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Review

Review of Control Techniques for Wind Energy Systems

Hooman Ghaffarzadeh [1,*] and **Ali Mehrizi-Sani** [2]

[1] School of Electrical Engineering and Computer Science, Washington State University, 355 Spokane Street, Pullman, WA 99164, USA
[2] Bradley Department of Electrical and Computer Engineering, Virginia Polytechnic Institute and State University, Blacksburg, VA 24061, USA; mehrizi@vt.edu
* Correspondence: hooman.ghaffarzadeh@wsu.edu

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Abstract: In recent years, penetration of renewable energy resources into the power grid has increased significantly. Wind, as a renewable, clean, and abundantly available source of energy, has an important share in the energy mix. However, increasing the penetration of wind power in the power grid can adversely affect the power quality and introduce new operational challenges. This paper discusses issues related to the integration of wind farms in the power system, such as maximum power point tracking, fault ride-through capabilities, interarea and subsynchronous oscillations, and voltage flicker, and provides a review of the existing control strategies to address these issues in Types I, II, III, and IV wind turbines. This paper also identifies challenges and opportunities ahead.

Keywords: converters; reactive power control; renewable energy sources; wind energy integration; wind power generation

1. Introduction

In recent years, due to high demand for electrical energy and limited fossil fuel resources, penetration of renewable energy resources into the power grid has increased significantly [1]. Wind, as a renewable and abundantly available source of energy, has an important share in the energy mix for moving away from conventional generation toward renewable generation. In the last decade, the installed global wind power capacity has increased exponentially [1]. According to the U.S. Department of Energy (DOE), wind energy can provide 10% of the U.S. electricity need by the year 2020, 20% by 2030, and 35% by 2050 [2]. However, increasing the penetration of wind power in the power grid can adversely affect the power quality [3–5] and introduce new operational challenges. Moreover, the IEEE standards, such as IEEE 1547.2018 (standard on smart inverters) and IEEE P2800 (standard for interconnection and interoperability of inverter-based resources interconnecting with associated transmission electric power systems), and grid codes recommend and mandate the grid operators with different rules for integration of the inverter-based resources into the grid [6].

Subsynchronous resonance (SSR) induced by a wind turbine connected to a series-compensated transmission line is an important side effect of integration of wind energy in the power system [7,8]. In general, SSR refers to the physical interaction and energy exchange between two power system components at frequencies below the system nominal frequency [9]. The three types of SSR are (1) subsynchronous induction generator effect (SSIGE), (2) subsynchronous torsional interaction (SSTI), and (3) subsynchronous control interaction (SSCI) [7]. The first two categories refer to the interaction between the electrical and mechanical components of the power system. The third category, however, is solely an electrical phenomenon related to the electrical components of the controller of the wind turbine converter and the series capacitor.

SSR can cause severe damage to both the wind generator and the series capacitor. As an example, in October 2009, in the Electric Reliability Council of Texas (ERCOT) service area, a single-line-to-ground fault occurred. Because of the topology change due to the line outage, a doubly fed induction generator (DFIG) wind farm became radially connected to a 50% series-compensated transmission line. Immediately after the line outage, rapidly growing subsynchronous currents and voltages were recorded, and shortly after damage occurred in both the wind turbine equipment and the series capacitor [10–12]. This, and similar incidents, show that there is a need for a strategy to mitigate SSR.

Another consideration in integration of wind energy is its low-voltage ride-through (LVRT) capability. LVRT capability is a demanding grid code requirement [13,14] for a generation unit to stay connected and support the power system during short periods of low voltage, for example, due a fault. When a fault occurs, due to large electromotive force induced in the rotor circuit, the rotor-side circuit and the DC-side capacitor of a wind turbine face sudden overcurrent and overvoltage, respectively [15,16]. This paper studies the control strategies to enhance the LVRT capability.

Due to variability of wind speed, wind turbines are designed to operate in different speed ranges. Cut-in and cut-out speeds are two wind speed thresholds that indicate the operation ranges of a wind turbine. As frequent start-up and shut-down of a turbine can increase mechanical stress and maintenance cost, there is a trade-off between the maximum extracted energy from the wind and the maintenance cost of the system. Different pitch angle control techniques are proposed in the literature to improve the maximum power point tracking (MPPT) capability of a wind turbine when the wind speed is below the rated speed and to help limit the rotor speed when the wind speed is above the rated speed.

Fluctuation in the output power of a wind turbine as a result of the variable nature of wind speed, tower shadow, and wind shear can cause voltage flicker [17], which in turn can affect the frequency response of the system [18,19]. While variable-speed turbines have better performance on flicker emission than fixed-speed turbines, there is still a need to mitigate the flicker induced by wind turbines [20]. The aforementioned categories represent the main challenges on the control and management of the wind systems. MPPT represents the control methods to increase the efficiency of the wind system. The flicker represents the control methods to improve the output power quality of the wind system. LVRT represents the control strategies to improve the performance of the wind systems from the protection aspects. Finally, SSR represents the control strategies to improve the dynamic response of the wind system. This paper reviews the existing control strategies to address these issues in Type I, II, III, and IV wind turbines. The contributions of this paper are as follows.

- A comprehensive review of existing supplementary control approaches for wind energy systems.
- A detailed classification of control strategies for Type I, II, III, and IV wind turbines based on the issues related to integration of wind farms in the power system.
- A review of the main challenges in implementing the existing control strategies and identifying the opportunities ahead.

The rest of this paper is organized as follows. In Section 2, a review of the classification of wind turbines is provided. Sections 3–6 discuss control strategies for Type I, II, III, and IV wind turbines. Section 7 summarizes the presented control techniques and discusses research opportunities ahead. Section 8 concludes the paper.

