriate use of Thyristor Controlled Series Capacitor (TCSC) and SVC FACTS devices due to their robust nature against alternating climatic conditions [71]. Traditional load models cannot precisely describe the characteristics of load shedding under low voltage. Xiao-yu Zheng et al. overcame this problem by presenting an improved and novel load model in [72] with several advantages.

2.1.2. Small Disturbance Voltage Stability

Small disturbance voltage stability is the ability of the power system, for a given initial operating condition, to maintain a steady voltage when subjected to a small disturbance such as an incremental change in load demand [18,73,74]. By making use of sensitivity information, factors affecting the small disturbance voltage stability can be determined. This needs to linearize the power system under an equilibrium state [75]. Load characteristics, discrete control, and continuous control at a given time-instant influences the

small disturbance voltage stability [76]. For the determination of small disturbance voltage stability, Liancheng Wang et al. proposed a novel Q angle index [77]. Using PMU with AR model adaptation, Chao Xu proposed a new technique for real-time small disturbance voltage stability analysis [78].

To assess small disturbance voltage stability, quite a few methods have been employed that use either local or global measurements. Although these methods are fast, but being less robust during the transient period, they cannot determine the precise equivalent parameters [79]. Keeping in view the fact that small disturbance voltage stability is independent of the nature of the disturbance, Robin Preece et al. proposed the risk-based probabilistic small disturbance security analysis (PSSA) to compute small disturbance stability risks [80]. Unlike large disturbance voltage stability, the small disturbance voltage stability is concerned with small incremental variations in the system load. The processes undergoing small disturbance voltage instability have a steady-state nature. The higher the reactive power injection to the system, the higher the voltage rise. Hence, this benchmark can be used to identify the small disturbance voltage stability by considering the performance of each bus in the system. Q-V sensitivity is the yardstick to check the stability. If Q-V sensitivity is positive for every bus, the system voltage is stable and vice versa [81,82]. Under various operating conditions, [73] carried out detailed analysis on grid-connected Wound Rotor Induction Generator (WRIG)-based wind turbine system to study the small disturbance voltage stability and concluded that the rotor resistance might reduce the voltage stability margin.

2.1.3. Long-Term Voltage Stability

Long-term voltage stability involves slower acting equipment such as tap-changing transformers, thermostatically controlled loads, and generator current limiters [18]. Caused by a large disturbance, long-term voltage stability is an interlinked local phenomenon that leads to power blackout [83]. The period of interest varies from 0.5 to several minutes [84]. Regardless of the use of power recovery components having load recovery characteristic and the extensive use of On-load Tap Changer (OLTC), voltage collapse course may still elongate, which is referred to as long-term voltage stability [85]. Inadequate supply of reactive power to some buses results in long-term voltage stability. Many key contributors like stressed power systems, maloperation of relays, load characteristics, improper fast reactive power resources, and tap-changer response leading to long-term voltage collapse have been reported in [86].

Based on the timescale, T.M.L. Assis et al. also presented midterm voltage stability [87] and proposed a novel technique for voltage security assessment. This methodology is a blend of the simulation techniques of Quasi Steady State (QSS) and Artificial Neural Networks (ANNs). Non-linear time domain dynamic simulations show the impact of induction generators on long-term voltage stability and also indicate that their existence squeezes the voltage stability margin in distribution networks [88]. OLTC with Line Drop Compensator (LDC) and Automatic Voltage Controller (AVC) relay has been used as a prevalent voltage control method. For preventing excessive tap changing, OLTC maintains an appropriate voltage at its secondary with a time delay of 30 to 60 s [89]. Model Predictive Control (MPC) is a magnificent technology because of its numerous benefits in long-term voltage stability improvement by performing trajectory sensitivity-based load shedding [90]. Angel Perez et al. briefly discussed various methods to evaluate long-term voltage stability [91]. Wenjie Zheng et al. [92] worked for the enhancement of long-term voltage stability through direct dynamic optimization.

2.1.4. Short-Term Voltage Stability

During the transient region, after being subjected to large disturbances, short-term voltage stability is one of the major concerns for a power system [93]. Short-term voltage stability refers to the dynamics of the faster components of load like HVDC converters, induction motors, and electronically controlled loads [18]. Various researchers have figured

out that the extensive use of capacitor banks, voltage-intensive loads, air conditioners, and compressor motors having low inertia made the short-term voltage stability a consequential phenomenon [94–97]. During short-term voltage instability, the motor loads frequently compensated by shunt capacitor banks draw very high currents [19]. The occurrence of voltage drop due to a fault leads to dynamic load to restore the consumed power. This eventually results in short-term voltage instability. Long-term instability may lead to short-term instability. It causes a synchronization loss of generators and delays for motors [98].

SVC and STATCOM are dynamic VAR compensators with appropriate control strategies that can efficiently improve the short-term voltage stability by supporting fast dynamic reactive power [99]. The methods to improve the short-term voltage stability problem can be classified in two ways as an emergency and preventive control [97,100]. Voltage instability problems with their solutions, including proper placement of dynamic VAR, are presented by Ashutosh Tiwari et al. in [95].

An appropriate solution of differential equations is required in the analysis of short-term voltage stability. The period for the short-term instability may vary from few to many seconds [18]. With the help of Quasi Steady State (QSS) time domain simulation, we can calculate short-term voltage stability considering short-term voltage stability points [85]. Based on the Neural Networks with Random Weights (NNRWs) algorithm and ensemble learning strategy, Yan Xu et al. proposed a hierarchical intelligence system (IS) in [101], and K. Kawabe et al. presented a PV plane stability boundary line indicating the deceleration or acceleration of the induction motor [102] for the assessment of short-term voltage instability.

2.2. Voltage Stability Assessment

Voltage stability assessment is imperative for taking precautionary measures to mitigate the complications leading to voltage collapse. Conventionally, PV and QV curves are used to estimate the voltage stability margin. Owing to the assiduous time-consuming repetitive power flow simulations under various loading conditions, researchers are more inclined toward Voltage Stability Indices (VSIs) [103]. Voltage Stability Indices are powerful tools for detecting the proximity to the voltage collapse point and providing valuable information regarding critical lines [104], system loading, and weak nodes of a loaded power system [105]. The weakest lines and buses are the ones that have a voltage stability index closest to a critical value. Therefore, it is essential to evaluate VSIs at each node of a system, and the value of VSI varies between 0 and 1 [106]. Voltage Stability Indices can be broadly categorized into two types, namely [3,107]:

1. Jacobian matrix and System variable-based Voltage Stability Indices.
2. Bus, line, and overall Voltage Stability Indices.

A system-based VSIs make use of system parameters such as line power, bus voltage, and admittance matrix and are advantageous for online monitoring, while 'Jacobian matrix-based VSIs' are suitable for the accurate calculation of the voltage stability margin, which is difficult to calculate by the former [108]. Moreover, system variable-based indices require much less computing time and a weak bus/line can be identified precisely, while the Jacobian-based indices are very effective in the discovery of the voltage collapse point and maximum load ability, but a very high computational time results in an inappropriate online assessment, which makes them less preferable [3,109]. Offline VSIs are used in planning while online VSIs determine the voltage collapse proximity for controlling voltage instability automatically or manually by the operator to prevent blackout [108]. Voltage Stability Indices are very helpful to observe the online changes in the system parameters, and they are scalar magnitudes, which quantify the distance of the voltage collapse point from the operating point, and they are derived from the properties of voltage collapse [110,111]. Table 1 summarizes different VSIs in terms of their characteristics, critical values, and their formulations.

Table 1. List of VSIs.

