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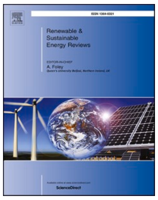

A review of wind power generation steady-state reactive power support requirements and improvement strategies

S. Ncwane [a,*], R.C. Bansal [a,b]

[a] University of Pretoria, Department of Electrical, Electronics and Computer Engineering, Pretoria, South Africa
[b] University of Sharjah, Department of Electrical Engineering, Sharjah, United Arab Emirates

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ABSTRACT

The penetration of wind power generation (WPG) facilities into power systems continues to increase globally. Wind power generation facilities have become increasingly important in providing reactive power support to help regulate power system voltage. To ensure that WPG facilities can provide adequate support, grid codes have been developed with specific requirements that must be met before they can reach commercial operation. However, WPG facilities are sometimes unable to meet the required reactive power support levels. Controller based solutions are commonly used to improve the reactive power capability of WPG facilities. This paper reviews recent developments in control strategies. Their response speed, benefits, and limitations are discussed to identify gaps and to propose future improvements. Current control strategies are not implemented using hybrid control structures, and mostly rely on classical and metaheuristic optimization algorithms. These control strategies can be slow, and sometimes increase the operation of the WPG facility's grid integration transformer on-load tap changer. Machine learning based hybrid control strategies have the potential to improve performance and enable WPG facilities to efficiently provide reactive power support.

ABBREVIATIONS

DG	Distributed generator
OLTC	On-load tap changer
POC	Point of connection
SynCon	Synchronous condenser
SCB	Shunt capacitor bank
SO	System operator
SR	Shunt reactor
STATCOM	Static synchronous compensator
SVC	Static var compensator
WPG	Wind power generation
WTG	Wind turbine generator
SYMBOLS	
θ	Angular difference between the active power and reactive power
Θ	SynCon transformer voltage angle displacement
a	Nominal transformer winding ratio
a_0	Transformer turns ratio when the tap changer is at the nominal position
Δa	Change in the transformer winding ratio
B_C	Shunt capacitor bank susceptance [S]
B_{Lmax}	Thyristor controlled shunt reactor susceptance [S]
C	Shunt capacitor bank capacitance [F]
D_{droop}	Voltage droop setting [%]
f	Power system frequency [f]
I_2	Transformer MV current [A]
I_d	Wind turbine generator active current [A]
I_q	Wind turbine generator reactive current [A]
I_S	Wind turbine generator apparent current capacity [A]
L	Shunt reactor inductance [L]
n	Transformer current tap position
n_1	Transformer HV winding turns
n_2	Transformer MV winding turns
P	Active power [W]
P_n	Wind power generation nominal active power capacity [W]
$P_{WTG,i}$	Wind turbine generator active power production [W]
$pf_{setpoint}$	Power factor setpoint
Q	Reactive power [var]
Q_{C_SVC}	Static var compensator injected reactive power [var]
Q_{POC}	Wind power generation point of connection reactive power reference [var]
Q_{pf}	Reactive power required to achieve the power factor setpoint [var]
Q_{rated}	Wind power generation facility rated reactive power capacity [var]
Q_{R_SVC}	Static var compensator absorbed reactive power [var]
Q_{SCB}	Shunt capacitor bank injected reactive power support [var]
$Q_{STATCOM}$	STATCOM reactive power support [var]
Q_{SR}	Shunt reactor absorbed reactive power [var]

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* Corresponding author.

E-mail addresses: u24325008@tuks.co.za (S. Ncwane), rcbansal@ieee.org (R.C. Bansal).

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Q_V	Reactive power required to achieve the voltage setpoint [var]
$Q_{WTG,i}^{avail}$	Wind turbine generator available reactive power [var]
$Q_{WTG,i}^{ref}$	Wind turbine generator reactive power reference [var]
Q_{SynCon}	SynCon reactive power support [var]
S	Apparent power [VA]
$S_{WTG,i}$	Wind turbine generator capacity [VA]
V	Shunt device terminal voltage [V]
V_1	Transformer HV bus voltage [V]
V_2	Transformer MV bus voltage [V]
$V_{measured}$	Point of connection measured voltage [V]
V_{MV}	Grid integration transformer MV bus voltage [V]
$V_{nominal}$	Point of connection nominal voltage [V]
$V_{setpoint}$	Wind power generation facility voltage setpoint [V]
$V_{STATCOM}$	STATCOM terminal voltage [V]
V_{SynCon}	SynCon terminal voltage [V]
X	Shunt reactor inductive reactance [Ω]
X_T	Transformer reactance [Ω]
Z_T	Transformer impedance [Ω]