2. Classification of Wind Turbines

Wind turbine technology has seen a significant progress in recent years and several types of wind turbines are in use [21,22]. In general, wind turbines can be classified into four types based on their power electronics: (1) fixed-speed (Type I), (2) variable-slip (Type II), (3) doubly fed induction generator (DFIG) (Type III), and (4) full converter (Type IV) wind turbines. Fixed-speed wind turbines operate with less than 1% variation in rotor speed, and their output power is in the range of kilowatts. Variable-slip wind turbines using a variable resistance in their rotor circuit can operate in wide range of operating speed (less than 10%) and their output power is less 1 MW. Variable-speed wind turbines based on DFIG employ a back-to-back AC-DC-AC converter in the rotor circuit which allows them to operate in the speed range of ±30% of the rated speed and their output power is in the range of 1 to 5 MW. The full converter wind turbines based on permanent magnet synchronous generator (PMSG) employ a back-to-back AC-DC-AC converter which allows them to operate in the speed range of 0 to 100% of the rated speed and their output power is in the range of 4.5 to 7 MW [1,23].

Variable-speed wind turbines, i.e., Types III and IV, are currently the most commonly used turbines [1]. According to the JRC database (Joint Research Center of the European Commission), in 2005 40% of the North American total wind power installed capacity was Type I and II, and 60% Type III. In 2014, almost 70% of the installed capacity was Type III, 29% Type IV, and less than 1% Types I and II [24].

3. Control Techniques for Fixed-Speed Wind Turbines (Type I)

Fixed-speed wind turbines (Type I) equipped with squirrel-cage induction generator (SCIG) are the simplest large-scale wind turbines. Figure 1 shows the schematic diagram of a Type I wind turbine. An SCIG is connected directly to the grid with no power electronics (some Type I wind turbines have blade-pitching capability). Although Type I wind turbines are reliable and robust, they allow very limited variation in the rotor speed, and thus their extracted power is suboptimal [1]. Moreover, they require reactive power compensation.

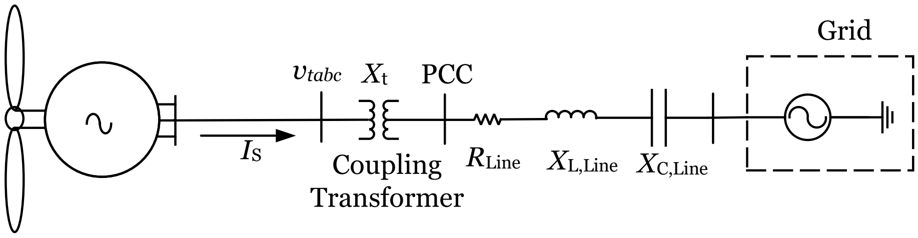

Figure 1. Schematic diagram of a Type I wind turbine.

In this section, the existing control strategies for a Type I wind turbine are studied. The potential advantages and disadvantages of the existing supplementary controllers to improve the MPPT and LVRT capabilities and mitigate SSR and voltage flicker for a Type I wind system are summarized in Table 1.

The authors of [25] propose a control strategy for a standalone Type I wind turbine distributed generation (DG) unit to balance the load and generation. In this method, a communication link is used to deliver commands and provide fast controls to stabilize the system during disturbances. However, the impact of delay in the communication link or availability of this link is not studied.

Gain scheduling is a commonly used technique to control a nonlinear system with variable parameters operating under a wide range of conditions [26–29]. In this method, the controller parameters are tuned based on the minimization of the distance between the current and the desired operating points [30]. Multiple-model adaptive control (MMAC) is similar to the gain scheduling method, but in this approach a finite number of more probable operating conditions are considered, and an appropriate linearized dynamic model is derived for each operating point. The MMAC has two levels: the first level is a set of controllers designed using standard control methods and the second level is a supervisory controller that chooses the first level controller based on the system conditions [8,30] (see Figure 2).

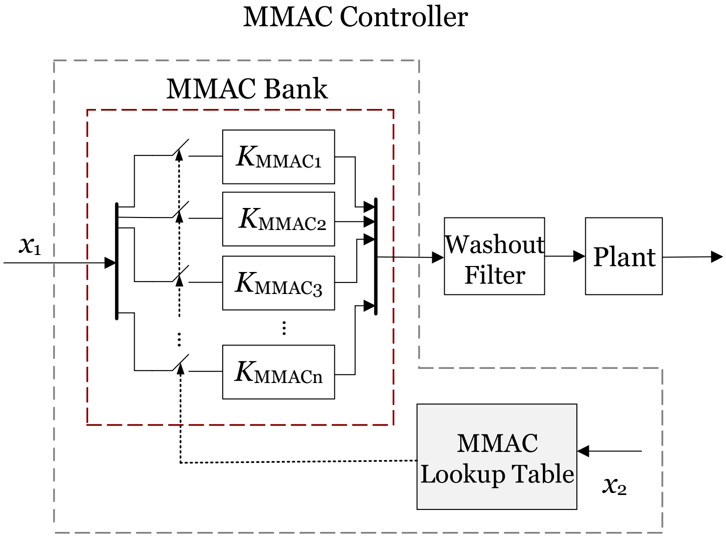

Figure 2. Schematic diagram of multiple-model adaptive control (MMAC) approach.

In [31], by using an optimal gain scheduling control approach, a pitch controller for a Type I active-stall wind turbine is presented. A frequency control technique for a standalone DG unit based on a Type I wind turbine under unbalanced system conditions is proposed in [32]. A three-phase dump load is used to control the system frequency and provide power balance between different phases. However, the power absorbed by the dump load in this method is a loss which lowers the efficiency.