Sr.	Index	Proposed by	Expression/Formula	Critical Value	Salient Features	Input variables (of Formula)	References
1	Fast Voltage Stability Index (*FVSI*)	Ismail Musiril et al.	$FVSI = (4Z2Q_j)/V_i{}^2X_{ij}$	Critical value ≥ 1	Used in determining the weakest bus, line criticalness, and maximum load-ability	Z = Line impedance X_{ij} = Line reactance Q_j = Receiving end reactive power V_i = Sending end voltage	[106]
2	Line Stability Index (L_{mn})	M. Moghavvemi	$L_{mn} = \frac{4xQ_r}{[V_s \sin(\theta-\delta)]^2}$	If $Lmn = 1$, system is near to voltage collapse; $Lmn < 1$ means system is stable; $Lmn = 0$ means system has no load	Based on ''Power flow through a single line.'' Uses little information like the specific local measurements	V_s= Sending bus voltage θ = Line impedance angle δ = Angle difference between the supply voltage and receiving end voltage Q_r = Reactive power flow of receiving bus $4X$ = Line reactance	[112–114]
3	Line Voltage Stability Index (L_i)	Arya et al.	$L_i = AvCos(\delta - \alpha)$ $\delta = \delta_k - \delta_m$	$L_i < 0.5$	This index halves at voltage collapse	$A = \frac{V_R}{V_S}$ V_R = Receiving end voltage V_S = Sending end voltage Phase angle across the line	[103]
4	Equivalent Node Voltage Collapse Index (*ENVCI*)	Yang Wang et al.	$ENVCI = 2E_kV_n\cos\ \theta_{kn} - E_k^2$	For strongest bus, $ENVCI = 1$; for weakest bus, $ENVCI = 0$	Useful for online assessment. It is quickly determined by using the voltage phasors	V_n= Voltage at Nth node E_k = Voltage of the external system $\theta_{kn} = \theta_k - \theta_n$	[115–117]
5	Novel Line Stability Index (*NLSI*)	A. Yazdanpanah-Goharrizi et al.	$NLSI = \frac{PR+QX}{0.25V_1^2cos^2\delta}$	Value close to 1 indicates voltage collapse point	Consider both active and reactive power; accurate results	P= Active power Q= Reactive power R= Resistance of line X= Reactance of line V_1= Sending end voltage δ= Angle difference between sending and receiving buses	[118–120]
6	Voltage Collapse Point Indicators (*VCPIs*)	M. Moghavvemi and O. Faruque	$VCPI(1) = \frac{P_r}{P_r(\max)}$ $VCP(2) = \frac{Q_r}{Q_r(\max)}$ $VCPI(3) = \frac{P_l}{P_l(\max)}$ P_l = Real power loss in the line $P_l(\max)$ Maximum possible real power loss $VCPI(4) = \frac{Q_l}{Q_l(\max)}$	Lmn = 1 means system is near to voltage collapse; Lmn < 1 means system is stable; Lmn = 0 means system has no load	Based on ''Power flow through a single line.'' This is based on the concept of maximum power transferred through the lines of the network. A higher degree of reliability; higher accuracy; simple; easy to calculate; We do not need the information on other lines in the system for calculation. We need specific local measurements	P_r = Real power transferred to the receiving end $P_r(\max)$ = Maximum real power that can be transferred Q_r = Reactive power transferred to the receiving end $Q_r(\max)$ = Maximum reactive power that can be transferred P_l = Real power loss in the line $P_l(\max)$ = Maximum possible real power loss Q_r = Reactive power loss in the line $Q_r(\max)$ = Maximum possible reactive power loss	[3,121,122]
7	LQP index	Mohammad et al.	$LQP = 4(X/V_s{}^2)(X/V_s{}^2(P_s{}^2 + Q_R))$ $LQP = 4(\frac{X}{V_i^2})(Q_r + \frac{XP_i^2}{V_i^2})$	LQP =1 means the system is near to voltage collapse	Based on line stability factors; fast computation capability; helps to find the cause of voltage collapse	X = Reactance R = Resistance V_i = Input Voltage P_i = Input power Q_r = Reactive power at receiving end	[123,124]
8	*VSI*_1	Y. Gong et al.	$VSI_1 = (\frac{P_{margin}}{P_{max}}, \frac{Q_{margin}}{Q_{max}}, \frac{S_{margin}}{S_{max}})$	$VSI_1 = 0$ System collapse	Provides voltage stability margin of each bus. Also diversifies the most critical load bus	$P_{margin} = P_{max} - P$ $Q_{margin} = Q_{max} - Q$ $S_{margin} = S_{max} - S$ P_{margin} = Active load margin Q_{margin} = Reactive load margin S_{margin} = Apparent load margin	[125,126]

Table 1. *Cont.*

Sr.	Index	Proposed by	Expression/Formula	Critical Value	Salient Features	Input variables (of Formula)	References
9	Power Transfer Stability Index (*PTSI*)	M. Nizam et al.	$PTSI = \frac{2S_L Z_{Thev}(1+\cos(\beta-\alpha))}{E_{Thev}^2}$	1 indicates voltage collapse point	Helps in finding dynamic voltage collapse	E_{Thev} = Thevenin voltage Z_{Thev} = Thevenin impedance S_L = Maximum load apparent power β, α = Load phase angles	[127]
10	Line Index (L_{ij})	C.Subramani et al.	$L_{ij} = \frac{4Z^2 Q_j}{V_i^2(R\sin\delta + X\cos\delta)^2}$	L_{ij} = 0 line is close to voltage collapse	Easily identifies the weak areas of a nearly stressed system	Z = Line impedance X = Line reactance V_i = Sending end voltage Q_j = Receiving end reactive power	[128,129]
11	L_{SR}	Mario A. Albuquerque and Carlos A. Castro	$L_{SR} = \frac{S_r}{S_{r\ max}}$	L_{sr} = 1 voltage stability indication	Easily used in real time; exactly recognizes the critical contingencies	S_r = Apparent power flow $S_{r\ max}$ = Maximum power transfer	[130]
12	New Voltage Stability Index (*NVSI*)	R. Kanimozhi et al.	$NVSI = \frac{2X\sqrt{P_j^2+Q_j^2}}{2Q_j X - V_i^2}$	1 indicates critical line	This index relates real and reactive powers; high standard voltage instability prediction; relates real and reactive power; exact voltage stability prediction	X = Line reactance P = Real Power V_i = Sending end voltage Q_j = Reactive power at receiving end	[131,132]
13	Voltage reactive power index (VQI_{Line})	F.A. Althowibi et al.	$VQI_{Line} = \frac{4Q_{km}}{\lvert B_{km}\rvert.\lvert V_k\rvert^2}$	1 is the point at which voltage collapses	Easily tells the distance from the point of voltage collapse of any line; high speed and accuracy	Q_m = Receiving reactive power at bus V_k = Sending voltage at system bus Y_{km} = Line admittance between bus k and m $B_{km} = Y_{km}\sin\theta$	[133]

2.3. Voltage Stability Improvement by FACTS Devices

Originated by a reactive power imbalance, voltage instability has always been a serious attention-seeking problem in a power system. Fast control features of FACTS devices make them a great candidate to control and regulate both active and reactive powers, thereby restricting the voltage magnitudes within the stability margins [134,135]. FACTS are the power-electronic devices used to escalate reactive power generation and hence can improve voltage stability [136]. Suitable site selection for the allocation of FACTS devices is a must to exploit them efficiently. Incorporating these devices at the weakest bus yields in boosting up the voltage profile of a power system [13,137,138]. The evolutionary algorithm-based method concerning cost function is presented in [139] and the Genetic Algorithm (GA)-based novel technique is presented in [12,140,141] to dilate the voltage stability margin and diminish system losses by the optimal allocation of Multi-type FACTS devices. Introduced by Eberhart and Kennedy, the Particle Swarm Optimization (PSO) algorithm can also be employed to maximize system load-ability regarding a minimum cost of the installation of the devices [142]. However, the Group Search Optimizer with Multiple Producer (GSOMP) algorithm has been used in [143] for improving voltage and lessening the real power loss by multiple FACTS devices. It is effective for finding the multiple FACTS device parameters, because it gives better results in average and minimum form for power loss optimization as compare to Particle Swarm Optimizer (PSO).

Dr. J. Amarnath et al. suggested the optimal location of Static VAR Compensator at the particular bus that has the most negative sensitivity index for the voltage stability enhancement, whereas the optimal location for Thyristor Controlled Series Compensator (TCSC) is the bus with the most positive loss sensitivity index [144]. Reference [135] examined the effectiveness of TCSC, SVC, and UPFC to study voltage stability in various scenarios by implementing them in a common Newton Raphson power flow. The authors concluded

that UPFC amalgamates the benefits of both TCSC and SVC, namely reduction in active power loss and improvement in voltage profile. The authors of [145] proposed a general methodology for the improvement of steady-state voltage stability using FACTS devices in an IEEE 39-bus test system environment. A. Rathi et al. offered a different Distributed Flexible AC Transmission System (D-FACTS), for controlling system voltage by examining sensitivities of voltage magnitudes with respect to variations in line impedances [146]. Figure 1 demonstrates types of FACTS devices, and Table 2 summarizes some important FACTS devices used for voltage stability improvement with special findings asserted by several researchers.