1. Introduction

Several countries are aligning with the United Nations Sustainable Development Goal 7, which aims to provide affordable and clean energy to the global population by 2030 [1]. Progress toward this goal is driven by the increased integration of distributed generators (DGs). However, higher DG penetration requires these resources to support power system voltage regulation and efficient system operation. Distributed generators are sized and located within the power system to optimize system performance [2,3]. In addition to DGs, shunt reactive power devices are sized and located to improve power system voltage regulation and operational efficiency [4–6].

Given the coexistence of DGs and shunt reactive power devices, control strategies have been developed to coordinate their operation with the system transformers' on-load tap changers (OLTCs) [7–9]. These control strategies optimize objective functions such as reactive power margin, reactive and active power losses, and voltage deviation using algorithms including the reduced gradient method, particle swarm optimization, multilayer perceptron networks, deep deterministic policy gradient, and soft actor–critic based deep reinforcement learning [7–11].

Wind power generation (WPG) is a DG technology used to decarbonize energy production by harnessing wind, a renewable, non-fossil fuel energy source. Globally, the integration of onshore and offshore WPG facilities into power systems is increasing [12]. The integration of WPG facilities can affect the quality of power supply to consumers [13,14]. Also, it can impact power system stability classified in Ref. [15], namely: frequency stability [16,17], voltage stability [18,19], resonance stability [20,21], transient stability [22,23], and small signal stability [24,25].

To ensure that WPG facilities maintain stable power system operation, grid codes have been developed by various countries [26]. Grid codes require WPG facilities to assist in regulating power system voltage during steady-state operation by providing reactive power support [27–29]. However, WPG facilities may not always have adequate capacity to provide the required support [30–32]. To increase reactive power capacity, it is common to integrate shunt reactive power devices into WPG facilities [30,31]. These devices supplement the reactive power produced by the wind turbine generators (WTGs), improving the facilities reactive power capacity.

Several studies have reviewed the solutions proposed to improve the reactive power support that WPG facilities provide to the power system during steady-state power system operation [33,34]. These reviews focused on: (1) controller based solutions [33], and (2) hardware based solutions [34]. The current review papers mainly considered classical based algorithms, with minimal application of metaheuristic algorithms to optimize reactive power production during steady-state power system operation. The review papers are outdated and do not consider the latest developments such as the transition from classical to metaheuristic based optimization control strategies and their performance in steady-state reactive power control. A review paper that provides a comprehensive analysis of the latest developments in control strategies will guide power system planners, operators, and researchers in resolving reactive power support issues in WPG facilities to improve compliance to grid codes.

This paper provides a comprehensive review of grid codes used to benchmark the performance of WPG facilities, and recent developments in control strategies and hardware solutions used to improve the reactive power support the facilities provide to the power system. A comparative analysis of the grid codes reactive power support and performance requirements is performed to determine which have the most comprehensive and stringent requirements. Additionally, a comparative analysis of shunt reactive power devices based on cost, response time, and reactive power range is presented to highlight their application in supplementing the reactive power support WPG facilities provide. In addition, control strategies are categorized based on the control structure they utilize, and their performance is assessed based on response times, benefits, and limitations. Optimization algorithms used to coordinate reactive power production are evaluated based on convergence speed and real time control capability.

The paper findings highlight that the grid codes are for single technologies, and do not cater for hybrid facilities, making it unclear how these facilities are tested before being integrated into the power system. Additionally, the current reactive power strategies can be slow due to the use of classical and metaheuristic based algorithms, and these control strategies can increase the operation of the facilities grid integration transformers' OLTCs.