Due to highly variable generation and load in a microgrid, its frequency tends to vary more widely than a conventional power grid. The authors of [33] propose a voltage control method for a Type I wind farm connected to the grid with a STATCOM under unbalanced network condition in which the positive and negative sequences of the voltage are controlled independently. To improve the voltage stability of a Type I wind farm during low voltages, a minmax Linear Quadratic Gaussian (LQG) approach is used in [34] to design simultaneous STATCOM and pitch angle controllers. However, methods based on flexible AC transmission systems (FACTS) devices are expensive.

The authors of [35] study the application of a SPAACE (set point automatic adjustment with correction enabled) controller to improve the speed and torque control capability of a Type I wind generator. SPAACE is an autonomous control strategy that operates between the primary and secondary controllers of an apparatus and adjusts the set point sent by the secondary controller to mitigate transients that may violate operational limits of that apparatus [6,36–38]. SPAACE is added to the control loop of the STATCOM, which increases reactive current during a fault and mitigates the electromagnetic torque overshoot after the fault clearance [35].

The authors of [39] study the performance of FACTS devices in mitigating the SSR between a Type I wind turbine generator system and a compensated transmission line. Two FACTS devices, one a gate-controlled series capacitor (GCSC) and another a thyristor-controlled series capacitor (TCSC), are implemented. A supplementary damping controller is also developed for the GCSC [39].

Table 1. Supplementary controllers for Type I wind turbines.

Issues	Control Strategies	Potential Advantages	Potential Disadvantages
MPPT	[31] Optimal gain scheduling [34] Minmax LQG—FACTS	- Is robust and operates in a wide range of operating conditions [31]. - Improves the stability.	- Is complicated and hard to realize [34].
LVRT	[33] FACTS devices [34] Minmax LQG—FACTS [35] SPAACE	- Improves the voltage stability. - Operates under unbalanced condition [33]. - Improves the steady state performance [34].	- Is expensive to implement [33,34]. - Is complicated and hard to realize [34].
Power Quality	[25] Load shedding [32] Three-phase dump load [33] FACTS devices	- Provides balance between load and generation. - Improves the frequency response. - Improves the steady state performance.	- Needs a communication link [25]. - The power absorbed by the dump load is lost [32].
SSR	[39] FACTS devices	- Has a simple structure.	- Is expensive to implement.

4. Control Techniques for Variable-Slip Wind Turbines (Type II)

Variable-slip wind turbines (Type II) equipped with wound-rotor induction machines employ a DC-DC converter to control the external rotor resistance. A Type II wind turbine is cheaper than a Type III [1], but it does not provide independent reactive power control and power is lost as heat in the rotor resistance. Moreover, the speed variation is limited to about 10% of the rated speed [40].

Figure 3 depicts the schematic diagram of a Type II wind turbine. Although Type II wind turbines have not been very popular in recent years, they are still present in the grid [41]. In this section, the existing control strategies for the Type II wind turbines are studied as summarized in Table 2.

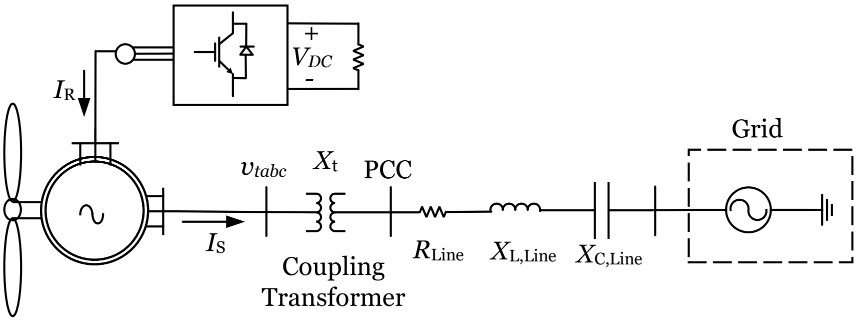

Figure 3. Schematic diagram of a Type II wind turbine.

The works in [40,42] propose a control method to manage the output power of a Type II wind turbine. The controller adjusts the external rotor resistance using a DC-DC converter to inject a constant real power to the grid. In this method, the Ziegler–Nichols tuning approach is used to tune the parameters of the controller [43,44].

In a Type I wind turbine, the pitch angle controller allows the wind generator to increase its reserve power. The reserve power capability is a feature of the system that uses the generating capacity to improve the frequency response when a fault occurs. In a Type II wind turbine, in addition to the pitch controller, the rotor external resistance can also be used to provide reserve power and frequency support [45]. In [45], strategies to improve the response of the wind turbines to frequency events are studied and different control techniques to enhance the reserve capability of Type I and Type II wind turbines are presented.

The authors of [41,46] study the occurrence of SSTI as a result of interactions between a Type II wind turbine and a series-compensated transmission line. The wind turbine is equipped with a DC-DC converter connected to the rotor winding as an external rotor resistance. In this method, a power system stabilizer (PSS) is added in the control loop of the DC-DC converter. The PSS consists of a lead-lag controller, a gain, and a bandpass filter. In [47], a control strategy to mitigate the electromechanical SSR oscillations in a Type II wind turbine is proposed. In this method, the reference output power of the wind turbine is used to calculate the duty ratio of the DC-DC converter. Moreover, a supplementary controller consists of a bandpass filter and a constant gain is added to the control loop of the converter. The proposed controllers in [41,46,47] have a simple structure, but they are not robust and are designed to operate in a specific operating condition.

Table 2. Supplementary controllers for Type II wind turbines.

Issues	Control Strategies	Potential Advantages	Potential Disadvantages
MPPT	[40,42] Ziegler-Nichols	- Increases the generated power. - Controls the desired output power.	- Needs to retune the parameters of the controller. - Is not robust to the change of operating conditions.
Power Quality	[40,42] Ziegler-Nichols [45] Proportional-integral	- Improves the power quality. - Improves the reserve power.	- Needs to retune the parameters of the controller [40,42].
SSR	[41,46] Power system stabilizer [47] Constant gain and band-pass filter	- Has a simple structure.	- Is not robust to the change of operating conditions.