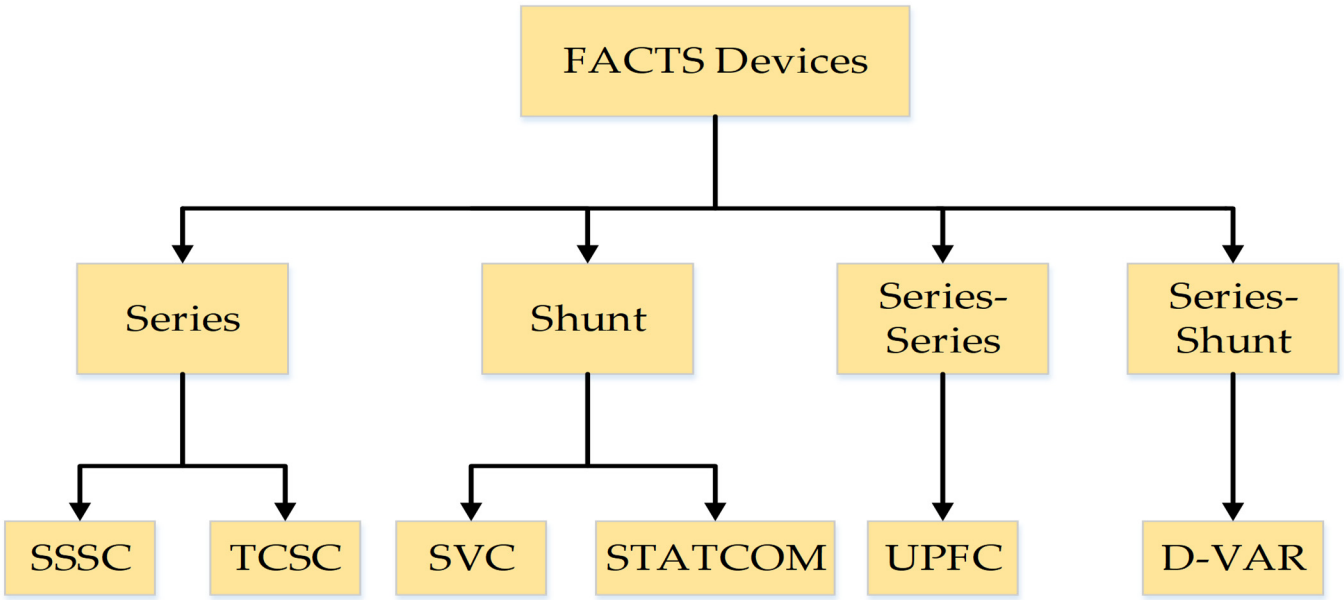


Figure 1. Classification of FACTS devices.

Table 2. List of FACTS devices.

Sr	FACT Device	Category	Salient Features	Special Findings	Refs.
1	SSSC	Series	• To elude voltage unbalance, SSSC uses the voltage source inverter (VSI), which controls the rotor current, which in turn controls the reactive and active power fed from the wind farm to the connected grid • Provides a better series of compensation • Provides the active DFIG	• C. Udhaya Shankar et al. conducted tests at a specific bus of two machine power systems and concluded via simulations that voltage stability had been improved along with the damped power oscillations using SSSC. • SSSC has been called the best controller for voltage stability improvement by Hridya.K.R et al. based on their simulations in PSAT. They made use of line index voltage stability L_{mn} to conduct the test to simulate two disturbances to get the desired outcomes.	[147–150]
2	TCSC		• It is located at the line that held the most positive 'loss sensitivity index' for reactive power load reduction • Used at the line having the most negative 'sensitivity index' for PI method • Can be operated in both capacitive and inductive regions and hence acts as a controllable series impedance for wind voltage instability	• F. Z. GHERBI and ABDSALLEM analyzed the impact of integrating wind generation and FACTS on the voltage collapse and active losses of IEEE 30 bus system, and they concluded that TCSC is the best choice for the active power control. • Joshi and Mohan used the TCSC for the interconnection of wind turbines to grid in terms of voltage stability issues. In their literature, they performed modeling of TCSC connected to a wind turbine along with an induction generator that resulted in its effectiveness for voltage unbalance compensation and fault current limitation.	[151–154]

Table 2. *Cont.*

Sr	FACT Device	Category	Salient Features	Special Findings	Refs.
3	SVC	Shunt	• SVC is based on thyristor-controlled rectifier (TCR) • SVC has to be located at a bus with the greatest negative 'Cij sensitivity index' • Controls the equivalent resistance of a bus to control its voltage and SVC is like a shunt reactor • SVC improves the bus voltage more than that of a TCSC present in a line, so SVC is better • Based on annual operating cost expectation, location of SVC has been proposed	• By employing SVC in a wind farm with PSCAD/EMTDC program, Zakieldeen Elhassan et al. presented that terminal voltage (V_T) has improved from 0.9078 pu to 1.0 pu. The voltage at the point of common coupling (V_{PCC}) is enhanced from 0.9395 pu to 1.003 pu. • Tang Baofeng et al. presented a substation in Liutun connecting three 220 kV fault buses of Hancun, Cangxi, and Yuzhuang. The simulation result showed enrichment in voltage profile by SVC usage from 0.004 pu to 0.009 pu at Liutun substation.	[144,155–158]
4	STATCOM		• Gives fast and smooth steady state and moreover the transient voltage control at the points of voltage dips in the system • The response is faster in STATCOM as compared to SVC • As compared to SVC, compensating current of STATCOM is independent of common point voltage. So, it does not change with a voltage dip • Operates at full capacity even during low voltages	• Keping Zhu et al. employed cascade STATCOM with a grid-connected wind form to enhance voltage stability. Through simulations, they showed that cascade STATCOM could govern the voltage profile quickly and smoothly by providing reactive power to the grid-connected wind farm. • Ahvand Jalali et al. showed how to upsurge the voltage stability of power networks with embedded wind farms by combining STATCOM with Energy Storage Systems (ESSs) and also highlighted the placements of these devices to boost up VSM.	[159–162]
5	UPFC	Combined series shunt	• Controls active and reactive power in both ways either simultaneously or selectively • Gives direct bus and line control • Good series compensator • Phase shifter • Controls power flow for only one transmission line • UPFC arrangement with the wind form sustains the voltage imbalance during integration with the grid	• Yasser M. Alharbi et al. applied UPFC to improve the LVRT capability of DFIG-based wind turbine systems. Via simulations, they showed that the proposed controller for UPFC can appreciably improve the LVRT ability of the wind turbines and assure the continuity of power delivery during small voltage dips. • A. Papantoniou et al. simulated a wind farm model whose voltage profile was 10% less than the nominal voltage and stabilized to nominal value after insertion of UPFC.	[163–165]
6	D-Var		• A type of STATCOM • Effectively solve the problems of wind energy generation • Controls the overall voltage profile at the collector bus • Additionally, it controls the nearby switching of capacitor devices to improve voltage stability • Diminishes the transients of capacitor-switching	• A. Kehrli et al. presented an 8 MVar D-Var system controlling nine banks to correct power factor. Between the utility and turbine, 1 MVA D-Var incorporated injections of about 2.3 MVar at point of common coupling to diminish the voltage dip and bring the wind farm to the normal condition after the voltage dips.	[159]

2.4. Identification of Weakest Bus

Power system stability is at stack when the voltage of one of the buses approaches its collapse point, and ultimately, the system leads to a blackout. To ensure the operation of the power system is within the security constraints, it is utmost important to figure out the weakest bus in the power system under various operating conditions [166,167]. The weakest bus is the one that is heavily loaded, has the most sensitive voltage, and first reaches the minimum/maximum limit after which system security gets affected. The most influential factors that determine the strength of a bus are the R/X ratio of interconnections, load directions, load models, the different network configuration, installation of compensators, and generators. Moreover, the lack of local and remote VARs can have the worst impact on the critical bus [168–171]. A power system can be analyzed in two aspects: one is static and

the other is dynamic. The former approach is utilized to signify the weakest bus. However, this approach can cause the loss of dynamic stability of the system [172]. The purpose of weakest bus identification is to improve the voltage profile on these buses for increasing the power transfer capability and maximum loading limit [173]. Secondly, it furnishes the exact information about the optimal reactive power planning, and it directs better sites for the installation of reactive power sources [174]. As it is vital to determine the weakest bus in the system, different researchers used various computational tools and methods to spot such a bus. For example, reference [175] deals with the voltage collapse proximity indicator (VCPI) method; the Singular Value Decomposition (SVD) method is examined in [176]; in [177], the authors used the real-coded simple Security Constraint Genetic Algorithm (SCGA) to compute the maximum loading limit for different IEEE standard bus systems; and [178] makes use of the nodal voltage security assessment tool. M. K. Jalboub et al. made use of Singular Value Decomposition, multivariable control, and modal analysis to study voltage stability and determine the weakest bus in the system [179].