To address these limitations, reactive power envelopes for hybrid facilities should be investigated to provide inputs into the development of grid codes for these facilities. Additionally, machine learning based hybrid control strategies that utilize centralized and distributed control structures are proposed to enable WPG facilities to provide the required reactive power support while improving controller performance. The major contributions of this review paper are:

(1) We reviewed grid codes from selected countries in Africa, Asia, and Europe to identify steady-state reactive power support requirements for WPG facilities. Our analysis indicates that grid codes not only stipulate requirements for reactive power capacity and reactive power control modes, but also include performance criteria, such as the time WPG facilities should take to reach new voltage, reactive power, and power factor setpoints. Additionally, some grid codes require WPG facilities to operate within specified tolerances once they reach the new setpoints. Given that current grid codes have not been developed for hybrid facilities, we recommend that future studies should focus on investigating the facilities' reactive power envelopes for input into new grid codes.

(2) We reviewed control strategies developed to improve the reactive power support that WPG facilities provide to the power system during steady-state operation. We categorized the identified control strategies based on whether they use centralized, distributed, or decentralized control structures. We further subdivided the control strategies into conventional controllers and adaptive and coordinated controllers, and highlighted the devices they control. We also considered their speed, benefits, and limitations to identify gaps and propose potential improvements for future research.

(3) We propose novel machine learning based hybrid control strategies to improve controller performance and the reactive power support WPG facilities provide to the power system. The control strategies should be based on a combination of centralized and distributed control structures to provide facility wide reactive power coordination while enabling real time control.

The rest of this paper is organized as follows: Section 2 reviews grid code requirements from selected countries in Africa, Asia, and Europe, focusing on steady-state reactive power support from WPG facilities, Section 3 discusses control strategies for controlling the reactive power from WTGs, Section 4 examines grid integration transformers' control strategies, Section 5 reviews control strategies for WPG facilities integrating shunt reactive power devices, Section 6 classifies these control strategies and discusses their benefits, limitations, and recommends areas for future research, Section 7 concludes the literature review.

2. Grid code requirements

2.1. Reactive power capability

The performance of WPG facilities against grid code requirements is assessed before they can commence commercial operation to ensure they do not negatively impact other customers connected to the power system. Grid code compliance is evaluated using simulations and on-site testing [30,35,36]. Compliance enables WPG facilities to provide the required support to stabilize the power system during both normal and abnormal operating conditions. To ensure that WPG facilities support the power system voltage during steady-state operating conditions, their compliance with reactive power support requirements such as P-Q capability [30,37,38], voltage control [30,36], and power factor control [36] has been assessed in multiple studies.

Grid codes from selected countries in Africa, Asia, and Europe are reviewed to determine their steady-state reactive power support requirements for WPG facilities. The countries selected in Africa were Kenya [29], Namibia [39], Nigeria [40] and South Africa [41]. Asian countries were the Philippines [42], Saudi Arabia [43], and the United Arab Emirates (UAE) [44]. The European countries were Finland [27], Ireland [28], and the United Kingdom (UK) [45]. During steady-state operating conditions, WPG facilities should provide reactive power support to assist in regulating the power system voltage level. To provide the required reactive power support, WPG facilities must have sufficient reactive power capacity. Grid codes quantify the reactive power capacity that WPG facilities must maintain as a ratio of their active power capacity [29,39,40]. A WPG facility's reactive power capacity is derived from the power factor required by the grid codes using Eqs. (1) and (2).

$$\theta = \cos^{-1}(pf) \tag{1}$$

$$Q = P_n \tan\theta \tag{2}$$

where θ is the angular difference between the active power and reactive power, pf is the power factor, Q is the reactive power, and P_n is the nominal active power capacity.

Table 1 summarizes the reviewed grid codes for the reactive power requirements of WPG facilities. Most grid codes require WPG facilities to be capable of operating with a ±0.95 power factor range and to provide up to 33% of their active power capacity as reactive power. However, the Saudi Arabian grid code stipulates only the reactive power capacity, not the power factor range. The Philippine grid code requires WPG facilities to provide up to 20% of their active power capacity as reactive power and to be capable of operating with a ±0.98 power factor range. Moreover, the grid codes from Kenya and Namibia require WPG facilities to provide up to 35% and 48%, respectively, of their active power capacity as reactive power. These grid codes also specify that WPG facilities should be capable of operating within a ±0.944 and ± 0.90 power factor range, respectively. Overall, grid codes from different countries require WPG facilities to have varying reactive power capacities and power factor ranges.