5. Control Techniques for DFIG Wind Turbines (Type III)

Variable-speed wind turbines based on DFIG (Type III) employ a back-to-back AC-DC-AC converter in the rotor circuit which allows them to operate at wind speeds below or above the grid frequency (50 or 60 Hz). Therefore, the extracted energy from the wind in a Type III wind turbine can be higher than a Type I and Type II. Moreover, the conventional vector controller [48] is used in the rotor-side converter (RSC) and the grid-side converter (GSC) control loops to provide decoupled real and reactive power control. As the converter is placed in the rotor circuit of the turbine, it does not need to be rated for the machine full output power and is typically rated at 30% [1]. Figure 4 shows the schematic diagram of a Type III wind turbine. In this section, the existing control strategies for the Type III turbines are reviewed as summarized in Table 3.

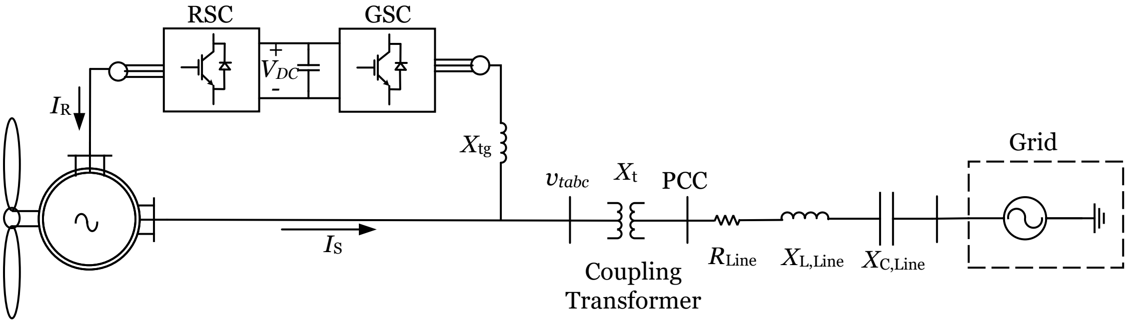

Figure 4. Schematic diagram of a Type III wind turbine.

5.1. Pitch Angle Controller

A pitch angle controller is used in a Type III wind turbine to improve its frequency response and avoid instability due to a grid fault or wind speed variations. The pitch controller can also improve the MPPT capability. In [49], a two-step control method is proposed to improve the frequency response of the wind turbine. A droop control along with a transient gain control controller is used to improve the performance of the existing pitch angle controller of turbine. In this method, a reserve margin is considered and, during a frequency event, the controller increases the output power of the wind turbine by tuning the pitch angle of turbine blade. The supplementary controller is a simple P controller that is added to the existing controller of wind turbine to improve the steady-state frequency response. Moreover, an additional controller is introduced to improve the transient response of the turbine. The proposed controllers in [49] have a simple structure and their implementation is straightforward. However, there is a need for an algorithm to adjust the parameters of the controller to cover the operating conditions of the system. To address the drawbacks of the aforementioned approaches, different more complicated methods are proposed. The work in [50] discusses a pitch angle control method using a linear quadratic regulator (LQR) to address the limited robustness of the conventional PI controllers. In the classic LQR approach, an optimization algorithm is used to find the optimal solutions for the defined cost function [51]. A fuzzy logic-based control approach is proposed in [52] to actively adjust the turbine blade angle. The Genetic Algorithm is also utilized to improve the performance of the proposed controller. The methods proposed in [50,52] can extend the operating region of the pitch controller; however, because of high computational cost, the proposed approaches cannot provide a quick response during abnormal conditions [53]. In [54], a nonlinear control approach with four subcontrollers for a system with uncertain aerodynamic and mechanical parameters is developed to adjust the output real power in the power regulation mode and maximize it in the MPPT mode. In the proposed structure, the blade pitch angle and rotor voltage are used as the input control signals. The authors of [55] propose a discrete-time sliding-mode controller to enhance the MPPT capability of a Type III wind turbine. In this approach, the supplementary controller, based on the wind speed, provides the reference set point for the RSC controllers.

5.2. Converters and DC Link Voltage Controllers

The controller of the back-to-back AC/DC/AC converter in a Type III wind generator consists of four control loops that in general are designed using the conventional vector control technique [48]. Figures 5 and 6 show the schematic diagrams of the RSC and GSC controllers [8]. The RSC injects an AC voltage at slip frequency to the rotor circuit and operates as a controlled voltage source. The GSC injects an AC current at synchronous frequency to the grid and operates as a controlled current source [56]. The GSC and RSC control loops are responsible for maintaining a constant DC link capacitor voltage and controlling the real and reactive power exchange between the turbine and the power grid, respectively [1,57].

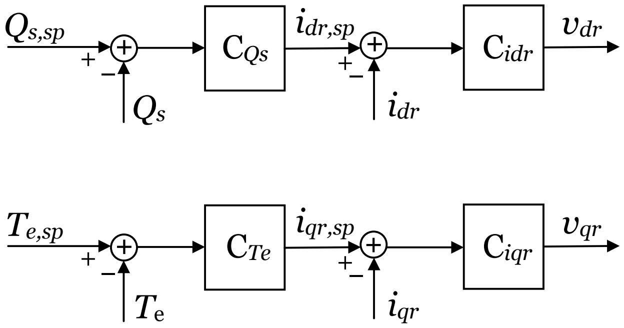

Figure 5. Schematic diagram of the rotor-side converter (RSC) controller.