In references [171,180], various Voltage Stability Indices have been explained to evaluate the strength of a bus irrespective of the load type. These are:

- ❖ voltage sensitivity factor;
- ❖ reactive power margin;
- ❖ L-Index.

The estimated value of L-Index varies between 0 and 1 [181]. In a nutshell, determination of the weakest bus in a power system is inevitable to restrict the system within permissible limits.

3. Wind-Integrated Power Systems

Due to the intensive demand growth for electric power in every sector of life, the appropriate financial and environmentally friendly resources are getting a great deal of attention. The wind energy market has been a far-reaching subject of interest, especially in European, North American, and Asian countries like China in the several past decades. A glance over some statistics about wind power capacity in the near past indicates that the wind capacity has increased from 6000 MW (1996) to 197,000 MW (December 2010) [177]. Up until 2006, the countries with the highest total installed capacity were Germany (20,622 MW), Spain (11,615 MW), USA (11,603 MW), India (6270 MW), and Denmark (3136 MW), and this kept on increasing year after year [182]. In 2015, the increase in wind generation was equal to almost half of the global electricity growth [183]. Globally, the year 2015 crossed the 60 GW mark for the first time in history, and 63 GW of online power capacity was injected to the system. In Asia, China sustained its premiership position and installed 30.8 GW of wind energy at the end of 2015. India remained unbeatable at the second position in Asia and installed 2623 MW for the total of 25,088 MW. The US market, which is the second single largest market after China in terms of total installed capacity, added 4000 new turbines for the total capacity of 8598 MW in 2014 and got a 77% increase over the year 2014 [183]. At the end of 2016, the new installed capacities for different regions around the globe include Africa and Middle East (418 MW), Asia (27,680 MW), Europe (13,926 MW), Latin America and Caribbean (3079 MW), North America (9359 MW), and the Pacific Region (54,600 MW) [178]. The study on the rate and pace of wind energy growth reflects that 12% of all the electricity generation will come from wind resources by 2020 [184,185]. Figure 2 graphically shows the gradual increase in the wind market over the last two decades, whereas the regional installed capacity (MW) by the end of 2016 is shown in Figure 3 [186,187].

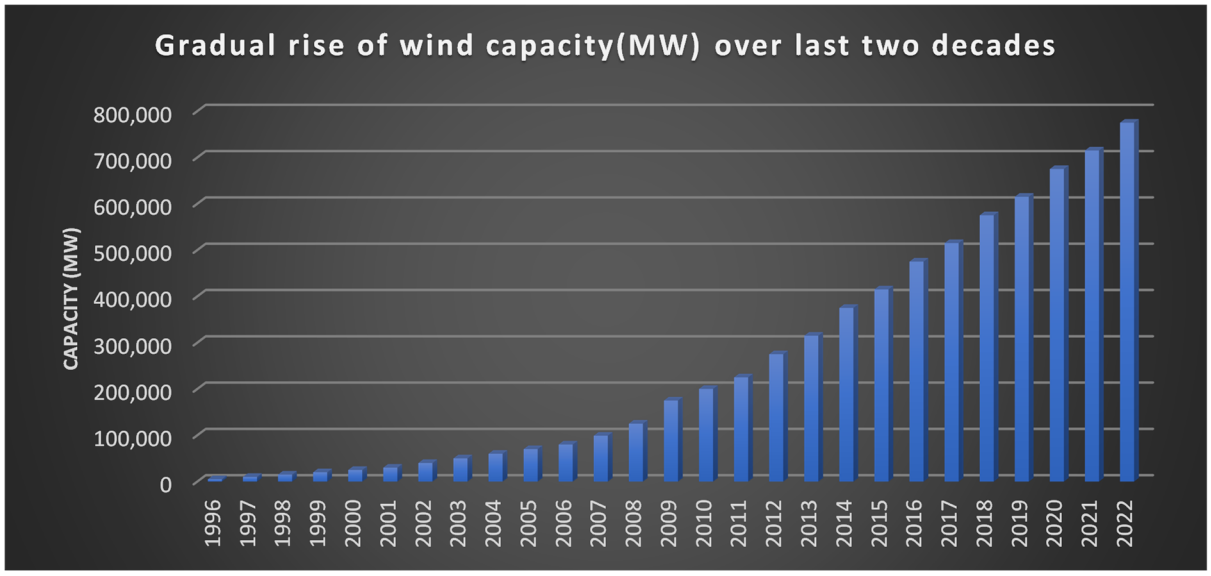


Figure 2. Gradual rise of wind capacity (MW) over last two decades.

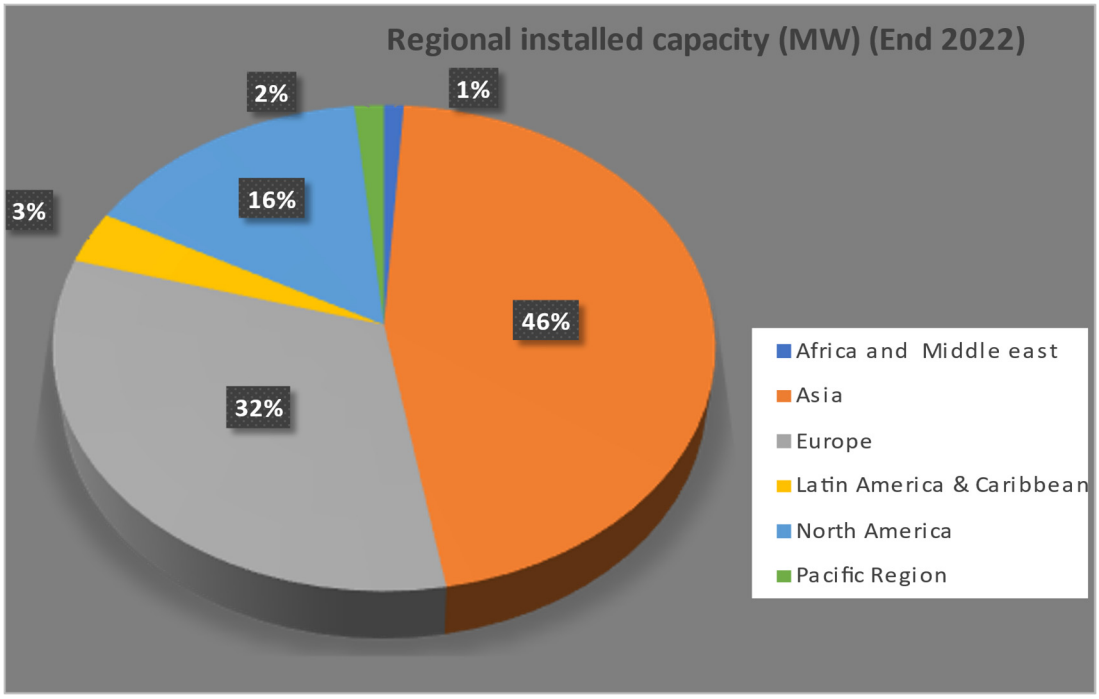


Figure 3. Regional installed capacity (MW).

Pakistan, a developing country, has been going through energy crises for the past several decades. Currently, the amounts of generating and demanding power are not getting closer. Hence, researchers and engineers are trying to explore more resources of power generation to get rid of the energy crises. Among renewable energy resources, wind energy is also being paid heed in many areas of Pakistan. The availability of wind speed needed to operate wind turbines is low in Pakistan [188]. A few areas have sufficient wind speed like the Jhimpir Wind Power Plant that is located at Jhimpir in Thatta, District of Sindh province in Pakistan. This power plant comprises 33 wind turbines, injecting a total capacity of 56.4 MW of power into the system. At present, 45 wind power projects are working in Pakistan, with 3200 MW capacity [189].

3.1. Grid Codes

Nature has gifted us numerous efficient wind sites around the globe, but unfortunately, most of them exist far away from the load centers and are weakly interlinked via long transmission lines. Under such conditions, the steady state voltage level gets affected by pouring a large amount of power into the system. To make the system secure, stable, and reliable, we have to consider grid codes [190]. Grid codes are formulated to ensure steadfast operating conditions and to correlate the on-working generating unit disturbances. A grid code presents the requirements for the proper interconnections of wind power plants with the grid [191]. At the point of interconnection, grid codes primarily circumscribe the grid specifications and requirements. Grid codes differ substantially on several bases such as the nature of country/region or the type of transmission and distribution system [192]. The main causes of varying requirements of grid codes correlate with the network structure, short circuit capacity, the technology used in the wind turbine, total installed capacity, and the amount of the penetration level [193]. There are plenty of mandatory requirements in grid codes, but from the wind farm outlook, some are as follows [192]:

- active power control;
- frequency control;
- voltage regulation;
- frequency variations;
- overvoltage conditions;
- fault ride-through;
- voltage regulation and power factor;
- power quality.