Table 1
Wind power generation grid code reactive power and power factor support requirements from countries in Africa, Asia and Europe.

Ref.	Country	Reactive power capacity	Power factor
[27]	Finland	$\pm 0.33 \times P_n$	±0.95
[28]	Ireland	$\pm 0.33 \times P_n$	±0.95
[29]	Kenya	$\pm 0.35 \times P_n$	±0.944
[39]	Namibia	$\pm 0.48 \times P_n$	±0.90
[40]	Nigeria	$\pm 0.33 \times P_n$	±0.95
[42]	Philippines	$\pm 0.20 \times P_n$	±0.98
[43]	Saudi Arabia	$\pm 0.33 \times P_n$	×
[41]	South Africa	$\pm 0.33 \times P_n$	±0.95
[44]	UAE	$\pm 0.33 \times P_n$	±0.95
[45]	UK	$\pm 0.33 \times P_n$	±0.95

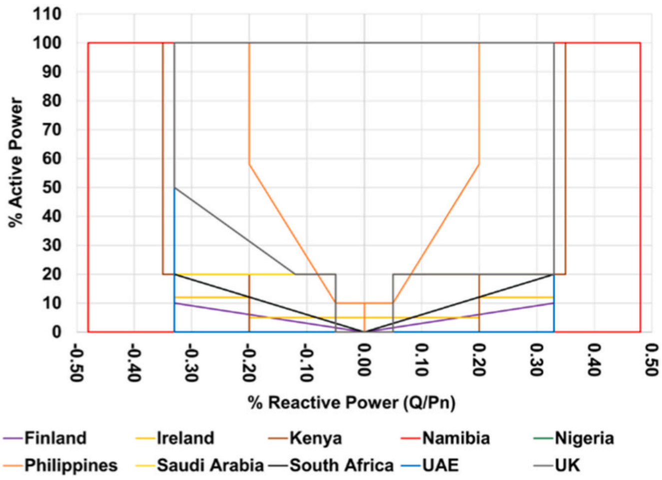

Fig. 1. Grid code requirements for P-Q capability from selected countries in Africa, Asia and Europe.

2.2. P-Q capability

The P-Q capability requirements indicate the limits of active power production and reactive power support that WPG facilities should be capable of providing at their Point of Connection (POC) to the power system [28,41,44]. The P-Q capability curve represents the combination of active and reactive power operating points WPG facilities should achieve [27,29,43]. Fig. 1 shows the P-Q capability requirements from the reviewed grid codes. Among the reviewed grid codes, the Namibian grid code has the most stringent P-Q capability requirements. It requires WPG facilities, while operating at maximum active power production, to provide up to 48% of their active power capacity as reactive power support [39]. In contrast, the Philippine grid code has the least stringent requirement, requiring WPG facilities to provide only up to 20% of their active power capacity as reactive power support [42].

The P-Q capability ensures that WPG facilities are designed and constructed with adequate capacity to provide the required reactive power support to the power system. In addition to P-Q capability, grid

Table 2
Wind power generation facilities reactive power control grid code requirements from countries in Africa, Asia and Europe.

Ref.	Country	Reactive power control	Voltage control	Power factor control
[27]	Finland	✓	✓	✓
[28]	Ireland	✓	✓	✓
[29]	Kenya	✓	✓	✓
[39]	Namibia	✓	✓	✓
[40]	Nigeria	✓	✓	✓
[42]	Philippines	×	✓	✓
[43]	Saudi Arabia	✓	✓	×
[41]	South Africa	✓	✓	✓
[44]	UAE	✓	✓	✓
[45]	UK	✓	✓	✓

Table 3
Wind power generation reactive power control performance grid code requirements from countries in Africa, Asia and Europe.