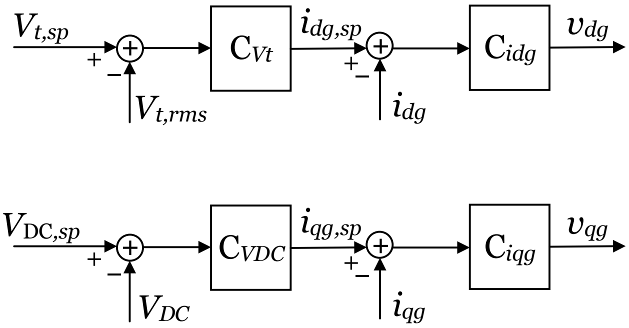

Figure 6. Schematic diagram of the grid-side converter (GSC) controller.

5.3. Supplementary Controllers

In previous subsections, the main controllers of a Type III wind turbine are reviewed. The conventional controllers of a wind turbine are expected to handle its normal operation. However, following a large disturbance (e.g., a fault in the system), the power system may tend toward instability. In such cases, an auxiliary controller can be added to the control loops to prevent instability [8]. In this subsection, different issues related to integration of a Type III-based wind farm in the power system are discussed and the existing control strategies to address these issues are discussed.

5.3.1. Low-Voltage Ride Through

Due to increased penetration of wind turbines into the grid, the system operators have revised their grid codes and made strict requirements for low-voltage ride-through capability of wind turbines for grid faults resulting in a 85% voltage drop or even more [58]. In this subsection, the control methods that are proposed to improve the LVRT capability of Type III wind turbines are reviewed. The work in [59] introduces a feedforward transient compensation method to improve the LVRT capability of a Type III wind farm using a proportional-integral-resonant (PIR) current controller. When a fault occurs, due to large electromotive force induced in the rotor circuit, the rotor-side circuit and the DC-side capacitor of a DFIG experience abrupt overcurrent and overvoltage conditions, respectively [15,16]. To deal with this issue, the authors of [60] propose employing an energy storage device to enhance the voltage support of the DC bus and LVRT capability of a Type III wind system. Moreover, a transient reconfiguration method is introduced such that when a fault occurs, the GSC circuit is changed and connected in parallel to the RSC circuit to protect the DFIG from rotor overcurrent. An inductance-emulating control strategy to mitigate the rotor circuit overcurrent is proposed in [61]. In this approach, the RSC is controlled to operate as a variable inductance to improve the LVRT capability. The authors of [58] use a fuzzy controller to improve the fault ride-through capability of a Type III wind turbine. In this method, the proposed controller is designed and tuned using the genetic algorithms, and it is added to the existing controllers of the rotor-side converter. The main advantage of using a metaheuristic inspired optimization algorithm is that the derivation of fuzzy controller rules is complicated and it cannot be realized using a simple fuzzy reasoning [58]. However, because of high computational cost, the proposed approaches cannot provide a quick response during abnormal conditions.

5.3.2. Power Quality

In [62], the stability of a multi-machine power system with a combination of the conventional synchronous generators and Type III-based wind farms equipped with a PSS is studied. This PSS is used to mitigate power oscillations with a frequency between 0.1 Hz and 2 Hz (interarea modes). The PSS has a simple structure and can be designed with common control design approaches. However, a fixed-parameter PSS cannot be effective in applications with variable operating condition such as wind systems.

To deal with system uncertainties such as variations in wind speed, load, and generation, a coordinated robust controller for a Type III turbine equipped with power oscillation damper is developed in [63]. An improved firefly algorithm [64] is used to calculate the coefficients of a SISO second-order lead-lag controller to build the PSS and a power oscillation damper [63]. Although using the firefly optimization algorithm can improve the system performance, its implementation is time-consuming and it is not appropriate for a real-time application.

An H_∞ robust controller is proposed in [65] to improve the response of a Type III wind system to grid voltage distortions resulting from asymmetric voltage dips and grid harmonics. Because the stator winding of a DFIG is directly connected to the grid, voltage distortions can generate harmonics in both stator and rotor currents, and can eventually lead to significant electromagnetic torque oscillation. The controller developed in [65] is placed in the RSC control loop to mitigate these rotor current harmonics. A dual-loop control method with a conventional current controller and an additional flux controller is presented in [66] to mitigate the transient flux oscillations in the stator circuit and avoid the rotor overcurrent. The main drawback of this method is that flux cannot be directly measured. In [67], a solution based on the unscented Kalman filter (UKF) dynamic state estimation scheme is introduced to indirectly measure the flux.

To deal with interarea oscillations, a two-level hierarchical control method is developed in [68]. A controller with a centralized power oscillation damper is implemented in a Type III wind turbine and a PSS controller is installed for the synchronous generators. The PSS receives input signals from the control center. The control center gathers information from synchronized phasor measurement units (PMU). In this paper, the impact of delay in the communication link or availability of this link is not studied.

Type III wind turbines do not contribute to the inertia of the power system and, as they generally follow MPP, they cannot provide a power reserve margin unless the wind turbine is equipped with a supplementary droop controller or deloaded controller. Therefore, there is a need for a technique to improve the frequency response and mitigate the flicker and harmonics on the rotor circuit of a Type III wind turbine. The authors of [69] use a selective harmonic elimination approach to address this issue. In this approach, an iterative algorithm using the Newton–Raphson method is developed to calculate the switching angle of the back-to-back converter. In [70], a control strategy based on the droop control is introduced to provide emulated inertial response for the wind turbines and improve their frequency response. It is shown that the droop control can be an appropriate alternative for the synthetic inertia strategy that needs parameter tuning to operate in a wide range of operation conditions. Similarly, in [71], the role of droop control in improving the frequency response of the wind systems and smoothing the power fluctuations due to the change in the wind speed of a Type III wind turbine is investigated. The authors of [72] propose a dual-loop control approach to improve the frequency response of the Type III wind turbines. Moreover, the impact of the deloaded control of a wind turbine in enhancing its frequency response is investigated. The proposed controllers in [70–72] have a simple structure and their implementation is straightforward. However, there is a need for an algorithm to adjust the parameters of the controller to cover the operating conditions of the system. To address this issue in [73], an artificial neural network-based controller is introduced to actively tune the gains of the droop controller. This strategy improves the performance of the droop controller and expands the operating condition of the frequency controller.