Andreas Armenakis et al. proposed some additional parameters such as requirements for reactive power, short-circuit current, and provision of ancillary services on significant grid users for the small wind farms connected to small distribution grid in Cyprus [194]. The reactive power output control for the wind farm is essentially regulated within the reactive power range to reach this set point [195]. E. Fagan et al. proposed the Irish grid code design and examined the supplementary requirements like provision of signals, control, and communications added on by the System Dispatch Codes. To employ the voltage and frequency requirements, the signals and control commands are needed for transmission system operators (TSOs) [196]. Another requirement for the Irish wind grid code is that the wind farm should be adequate to supervise the ramp rate of its active power output with a maximum MW per minute ramp rate that is adjusted by the transmission system operators (TSOs) [193]. Germany (EON) spells out both the maximum permissible active power change and the minimum required active power reduction capability. While the grid codes of China (SGCC), Britain (NGC), and Ireland (ESB) only set the maximum ramp rate [193].

3.2. Wind Farm Integration

To overcome the deficiency of non-renewable energy sources, wind energy has turned out to be the most popular energy generation method, and wind farms are being integrated with the conventional grid at a high rate and pace in many developed countries [196]. In this process, one of the serious problems that we have to deal with is the voltage instability, which arises due to the fluctuating nature of wind power [197,198]. That is why, now, power system utilities' interests are more inclined towards stability issues rather than power quality [199,200]. Generators used in wind turbines can be broadly categorized into two classes, which are fixed speed and variable speed. Squirrel Cage Induction Generator (SCIG) falls in the first category as its output is directly coupled with the grid. SCIGs can only absorb reactive power, whereas variable rotational speed DFIGs can produce or consume reactive power. This makes DFIGs a better choice in wind farm integration [196,199,200]. The installation of Automatic Voltage Regulators (AVRs) in all the generators can be helpful to avoid the small fluctuations in voltage and restore grid stability after the integration of wind farm [201].

Without sufficient reactive power support, the wind farm connected to a weak node may be tripped due to AC under-voltage protection if the node voltages stay too low, eventually leading the system towards voltage collapse [202]. The increased wind power capacity decreases the voltage stability margin even in the presence of the crowbar; the voltage stability of DFIG-based systems remain vulnerable at the point of fault clearance as long as the fault persists [203]. Different types of wind turbines can be integrated with the conventional grid, and the impact of some of the turbines on voltage stability has been reported in [202]. The impact on voltage stability with respect to the type of wind turbine, for e.g., DFIG vs. full-converter, depends on various factors. One of the major factors is reactive power control capability. Full-converter wind turbines offer high flexibility in reactive power control. Regardless of the amount of active power generation, they can absorb and inject reactive power to provide voltage regulation and grid stability. On the other hand, reactive power control capabilities of doubly-fed induction generators (DFIGs) are very limited. In order to provide adequate reactive power support, they usually require additional equipment such as static var compensators (SVCs). Consequently, under certain conditions, DFIG-based wind farms are more prone to voltage dips. Another important factor is the fault ride-through (FRT) capability. During temporary faults or voltage dips, wind turbines with strong FRT capabilities can remain connected to the grid. Therefore, the impact on grid stability will be minimized, cascading outages can be prevented, and faster recovery of the grid is possible. However, during faults, wind turbines with weaker FRT capabilities may detach from the power grid, posing a risk to system stability and further exacerbating voltage dips. Furthermore, wind turbines associated with weak grids (high line impedance) or operating at low power may not be able to provide sufficient reactive power support during faults and therefore are more likely to contribute to voltage drops. Conversely, necessary reactive power support can be provided by the wind turbine attached to strong grids or operating at high power to enhance voltage stability. Therefore, owing to strong FRT capabilities and flexible reactive power control, full-converter wind turbines are preferred for voltage stability. However, with careful planning and an appropriate grid support, DFIG wind turbines can also be installed. Operating conditions and the entire system configuration play a vital role in any wind turbine type's response to the faults. Consequently, in order to analyze the impact of wind integration, detailed studies and simulations must be carried out on a case-by-case basis. Based on simulation results, reference [204] concluded that the increase in the penetration level of wind farm results in system instability that imposes severe effects on the voltage profile of the system.

Hierarchical Security Constrained Optimal Power Flow (SCOPF) is a cost-saving method used for large wind-integrated system that makes the calculations easy by separating the AC system from the DC system [205]. The effect of wind farm integration on the system's voltage stability is dependent on the load characteristics. Based on load types, a comparative study is conducted in [206], with and without considering load voltage dependency, concerning the location of the synchronous compensator and penetration of wind farm generation.

3.3. Weak Grids

Integration of wind farm with the conventional grid possesses serious threats on the stability, security, and reliability of the normal operation of a power system. The bulk amount of wind energy injection via long transmission lines with a limited short circuit ratio (SCR) result in low short circuit current and hence diminishes the system strength. When a wind farm is being integrated with a weak grid, it leads the system stability to a more precarious state. Keeping in mind the severity of the fact, many of the researchers have paid due attention to this troublesome phenomenon [207–209]. Considering the static and dynamic performance, IEEE standard 1204 [210] defines the weak alternating grid:

1. the AC system impedance may be high relative to DC power at the point of common coupling (PCC);

2. AC system mechanical inertia which may be inadequate relative to the DC power infeed [210,211].

Among various gauges mentioned in the literature, Low Short Circuit Ratio (LSCR) is the main indicator of the weakness of a grid [207]. In [209], Short Circuit Ratio (SCR) is described as:

$$SCR = S''_{K_PCC}/S_{wind_power_plant} \quad (1)$$

where S''_{K_PCC} = short circuit power at the wind power plant point of common coupling and $S_{Wind_Power_Plant}$ = wind power plant capacity.

Refs. [211–213] designated the grid as strong when the SCR is between 20 and 25, and for weakness, the value lies below 6–10. A grid is recognized as weak if the value of the effective SCR is less than 2.5 [214]. Low effective DC inertia constant also acts as an indication of a weak grid [215] if its value is below two [214,216,217], which addressed different problems associated with the weak grid itself and when it is connected with the wind farm and provided some useful solutions for the issues. Among innumerable complications of the weak grid, voltage instability is a drastic one, because the occurrence of fault at the point of common connection (PCC) will cause a voltage dip that results in tripping of several turbines if not controlled well in time [218]. To meet the challenge for voltage control, the adequate amount of reactive power compatibility is ensured. Under a weak grid, the dV/dQ sensitivity is high. According to [219], a grid having the value of its SCR less than three is considered as feeble. Consequently, an SCR less than its threshold value leads to noncompliance action of the turbine, thus generating voltage oscillations. Voltage stability analysis is performed that is based on PV and QV curve method with the different short-circuit ratios and X/R of the external grid [217].

The impedance could increase further because of several faults, load dynamics, and line tripping [220]. Furthermore, the electromagnetic stability is associated with the mechanical design. The Permanent Magnet Synchronous Generator (PMSG) and DFIG may cause electromagnetic stability problems in a weak grid. DFIG output variation causes the worst voltage fluctuation in a weak grid [221]. Electromagnetic stability can be improved by modifying specific mechanical design features, which includes elimination of the gearbox. This helps to improve the overall system efficiency and reduce the potential of mechanical failures. Furthermore, a faster reactive power response can be achieved to enhance stability. To improve the power output smoothness and minimize the torque fluctuations, an optimal aerodynamic design of the blades can be developed. It will also improve voltage and electromagnetic stability and reduce stress on the electrical system. Additionally, stability can be improved by using a composite material such as carbon fiber to create lighter blades. The overall system stability can be enhanced by utilizing damped or tuned mass damper systems in the tower design, contributing to mitigate oscillations and vibrations caused by the wind gusts. To mitigate the voltage fluctuations due to DFIG wind turbines in weak grids, control algorithms to dynamically adjust the reactive power output according to the grid need can be implemented. Furthermore, grid support technologies such as SVCs, battery energy storage systems (BESSs), and FACTS devices can be employed to improve the overall grid stability and mitigate DFIG-induced fluctuations. To minimize localized voltage disturbances, multiple DFIG wind farms can be coordinated effectively for balanced reactive power contributions. Moreover, upgrading the existing transmission infrastructure and deploying smaller, distributed generation sources closer to wind farms can help mitigate the DFIG-induced fluctuations on longer transmission lines and support local voltage profiles.