Ref.	Country	Reactive power control	Voltage control	Power factor control
[27]	Finland	• Reach the reactive power setpoint within 10 s.	• Within 0.2 to 1 s, reach 90% of the reactive power support that is required to achieve the voltage setpoint. • Within 5 s, reach the reactive power support that is required to achieve the voltage setpoint. • Once the voltage setpoint is achieved, the reactive power support should be within a ±5% tolerance, up to a maximum of 1 MVAr.	• Reach the power factor setpoint within 10 s.
[28]	Ireland	• Reach the reactive power setpoint within 20 s. • The reactive power support tolerance should not exceed the smaller value between ±5% of the reactive power capacity or ±5 MVAr.	• Within 1 s, reach 90% of the reactive power support that is required to achieve the voltage setpoint. • Within 5 s, reach the reactive power support that is required to achieve the voltage setpoint, and be within a tolerance of ±5% of the reactive power capacity. • Reach the voltage setpoint within 20 s.	• The reactive power support that is required to achieve the power factor setpoint should be within a ±0.5% tolerance of the reactive power capacity. • Reach the power factor setpoint within 20 s.
[29]	Kenya	• The reactive power support tolerance should not exceed the smaller value between ± 5% of the reactive power capacity or ± 5 MVAr.	• Within a time t1 that the SO can select to be between 1 and 5 s, reach 90% of the reactive power support that is required to achieve the voltage setpoint. • Within a time t2 that the SO can select to be between 5 and 60 s, reach the reactive power support that is required to achieve the voltage setpoint. • The reactive power support required to achieve the voltage setpoint should be within a ±5% tolerance of the reactive power capacity.	• The SO determines the required reactive power support to achieve the power factor setpoint and the maximum time that can be taken to reach the setpoint.
[39]	Namibia	• Reactive power support should be within a ±2% tolerance of reactive power capacity.	• A voltage control ramp rate with a range of 0.10 kV/min up to 100 kV/min is required. The voltage ramp rate should be configurable with a maximum step size of 0.10 kV/min.	• Once the power factor setpoint is reached, it should be within a ±2% tolerance of the power factor capability.
[40]	Nigeria	• Reach the reactive power setpoint within 120 s. However, the SO can request a longer period. • The reactive power support should be within a tolerance that is the larger of ±2% of the reactive power setpoint or ±2 MVAr.	• Reach the required reactive power support to achieve the voltage setpoint within 120 s. However, the SO can request a longer period. • The reactive power support required to achieve the voltage setpoint should be within a tolerance that is the larger of ±2% of the required reactive power or ±2 MVAr. • The voltage at the POC should be within a tolerance of ±1 kV of the voltage setpoint.	• Reach the reactive power support that is required to achieve the power factor setpoint within 120 s. However, the SO can request a longer period. • The reactive power support that is required to achieve the power factor setpoint should be within a tolerance that is the larger of ±2% of the required reactive power support or ±2 MVAr.
[42]	Philippines	×	• Within 5 s, reach 90% of the reactive power support that is required to achieve the voltage setpoint. • Within 30 s, reach the required reactive power support that is required to achieve the voltage setpoint. • The reactive power support that is required to achieve the voltage setpoint should be within a tolerance of ±5% of reactive power capacity. • The voltage should be within a tolerance of ±0.01 pu of the voltage setpoint.	×
[43]	Saudi Arabia	• The reactive power support should be within a ±2% tolerance of the reactive power setpoint, up to a maximum of 1 MVAr.	• The voltage should be within a tolerance of ±1 kV of the voltage setpoint.	×
[41]	South Africa	• Reach the reactive power setpoint within 30 s. • Reactive power support should be within a tolerance that is the larger of ±2% of the reactive power setpoint or ±0.5% of the reactive power capacity.	• Reach the voltage setpoint within 30 s. • The voltage should be within a ±0.5% tolerance of the nominal voltage. • The reactive power should be within a tolerance of ±2% of the required reactive power support based on the voltage droop setting.	• Reach the power factor setpoint within 30 s. • The power factor should be within a tolerance of ±0.02 of the power factor setpoint.
[44]	UAE	• Reactive power support should be within a tolerance that is the smaller of ±5 MVAr of the reactive power setpoint or ± 5% of the reactive power capacity.	• The reactive power support that is required to achieve the voltage setpoint should be within the time frames agreed with the SO.	• The reactive power support required to achieve the power factor setpoint should be within a tolerance of ±0.5% of the reactive power capacity.
[45]	UK	• Reactive power support should be within a tolerance that is the smaller of ±5 MVAr of the reactive power setpoint or ± 5% of the reactive power capacity.	• When the reactive power must change from zero to maximum injection, or from zero to maximum absorption, then within 1s, reach 90% of the required reactive power support to achieve the voltage setpoint. • When the reactive power must change from maximum injection to maximum absorption, and vice versa, then within 2 s reach 90% of the	• Power factor control is not mandatory. However, should it be required, the bilateral agreement will contain the time required to reach the power factor setpoint and the required reactive power support tolerance.