5.3.3. Subsynchronous Resonance

In general, wind power plants are located far from the main power grid to take advantage of more favorable wind conditions. To transfer the generated electrical energy to the grid, the compensated transmission lines are utilized. However, radial connection of a Type III-based wind farm to a compensated transmission line increases the risk of subsynchronous resonance (SSR) and instability [8]. In this subsection, the existing strategies in the literature to address this issue are reviewed.

A comprehensive stability analysis of an induction machine-based wind system under SSR phenomenon is provided in [74]. The focus of this letter is on induction generator effect (IGE) as a type of SSR. For this purpose, a simplified model of a induction machine in $\alpha\beta$-frame is introduced. A series of simulation results is provided in [74], which provides a relationship between the machine and transmission line parameters under different modes of operation. A detailed characteristic analysis of SSR in practical Type III wind systems is provided in [75]. In this paper, using the field data and practical observations from the real SSR events, the necessary conditions for SSR occurrence in a series compensated wind farm are discussed. The authors of [76] introduce a two-degree-of-freedom supplementary controller to mitigate SSR for a wind farm radially connected to a compensated transmission line. The controller uses the current control loop of the RSC to increase the damping of overall control system. In [57], a supplementary damping controller using the residue-based method is proposed. This controller consists of a classical gain with phase compensation and a bandpass filter. A supplementary controller by adding a control signal in the reactive power control loop of the GSC is proposed in [77]. A lead-lag controller with bandpass and washout filters are used to produce a control signal to mitigate SSR in a Type III wind farm.

In [9], three different techniques (all based on FACTS devices) to mitigate SSR in a series-compensated DFIG wind turbine system are discussed. The first method uses a TCSC to improve damping against SSR. The second method uses a GCSC for SSR damping. The third method uses a supplementary controller as part of the DFIG converter controllers. The proposed controller is a fixed-parameter controller added to the GSC control loop. Similarly, a Kalman filter-based control method is proposed in [78]. This method is useful for the transmission systems that utilize static series synchronous compensation (SSSC) to improve their transfer capability. In this approach, a Kalman filter is designed to extract the subsynchronous component of torsional frequencies. To mitigate SSR, SSSC injects a subsynchronous voltage in proportion to the estimated subsynchronous components of line current [78]. Moreover, a genetic algorithm-based method is used to update the parameters of the Kalman filter damping controller. The authors of [79] introduce a subsynchronous damping controller which improve the positive damping of the wind system. In this method, by extracting subsynchronous components of line current, the critical unstable modes of the system are identified and a proportional voltage in injected to suppress the subsynchronous current.

In [80], a static VAr compensator (SVC) is used at the point of common coupling (PCC) to mitigate SSR in a Type III wind farm. A centralized damping controller is also developed to control the SVC and mitigate subsynchronous oscillations in the system. In [81], a controller is proposed to mitigate SSCI. In this work, the damping controller is designed using a lead-lag controller in the current control loop of the RSC and a second-order low-pass filter in its real power control loop. Three other SSCI mitigation techniques, i.e., adding a bypass filter across the series capacitor, using a full converter wind turbine (Type IV) to increase positive damping, and installing a protection system are proposed in [81].

The proposed supplementary control methods to mitigate SSR in the mentioned references generally have a similar structure (a washout filter and a damping controller using PID) and are added to the RSC or GSC control loops. These controllers have a simple structure; however, they are not robust and are designed to work only in a specific operating point. The approaches that use a FACTS device to add positive damping to the system generally are expensive and their implementation is not straightforward.

To address the drawbacks of the aforementioned strategies, a supplementary adaptive controller using the MMAC control approach is introduced in [8]. The proposed controller has two levels: the first level is a set of controllers designed using the standard control methods, and the second level is a supervisory controller that selects the level one controller based on the system current operation conditions [8]. Moreover, an optimization-based algorithm is introduced to simultaneously coordinate the parameters of the MMAC-based controller in a nonaggregated wind system [8].

Table 3. Supplementary controllers for Type III wind turbines.

Issues	Control Strategies	Potential Advantages	Potential Disadvantages
MPPT	[49] Droop control [50] Linear quadratic requlator [52] Fuzzy logic control [54] Nonlinear control [55] Sliding-mode control	- Improves the extracted power from the wind energy. - Has a simple structure [49]	- Is not robust to the change of operating points [49,52]. - Is complicated and slow [50,54].
LVRT	[58] Fuzzy logic control [59] Proportional-integral -resonant [60] Energy storage device [61] Inductance-emulating control	- Has a simple structure [59]. - Improves the frequency response. - Operates under balance and unbalance network condition.	- Is complicated and slow [58] - Is expensive to implement [60].
Power Quality	[62] Power system stabilizer [63] Coordinated robust control [65] H_∞ robust control [66] Dual-loop control (current and flux) [68] Hierarchical control [69] Selective harmonic elimination [70–72] Droop Control [73] Neural Network	- Has a simple structure [62,63,70–72]. - Improves the power quality of the system. - Operates under balance and unbalance network condition. - Improves the reserve power.	- Is not robust to the change of operating points [62]. - Is slow and hard to realize [63,65,69]. - Is unable to directly measure the flux [66]. - Needs a communication link [68].
SSR	[8] Adaptive MMAC [9] FACTS devices [57] Residue-based control [68] Hierarchical control [76] Two-degree-of-freedom control [78] Kalman filter-based control [77] Lead-lag control [80] FACTS devices [81] Lead-lag control	- Has a simple structure. - Is robust [8]	- Needs a communication link [68,80]. - Is hard and expensive to implement [9,78]. - Is not robust to the change of operating points.