3.4. Low Voltage Ride-through

In any power system, the stability of the grid functioning and the security of the power system are prominent aspects. For this purpose, the power generating plants, including turbines and generators, must have some suitable methodology and control capabilities. To achieve these objectives, the term Low Voltage Ride-Through (LVRT) is

presented, which can be put into words as the requisite to persist in the operation of the generating plants through short periods of low grid voltages [222]. Even if the voltage in any phase becomes less than 80% of its nominal value, then the generators should remain in operation and connected to the power system in an LVRT-capable power system [223]. LVRT is the ability to keep the wind turbines connected with the grid, even under faulty conditions [224]. For wind farms, LVRT is marked as an integral part of grid codes by the regulatory bodies. Popular DFIGs having partial converters do not have the capability of Low Voltage Ride-Through. Non-linear Control-based Modified Bridge-type Fault Current Limiter (NC MBFCL) application has been proposed in [225] for enhancing LVRT capability in DFIG-based wind farms under symmetrical and non-symmetrical faults. One of the top requirements of the grid codes is to keep the DFIGs connected with the load during LVRT.

LVRT capability of a power system is being improved through different superconducting power devices. Lei Chen et al. carried out MATLAB simulations to prove the superiority of the Superconducting Fault Current Limiter (SFCL) on Dynamic Voltage Restorer (DVR) in terms of economic and technical perspectives for improving LVRT of the micro-grid [226]. Huihui Song et al. proposed a new strategy for limiting the adverse impact of voltage drop that integrates the attenuation of L2 disturbance with energy-based control of DFIG. This improved strategy is preferable to conventional energy-based control methods in terms of internal and external faults of the grid [227]. Asymmetrical fault ride-through capability of the DFIG-based WECSs is presented in [228] to study the dynamic behavior of DFIG via the MATLAB/Simulink R2010b environment with the help of space vector control concept.

Large loads and different faults (short circuit or lightning) are considered to be some of the dominant causes of short-term voltage dips. Every grid connection requires a certification test, which is measured by its LVRT characteristics with the help of different simulation techniques for voltage dips at several scenarios [221]. The viable function of LVRT is to compare the characteristic with the terminal voltage. Use of LVRT results in the system's expensiveness because it suggests additional apparatus and modulation in the control design and approach [229].

Various testing methodologies exist to check the LVRT ability of wind turbines, which includes devices such as series connected Voltage Source Converter (VSC), autotransformers, synchronous generators, etc. Among these, impedance-based Voltage Source Generator (VSG) is mostly used for confirming the LVRT capability of wind turbines. By using the PSCAD/EMTDC time domain simulation, [230] demonstrated the VSC-based novel LVRT test technique, which can help in wind turbine voltage control.

The need for on-site LVRT testing cannot be over-emphasized because of the following reasons [231]:

1. it gives more realistic results as compared to the ones found in the laboratory;
2. to ensure the LVRT capability of all the installed wind turbines;
3. to counter-check the capability of wind turbines after major events in a system's maintenance.

To fulfil these requirements, the authors of [231] presented a novel technique for the on-site assessment of LVRT for Full Power Converter (FPC) wind turbines and showed via MATLAB-based simulations that without any hardware modifications, the on-site LVRT tests could be performed by proper modifications in the control algorithm. Reference [232] pointed out some of the latest methods of improving LVRT. It can exclusively be performed either by using external devices or by controller improvement methods. These have been summarized in Figure 4.

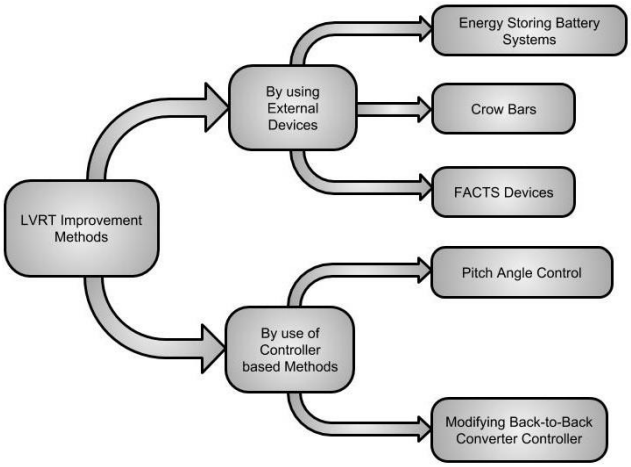


Figure 4. LVRT improvement techniques.

3.5. High Voltage Ride-through

Numerous grid code requirements must be accomplished to sustain the uninterrupted overall stability and reliability of any wind turbine system. Among these various requirements, the implementation of High Voltage Ride-Through (HVRT) capability is integral. Contrary to LVRT, the HVRT capability of the wind turbine is the ability to keep itself connected with the grid throughout the voltage rise circumstances up to a certain level. Australia is credited as a pioneer country in developing the criterion for HVRT [233]. Switching OFF large loads, single line to ground fault, unbalance faults, load shedding, or switching ON the capacitor banks can result in voltage swells, so HVRT becomes a critical event in terms of the system stability [234–236]. Since the use of DFIG in the wind industry is promulgating, a main concern with the DFIG is that its stator side is directly connected to the grid, and it makes DFIG more sensitive towards disturbances like voltage swells and voltage sags [237].

Few researchers have emphasized the control strategies for HVRT resulting from voltage swell [238]. In reference [239], the authors proposed a hybrid current controller scheme to enhance the Low and High Voltage Ride-Through capabilities of DFIG-based wind turbine systems. Under normal operating conditions, they used a standard proportional integral (PI) and current controllers to regulate the output currents of the rotor-side and grid-side converters. FACTS devices are also incredibly supportive in increasing the HVRT capabilities of DFIGs. For the improvement of the HVRT capabilities of DFIG systems, STATCOM is investigated in [240]. Using the MATLAB/SIMULINK environment, a suitable algorithm is developed by considering 30% voltage rise for HVRT, and a novel strategy is introduced for enhancing the ride-through capabilities of DFIG [241]. A hybrid current controller is proposed in [239] for HVRT as well as the LVRT improvement of wind farms. Reference [242] proposed a strategy for controlling HVRT based on GSC, while a cost-saving strategy requiring less hardware with little software algorithm changes is reported in [243].

Electric power can be generated under constrained conditions via wind turbines. The minimum speed at which a wind turbine starts generating power is referred to as cut-in wind speed and typically varies between 2 and 3 m/s, whereas it produces rated power in the range of 11–15 m/s [244]. However, there are certain circumstances when the wind speed overshoots these limits and approaches 25 m/s for a predefined spell or a 30–35 m/s sudden puff. Under such deteriorative conditions, it is necessarily important to implement a security feature termed as High Wind Speed Shutdown (HWSS). This technique saves the turbine from severe damage to its various parts, specifically turbine motor and blades, but results in an unpredicted loss of power generation [244,245].

3.6. Role of DFIG in Voltage Stability Improvements

The exploitation of fixed and variable speed induction generator is communal in the current era of wind industry [246]. Almost 78% of the total wind installed capacity has employed DFIGs for the generation of electricity [4]. Distribution network-connected wind farms often experience a higher-level voltage disturbance of about 2%. Such disturbances are coped with the use of DFIG [247]. DFIG is essentially a wound rotor induction generator, having its rotor coupled with a voltage source converter, frequently known as the Rotor Side Converter (RSC) [248,249]. Recognition of DFIG as the prevalent wind turbine system is based upon the following pluses [157,232,249–256]:

1. independent control capability for active and reactive powers;
2. constant frequency operation at variable speed for robust four quadrants' reactive power control;
3. handles 20–30% of total system power that eventually lowers power losses;
4. operate at a higher range of wind speed
5. lower mechanical stress and acoustical noise;
6. high energy efficiency;
7. lower cost due to low rating power electronic converters.

Another overwhelming plus point determined is the penetration level that is 60% more in case of DFIG as compared to its counterpart SCIG [246]. The most imperative responsibility of DFIG is to provide LVRT capability, so that wind farms remain connected with the grid as per grid code requirements when the voltage dip occurs for a shorter time interval [248]. Such low voltage scenarios impose serious threats on the system equipment, especially on the RSC [257]. A widely used protection technique is connecting the crowbar to the rotor circuit that will bypass RSC. Nevertheless, this technique reduces DFIG control competency, increases mechanical stress and power oscillations, and devours more reactive power from the grid, eventually leading to exaggerated fault conditions [251,257,258]. Figure 5 shows the schematic diagram of DFIG-based WT integrated with the conventional grid through GSC and RSC voltage source converters and a common DC bus. The main components of a DFIG-based wind turbine system are drive train, pitch angle control system, DFIG system control, and protection system (crowbar). Drive train helps to reduce the electrical torque during grid fault.