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Table 3 (*continued*)

Ref.	Country	Reactive power control	Voltage control	Power factor control
			reactive power support required to achieve the voltage setpoint. • Within 5 s of reaching 90% of the reactive power support that is required to achieve the voltage setpoint, the reactive power tolerance should be within ±5% of the reactive power capacity.	

codes require WPG facilities to provide voltage dependent reactive power support [28,41,45]. This ensures that the reactive power support does not negatively impact power system voltage regulation by causing excessively high or low system voltages. Furthermore, WPG facilities should be designed to meet the P-Q capability requirements while ensuring that their equipment does not overload, but operates within continuous operating voltage and loading limits. This prevents equipment tripping and potential damage.

2.3. Reactive power control modes

Reactive power control enables WPG facilities to provide reactive power support to the power system. The reactive power support depends on the control modes in which WPG facilities can operate in. Table 2 summarizes the reactive power control modes required by the reviewed grid codes. To provide steady-state reactive power support, grid codes require WPG facilities to have the ability to operate in one or more of three reactive power control modes, namely: (1) power factor control, (2) reactive power control, and (3) voltage control [41–45].

Among the reviewed grid codes, those from the Philippines and Saudi Arabia do not require WPG facilities to be capable of operating in reactive power and power factor control modes, respectively. However, grid codes from the other countries studied require that WPG facilities should be capable of operating in all three reactive power control modes. The control mode requirements in the grid codes are based on the characteristics of the power systems within their jurisdictions. In power systems where certain reactive power control modes could compromise stable operation, those modes may be omitted from the grid code. The ability of WPG facilities to operate in different reactive power control modes provides flexibility to system operators (SOs) during operations. The SOs can select the most appropriate reactive power control mode and associated setpoints to enable WPG facilities to provide the required reactive power support to the power system.

2.4. Reactive power control performance

To ensure that WPG facilities quickly provide adequate reactive power support during steady-state operation, some grid codes specify the time the facilities are allowed to take to reach power factor, voltage, and reactive power setpoints received from the SO [27,29,42]. The grid codes may also specify the tolerance within which WPG facilities should operate once the new setpoints are reached [28,39,43]. These reactive power control performance requirements ensure that WPG facilities can promptly provide the required reactive power support to improve power system voltage regulation. This capability helps maintain the quality of power supplied to consumers integrated into the power system under different operating conditions. The reactive power support required from a WPG facility to achieve a power factor setpoint can be quantified using Eq. (3). Additionally, for a given voltage droop setting, the reactive power support required from a WPG facility to achieve a voltage setpoint is given by Eq. (4).

$$Q_{pf} = P_n \times \frac{\pm\sqrt{1 - {pf_{setpoint}}^{2}}}{pf_{setpoint}} \tag{3}$$

$$Q_V = Q_{rated} \times \frac{\left(V_{setpoint} - V_{measured}\right)}{D_{droop} \times V_{nominal}} \tag{4}$$

where Q_{pf} and Q_V are the reactive power support required to achieve the power factor and voltage setpoints, respectively, P_n is the WPG facility's nominal active power capacity, Q_{rated} is the WPG facility rated reactive power capacity, $V_{setpoint}$ is the voltage setpoint, $V_{measured}$ and $V_{nominal}$ are the POC measured and nominal voltage, respectively, D_{droop} is the voltage droop setting, and $pf_{setpoint}$ is the power factor setpoint.

Table 3 summarizes the performance requirements of WPG facilities from the reviewed grid codes. The grid codes from Ireland, Nigeria, and South Africa specify both the time that WPG facilities should take to reach new power factor, voltage, and reactive power setpoints, and the tolerance within which they should operate once the setpoints are reached [28,40,41]. However, the grid codes from Finland, Kenya, the Philippines, and the UK specify time and tolerance requirements only when WPG facilities are operating in voltage control mode [27,29,42,45]. On the other hand, the grid code from Saudi Arabia specifies tolerance requirements when WPG facilities are operating in reactive power and voltage control modes, while the Namibian grid code specifies tolerance requirements for reactive power and power factor control modes [39,43]. Both grid codes do not require the facilities to reach new setpoints within a specified time.