6. Control Techniques for Full Converter Wind Turbines (Type IV)

The full converter wind turbines (Type IV) based on permanent magnet synchronous generator (PMSG) employ a back-to-back AC-DC-AC converter. The turbine is connected to the grid through the converter. Similar to Type III turbines, Type IV turbines can independently control the real and reactive power; however, the converter handles all the generated power and has to be rated for the machine rated power [1]. The schematic diagram of a Type IV wind turbine is shown in Figure 7. In this section, the existing control strategies for the Type IV wind turbines are discussed as summarized in Table 4.

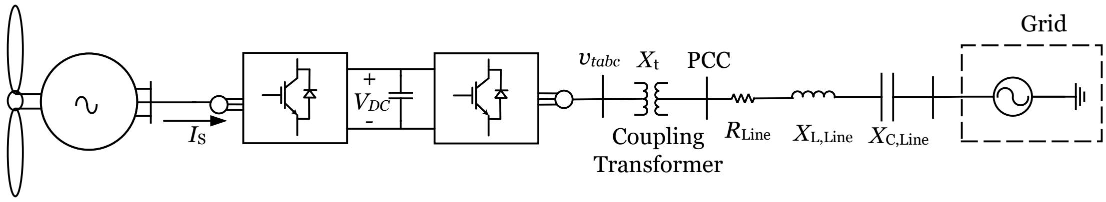

Figure 7. Schematic diagram of a Type IV wind turbine.

6.1. Pitch Angle Controller

A small variation in the blade angle of a wind turbine can have a dramatic effect on the extracted energy from the wind. Moreover, the efficiency of the aerodynamic system of a wind turbine is strongly related to the blade pitch angle and its direction relative to the wind speed [82]. A blade pitch angle controller and a DC link voltage controller to manage the real power flow of a Type IV wind turbine connected to a weak grid are developed in [83]. The proposed controller provides power balance between the wind generator and the load by managing the blade speed through a coordinated pitch angle and DC bus voltage controllers. Fuzzy logic controllers are commonly used to enhance the MPPT performance of a Type IV wind turbine [84,85]. In [84], a fuzzy controller is used to monitor the wind and generator speeds and track the MPP. In [85], a power control strategy for a wind farm with Type IV wind turbine at low wind speed is proposed. In this approach, a fuzzy logic control strategy is utilized for efficient switching of each wind turbine between different modes of operation. The pitch angle control methods discussed for other types of wind turbines are also applicable for Type IV turbines.

6.2. Converters and DC Link Voltage Controllers

Similar to a Type III wind turbine, the conventional vector control [48] is the most commonly used technique to control the back-to-back full-power converter in a Type IV wind turbine. The generator-side converter control loop is responsible for maximizing the extracted wind energy by controlling the turbine speed. The reference value of the rotor speed is obtained from a lookup table implementing an MPPT algorithm. Moreover, the reference set point of the real power controller comes from the rotor speed control loop [82]. The GSC controller is responsible for maintaining a constant DC bus capacitor voltage and controlling the reactive power exchange between the GSC and the power grid [86]. The work in [87] uses the sliding mode control approach to introduce a controller for a Type IV wind turbine. In this method, two controllers are designed to improve the tracking performance of the GSC and RSC and increase the extracted power of the wind turbine. The sliding model control is a well-known robust control approach for a highly nonlinear system. However, the performance of the sliding mode controller greatly depends on the sliding surface, and an accurate dynamic model of the system is needed to properly design and tune the sliding surface.

6.3. Supplementary Controller

6.3.1. Low-Voltage Ride-Through

In recent years, the grid codes for integration of distributed energy resources (DER) are modified and new requirements for operational condition control of the DERs are included. Based on the grid codes, the wind turbines must remain connected to the grid during grid faults and support the system stability [88]. Therefore, there is a need for an approach to improve the fault ride-through capability of wind turbines. In [89,90], a nonlinear adaptive controller to enhance the fault ride-through capability of a Type IV wind turbine is proposed. A perturbation observer is designed to estimate and mitigate the possible perturbation (i.e., external disturbances, parameter uncertainties, and unknown nonlinearities). This controller in is added to the GSC control loop. The authors of [88] use a type-2 fuzzy logic control approach to improve the transient stability of a Type IV-based wind system during grid faults. In this method, a three level neutral point clamped (NPC) model is considered for the back-to-back AC-DC-AC converter of the wind turbine a fuzzy-logic-based controller is designed to deal with nonlinear characteristics of wind system. The proposed approach in [88] can improve the fault ride-through performance of a Type IV wind turbine; however, the implementation of this method is not straightforward and the existing controller of wind turbines needs to be replaced with the proposed fuzzy controller. In [91], a LVRT control approach using the feedback linearization method is proposed. The feedback linearization theory is utilized to control the DC-link voltage of AC-DC-AC converter of Type IV wind turbine during the abnormal conditions. In this method, unlike the conventional control approach, the generator side converter controller is responsible to control the DC-link voltage and the grid-side converter controller controls the exchange of real power of wind turbine. The proposed controller in [91] can improve the LVRT capability of wind turbine by controlling the DC-side voltage of converter; however, the DC-link controller provides the generator power reference. Therefore, the efficiency of the wind turbine is less than the case that the MPPT controller provides the power reference. The authors of [92] discuss the stability of a Type IV wind system integrated to a weak grid under a low voltage condition. A small-signal stability analysis is performed and the impact of the PLL on the instability of the wind system during a fault condition is evaluated. A LVRT controller is proposed in [92] to improve the the dynamic response of the Type IV turbine during a low-voltage event. Moreover, they used a recursive least square algorithm to identify the parameters of the grid and improve the robustness of the LVRT controller. A comprehensive review of LVRT control methods for different types of wind turbine is provided in [93].