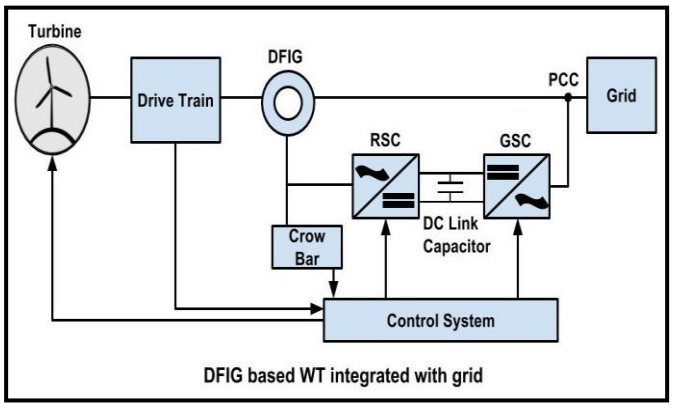


Figure 5. DFIG-based WT integrated with grid.

An apt balance in the demand and supply of reactive power of any system controls the voltage stability issues, and DFIG is remarkable in this regard due to its special design [259]. This capability of providing reactive power alters according to the power electronic converters' rating [260]. Jinho Kim et al. proposed a hierarchal voltage control scheme employing a wind generator (WG) controller and wind power plant (WPP) control [261]. Another control strategy employing both the GSC and RSC is presented in [262] to acquire voltage stability. RSC and GSC both control the active and reactive power injected by the generator

into the grid, while the GSC maintains the DC link voltage constant independent to the direction of rotor power flow. But GSC has the edge over RSC because the reactive power is primarily produced by GSC [7]. In a doubly fed induction generator (DFIG), RSC adjusts the amplitude and frequency of the voltage applied to the rotor winding to control the active and reactive power generation of the wind turbine. It establishes the connection between the DC link and the rotor windings with the help of IGBTs or GTOs. To maximize the energy generated from fluctuating wind speed, RSC enables the wind turbine to operate at different speeds, and both active and reactive power output control is possible to improve voltage stability and regulation. Furthermore, its cost is lower compared to full-converter wind turbines. However, reactive power control range is limited compared to that of full-converter wind turbines. Consequently, additional support such as SVCs are required in weak grids for full reactive power support. Furthermore, it can experience torque oscillations and stress under fault conditions. GSC controls the power flow between the grid and the wind turbine and maintains a constant DC link voltage. It establishes the connection between the DC link and the grid at the frequency and AC voltage that the grid requires. It maintains a constant DC link voltage and establishes a smooth connection between the wind turbine and the grid. Moreover, in order to improve grid stability, it can inject or absorb reactive power according to the requirement and provides independent control of the active and reactive power flow from the wind turbine. However, in order to maintain DC link voltage stability and grid synchronization, robust control systems need to be employed in GSC. Additionally, its hardware design is very complex, and advanced filtering techniques are required for harmonic generation. Consequently, the cost of GSC is much higher compared to simple grid-connected asynchronous generator. RSC can be used for many purposes like torque controller, speed controller, or active power controller to regulate the DFIG output [263]. However, a few challenges should be taken into consideration in the installation, like voltage sags and short circuits [264]. Owing to the voltage sag behavior of DFIG, early researchers have identified two main issues, namely overcurrent in the rotor and overvoltage in the DC link capacitor [239,255]. The DFIG response towards grid disturbances is more sensitive and requires additional attention for power converter protection as prescribed earlier [255,256,264]. If the imbalance in the voltage is not taken into consideration, the rotor and stator current can be highly unstable because of the negative impedance of DFIG [264]. One more issue with DFIG is the unavoidable use of brush gear and slip rings, and this put a question mark on the DFIG reliability; so, a brushless DFIG can be a better candidate [6].

3.7. Penetration Level of Wind Energy

A number of factors affect the permissible wind energy penetration level; some of those are system inertia, headroom, frequency sensitivity index, and the amount of governor responsive generation. Frequency sensitivity has a major impact on the penetration limit [265]. The power system must be stable enough to withstand the frequency fluctuations during penetration. During wind energy penetration, the whole cascaded system may lead to collapse if it is not strong enough to withstand the frequency variations within the reasonable limit [266]. To estimate how much variation within frequency limits is bearable, the following specified parameters are considered:

- frequency deviation range = $\pm$0.2 Hz;
- maximum predicted load disturbance = 0.04 pu.

Based on the simulation with the parameters given above, [265] concluded that in a stand-alone control area, the penetration level of wind power should not be more than the level required to create 30% reduction in inertia [267]. By appropriate placement of wind turbines, we can maximize the power generation. The maximum loading parameter decreases with the increase in the penetration level, and system moves quickly towards voltage instability. More active power generation and wind farm integration decrease the stability of the power system, as shown by the IEEE 14-bus test system [268]. Output power factor influences the maximum power injection in a system, which is specially controlled

by reactive power and simulation results, to show that the maximum power can be injected at a certain power factor [269].

3.8. The Optimal Location for Wind Farm

Driven by air puffs, the interconnected wind turbines impart electrical power to the system. To boost up power production level within effective cost criteria, it is preliminary to consider the determination of the most suitable wind farm installation site [270]. The intermittent nature of wind offers a bunch of troubles to designate appropriate sites to install wind farms. The elements like wind speed, disturbances to electrical substations, and the air density are taken into account to select an optimal wind farm location [1] amply. Generally, the selection of wind farm location is based on the following prominent characteristics:

- gusts-free availability of wind;
- regular smooth winds with least variations;
- strong air currents due to thermal gradients;
- distance from the power system;
- land cost and roads to approach the site.

Locations having such attributes are most probably hilltops, valley bottoms, vast plains, forests, and offshores significantly away from common mass [270,271]. The most substantial and significant factor in this regard is the accessibility of stiff wind at the point of installation. [272] presented the performance index PI to investigate the probability of wind availability by setting the criteria given below.

If μpi < PI, the site is not recognized as good for wind farm installation.

The power output of the turbine is defined by the power curve or p-v characteristic that varies with the wind speed. This power curve has three regions that need to be examined. Initially, to start the wind turbine, the wind speed must be greater than the cut-in speed, while the third region of the p-v curve is unsafe for turbine blades since the wind speed is at a higher level. To ensure safe turbine operation, it is made to operate between the 'cut in' and 'cut off' during the second region [273,274]. Various methodologies have been proposed by researchers and engineers to facilitate the diagnoses of the proper sites for wind farm plantation. This is a Multi-Criteria Decision Making (MCDM) problem. GIS (Graphic Information System) has been a useful tool for research and gathering information in this regard [1]. It is most often combined with MCDM, and this combination gives a concept termed as GIS-MCDM that is being frequently used in recent years for the purpose being discussed [275,276]. Geovanna Villacreses et al. [1] used OCRA, VIKOR, TOPSIS, GIS-MCDM, and AHP-based nine various methodologies for evaluating the location of wind farms in Ecuador, a South American country. Tim Höfer et al. [277], in their literature review, comprehensively enlisted the different techniques and approaches used by other researchers.

3.9. Wide Area Monitoring (Measurement) Systems

High rate and speedy advancement in the information technology sector and the deficiency of SCADA to respond to rapid system changes have stirred the researchers to make use of online tools for the quick assessment of security parameters [278]. To fulfill these necessities, a real-time monitoring system like WAMS is indispensable to assist the system operators with the real-time know-how about different instability occasions and enables them to bring about fast actions to mitigate these issues [279]. Wide Area Monitoring System (WAMS) is a modern concept, which is employed for the prior visualization and conception of transmission capacity and thermal state of the transmission line [280]. WAMS also monitors the oscillations in frequency or voltage to preclude the voltage collapse [281]. A remarkable plus point of WAMS is that the data collected are long-lasting and highly abundant [282]. A vast range of WAMS applications includes island operation and online stability assessment to trace the voltage security and stability against various interruptions in a power system [283,284].

Usually, WAMS is based on a reliable communication system, which connects the power system with the control centers. WAMS is frequently equipped with Phasor Measurement Unit (PMU) located at specific positions in a system to evaluate the phasor voltage of a station and the line current of the adjacent station [285]. The chief responsibility of PMU is that it samples and uploads the time-synchronized real-time data through that communication system [279]. A neuro-fuzzy based novel technique for the accurate online assessment of dynamic voltage stability is proposed in [286] that makes use of synchro-phasors determined by PMUs in a wide area monitoring system. Seyed Sina Mousavi-Seyedi et al. used an algorithm for online monitoring of series-compensated transmission lines. This technique used a few PMUs instead of installing PMUs on both ends of a line [287]. Figure 6 describes the simple flow-chart based on the basic operating scheme of WAMS. Several PMUs are located at different sites, and the signals from these sites are fetched by the Phasor Data Concentrator (PDC) via fast communication channels like fiber optics, and, in turn, the voltage and angle stabilities of the power system are monitored.

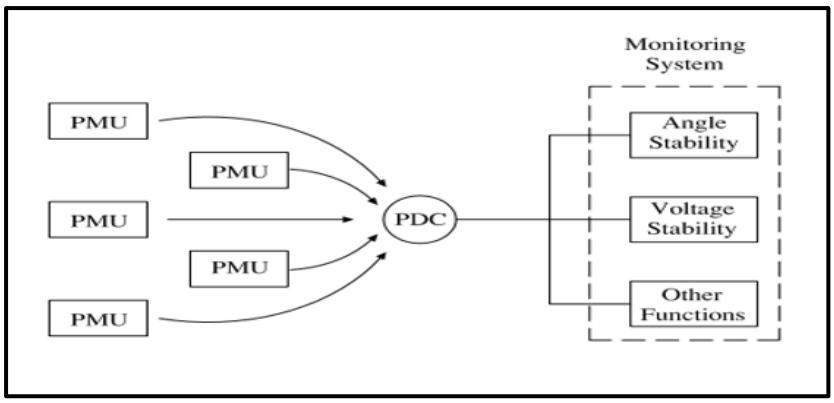


Figure 6. Flow chart of operating schemes of WAMS.

With the help of the synchro-phasor system, feasibility for the assessment of real-time transient stability has been increased. Due to fast and reliable real-time synchronized measurements by WAMS, the operator can perform the control actions by accurately monitoring the recently recovered system falling towards instability once again [288,289]. Many researchers have suggested various load shedding schemes based on WAMS, considering only the static characteristics of the induction motor to control the voltage within the permissible limits, but [290] implemented a novel load shedding control strategy based on the dynamic behavior of induction motor, incorporating WAMS with R-index, and proved its authentication on the Power System Analysis Software Package (PSASP) version 34. The authors in [291] derived WAMS-based voltage stability L-Q and L-P sensitivities, making use of the L-index, which determine the reactive power compensation and emergency load shedding for voltage control. In their case study, Pavel Hering et al. [292] presented the two key applications of PMU-based WAMS system in the distribution system. The first case study is about on-line ampacity monitoring by using WAMS, while the second application is about frequency oscillation monitoring. By using the WAMS/PMU technique, Chun Wang et al. [292] investigated the fault location model, which uses synchronized fault voltages.

In the real-time power system, paper [293] discussed a WAMS-based voltage stability indicator that takes into account reactive margin, generator capacity limit, etc., to evaluate system security and voltage collapse proximity. In [294], ZHAO Jinli et al. developed a method for the online assessment of voltage stability based on WAMS. Critical regions of voltage instability were determined by using the Recursive Spectral Partitioning algorithm.

To put into a nutshell, WAMS network has increased the system ability to respond to fast changes arising in system conditions. Even though the SCADA system is mature, the WAMS system has great accuracy with a higher speed of convergence [278].

4. Discussion

Despite significant efforts by the researchers, the voltage stability issue in the wind-integrated power systems still confronts many challenges. One of the major problems is the grid integration and intermittency of wind farms. It is very difficult to predict and manage the fluctuations in voltage caused by the unpredictable and intermittent nature of wind power, therefore resulting in grid instability. Furthermore, in developing countries, the majority of the existing power grids are not flexible and capable enough to integrate large wind farms, and stability concerns can be exacerbated owing to long transmission lines with limited current carrying capacity that are thereby unable to transfer reactive power from wind farms for voltage support. Moreover, reactive power management requires coordination among grid operators, wind farms, and distributed energy resources such as the energy storage system (ESS). Therefore, communication infrastructure and advanced control systems must be implemented for efficient coordination, which can be complex and costly. Tailored and flexible control strategies for each type of wind turbines are required as converter technologies in different wind turbines (e.g., DFIG vs. full-converter) have varying capabilities for reactive power control.

In order to effectively analyze the impact of wind integration on voltage stability in a complex grid, accurate modeling of the dynamic behavior of wind farms is still a challenge, especially with the increase in wind penetration levels. Furthermore, for accurate forecasting and control of the wind farms, data-driven approaches such as machine learning need to be incorporated. However, their integration in the existing grid requires further research and development. To deal with the forecasting issue owing to the inherent uncertainty associated with wind power, robust uncertainty management techniques must be employed to avoid a voltage stability problem. Another major challenge in the wind-integrated power systems is the cost involved for upgradation of existing grids in order to integrate grid support technologies such as FACTS devices or distributed generation (DG). Moreover, attractive regulatory frameworks must be developed for adequate incentivization of the investments in reactive power support and adaptable control strategies for voltage stability management. Establishment of protocols and clear standards for control and communication among grid operators and wind farms is still a major concern for the improvement of system-wide stability and to facilitate efficient integration of FACTS devices and DGs.

The integration of other renewable energy resources such as solar power in the wind-powered electrical systems may enhance the overall flexibility and reactive power support to improve the voltage stability. However, it poses further challenges owing to the intermittency and variability of solar power that need to be addressed in conjunction with wind power integration. Furthermore, in order to ensure grid stability and maximize the benefits of renewable energy integration, the optimal and coordinated control techniques for wind farms, solar plants, and other renewable energy resources (RES) still remain an ongoing challenge.

Continuous research efforts, technological advancements, and collaborations between researchers, policymakers, and industry stakeholders are required to address the aforementioned challenges. Therefore, we can pave the way for a reliable and efficient integration of wind power into power systems by devising innovative strategies and surmounting these hurdles.

5. Conclusions

Voltage stability in wind-integrated power systems is one of the major concerns to deal with for a secure and reliable grid. Therefore, a comprehensive analysis focusing on the complexities associated with voltage instability and its implications for wind power integration with the power system is provided in this manuscript. To ensure the stable and reliable integration of wind energy, the development and implementation of grid codes are necessitated, owing to the intermittent nature of wind power generation. In developed countries, the increasing integration of wind farms with the existing power network have resulted in voltage instability issues due to the fluctuation in wind power. Consequently,

the focus of power system utilities has been shifted towards stability concerns over power quality. To address the challenges of voltage instability, a range of techniques with a specific focus on FACTS devices and WAMS have been discussed. The significance of real-time monitoring systems such as WAMS is emphasized to alleviate potential issues by taking swift actions against instability events due to the availability of timely information. Moreover, to identify weak buses in the power system and assess overall voltage stability, a comprehensive list of Voltage Stability Indices is presented in the manuscript. It also serves as a practical tool for researchers in the evaluation and enhancement of voltage stability in wind-integrated power systems.

To maximize the benefits and the smooth transition of wind power, advanced forecasting and prediction models along with flexible and adaptive control systems and energy storage solutions should be employed. Furthermore, developments in material and blade design as well as an improved drivetrain and efficient generator design should be developed to optimize wind turbine technology. Moreover, to analyze the impacts of integrating other renewable energy resources with wind farms, further detailed studies are required.

Author Contributions: Conceptualization, F.H.M., Z.M.H. and M.L.; methodology, F.H.M., T.U.R., M.E. and M.F.; software, F.H.M., M.W.K. and Z.M.H.; validation, T.U.R., Z.M.H. and M.L.; formal analysis, F.H.M., M.E. and M.F.; investigation, M.W.K., T.U.R. and Z.M.H.; resources, T.U.R. and M.L.; data curation, M.W.K. and M.F.; writing—F.H.M. and Z.M.H.; writing—review and editing, T.U.R. and M.L.; visualization, M.W.K., T.U.R. and M.F.; supervision, Z.M.H. and M.L. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Data Availability Statement: Not applicable.

Acknowledgments: We are very grateful to the Office of Research, Innovation and Commercialization (ORIC), The Islamia University of Bahawalpur, Pakistan (No. 3900/ORIC/IUB/2021) for their support in this research.

Conflicts of Interest: The authors declare no conflicts of interest.

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