6.3.2. Power Quality

The probabilistic nature of wind power and the decoupled nature of the mechanical and electrical parts of a Type IV wind turbine introduce new operational challenges [94]. The authors of [94] discuss the impact of increased penetration level of the converter control-based generators in a large-scale power system and analyze their stability using the small-signal stability analysis. Unlike the previously discussed methods, the work in [95] proposes a control strategy for a modular multilevel converter (MMC)-based Type IV wind turbine to mitigate the voltage fluctuations and improve the LVRT capability of a Type IV wind turbine. The control strategy is based on a distributed braking chopper method for a back-to-back MMC. In addition, a method based on circulating current injection is proposed to mitigate the fundamental voltage component of DC-link capacitor during a voltage event in the grid. The implementation of the proposed approach in [95] requires a change in the hardware of the wind turbine converter and it could be a costly process.

A method to control the power exchange of a Type IV wind turbine with power grid in grid-connected and standalone modes is proposed in [96]. In this approach, a virtual generator controller is developed to control the wind turbine to emulate the behavior of a synchronous generator.

The work in [97] discusses the impact of the penetration of the Type IV wind farms on damping of the power system oscillations. To this aim, a residue-based analysis is provided and the impact of different operating conditions and feedback control signals on the electromechanical modes of the system is evaluated. The residue analysis is a tool to measure the sensitivity of each mode to a particular component within the system [98,99]. A flicker mitigation method by controlling the real power of a Type IV wind turbine is introduced in [82]. The controller damps real power oscillations by modulating the DC bus capacitor voltage of the back-to-back converter.

Table 4. Supplementary controllers for Type IV wind turbines.

Issues	Control Strategies	Potential Advantages	Potential Disadvantages
MPPT	[84,85] Fuzzy logic control [87] Sliding-mode control [96] Virtual generator control	- Is very flexible [84,85]. - Is robust [87,96].	- Is not reliable [84,85]. - Needs an accurate model of the system [87]. - Is hard to realize and slow [96].
LVRT	[88] Fuzzy logic control [89,90] Nonlinear adaptive [91] Feed-back linearization [92] Recursive least square	- Improves the frequency response of the system. - Is robust.	- Is complicated and hard to realize. - Is not efficient [91].
Power Quality	[82] Flicker mitigation control [94] Distributed braking chopper [97] Residue-based control	- Improves the power quality of the system. - Has a simple structure.	- Has poor performance in systems with unbalanced loads. - Is not robust to the change of operating points. - Requires hardware change and expensive to implement [94].

7. Summary and Future Trends

Although the conventional controllers of a wind turbine can handle its normal operation, several issues may arise when a large-scale wind farm is affected by events in the power grid. The variable and uncertain nature of wind speed and nonlinear and high-order dynamics of the wind turbines are among the major challenges in the control of a wind-integrated power system. Therefore, controllers are needed to consider different modes of operation. This paper comprehensively reviews the existing supplementary controllers for Types I, II, III, and IV wind turbines and discusses their characteristics.

As the grid codes become more restrictive to ensure immunity of the wind turbines to grid faults, Type III and IV wind turbines are the only practical choices for large-scale wind farms. Type IV wind turbines have several advantages over other types of wind turbine. However, they employ a fully rated converter that can result in higher converter loss and investment cost compared to a Type III wind turbine. Therefore, Type III wind turbines based on DFIG are currently the most commonly used type of wind turbine.

To maximize the extracted wind energy, different control techniques are proposed in literature. Low inertia, interarea and subsynchronous oscillations, and flicker induced by voltage fluctuations are other challenges in this area and have received attention in the recent years. However, the existence of parameter uncertainties and unmodeled dynamics in the wind turbine models are among the issues to be addressed in the future work.

Although the supplementary methods based on conventional fixed-parameters PID controllers can improve the performance of the system, the wind system requires a controller that can operate in a wide range of operating conditions. Nonlinear, robust, adaptive, and predictive control approaches as well as methods based on an optimization scheme are some of the well-known strategies to deal with the system uncertainties. The main challenges ahead in implementing these techniques include the following.

- Nonlinear and robust control: Even though nonlinear and robust control techniques based on sliding-mode control, feedback linearization, and H_∞ control approaches can enhance the performance of the system, in general, they are complicated to implement and linear control techniques are more common in wind-based systems.
- Optimization-based control: Methods based on an optimization scheme, such as the firefly and PSO algorithms, have received attention in the recent years. However, generally the computational complexity of these methods makes the real-time optimization difficult and time-consuming to solve and limits their applicability for real-time applications.
- Adaptive control: Unmodeled dynamics in the wind turbine models can adversely impact the performance of the conventional adaptive controllers. A controller with a simple structure and at the same time with adaptive characteristic such as the gain scheduling and multiple-model adaptive controllers can be a good choice for wind applications.

8. Conclusions

Penetration of renewable energy resources into the power grid has increased significantly. Several major challenges such as maximum power point tracking, fault ride-through capabilities, interarea and subsynchronous oscillations, and flicker induced by voltage fluctuations arise when a large-scale wind power plant is connected to a bulk power grid. In this paper, the conventional control strategies for different types of wind turbines are discussed. Moreover, a comprehensive review of existing supplementary control approaches for wind turbines is provided and potential advantages and disadvantages of these methods are summarized. This paper also identifies the challenges and opportunities ahead.

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