3. Control of wind turbine generators

3.1. Wind turbine generator capacity

Wind power generation facilities have multiple spatially dispersed WTGs that are integrated using an MV collector network [46,47]. The reactive power support from WTGs is used to regulate power system voltage and to reduce active power losses [48,49]. However, the active and reactive power that WTGs provide are limited by their capacity. Wind turbine generators must optimize active and reactive power to increase the energy produced by WPG facilities while also improving their reactive power capacity. The capacity of WTGs limits the active and reactive currents they can generate based on Eq. (5). Additionally, the active and reactive power produced by WTGs is limited by their capacity based on Eq. (6) [50,51]. To maximize active power generation, the reactive power support that WTGs provide is limited to ensure operation within capacity limits.

$$I_S \geq \sqrt{{I_d}^{2} + {I_q}^{2}} \tag{5}$$

$$S \geq \sqrt{P^2 + Q^2} \tag{6}$$

where I_S is the WTG's current capacity, I_d and I_q are the active and reactive currents produced by the WTG, S is the WTG's apparent power capacity, and P and Q are the active and reactive power produced by the WTG.

Fig. 2 shows the P-Q capability curve of a WTG that can operate with a ±0.95 power factor. The WTG's P-Q capability is voltage dependent and decreases with a reduction in the terminal voltage level. The P-Q capability is also governed by Eqs. (5) and (6) because it is limited by the

WTG's current and apparent power capacity, respectively. The curves are used in power system simulation tools to model the WTGs' voltage dependent active and reactive power capacity.

3.2. *Wind turbine generator control strategies*

Wind power generation facilities use WTGs as their primary source of reactive power supply. The reactive power WTGs provide is controlled to enable WPG facilities to support the power system [52,53]. Conventional and coordinated control strategies are used to manage the reactive power generated by WTGs [52–54]. The conventional control strategy implements centralized controllers [55–57]. The reactive power required at a WPG facility's point of connection (POC) to the power system is distributed proportionally among the WTGs based on their available reactive power capacity to ensure operation within P-Q capability limits [52,58]. The conventional control strategy apportions the reactive power support from each WTG based on Eq. (7) [52,59]. The reactive power support each WTG can provide based on its capacity and active power production is given by Eq. (8) [52,57]. Compared to WTGs closer to the facility's MV collector bus, the conventional control strategy can cause WTGs that are farther away to experience higher voltages. Improved voltage regulation can be achieved by coordinating the reactive power support from WTGs [59–61].

$$Q_{WTG,i}^{ref} = \frac{Q_{WTG,i}^{avail}}{\sum_{i=1}^{n} Q_{WTG,i}^{avail}} \times Q_{POC} \tag{7}$$

$$Q_{WTG,i}^{avail} = \sqrt{S_{WTG,i}^2 - P_{WTG,i}^2} \tag{8}$$

where $Q_{WTG,i}^{ref}$ is the reactive power support from a WTG, $Q_{WTG,i}^{avail}$ is the WTG's available reactive power, $S_{WTG,i}$ and $P_{WTG,i}$ are the WTG's apparent power capacity and generated active power, respectively, and Q_{POC} is the reactive power support required at the WPG facility's POC to the power system.

Control strategies that coordinate reactive power production among WTGs have been developed to optimize the reactive power support that WPG facilities provide to the power system. Single-objective and multi-objective optimization are commonly used by these control strategies to coordinate reactive power production [52,54,61,62]. The objective functions can either be minimized or maximized to obtain optimal solutions. The control strategies have optimized objective functions such as the WTGs' voltage deviation [53,54,62], the WPG facility MV collector network voltage deviation [54,61], the WPG facility's active power losses [54,58,61,63], the WPG facility's levelized production cost [52,57,64], the WPG facility's POC reactive power support [65], the WTGs' active power production error [53,54], the WTGs' reactive power production error [54], the WTGs' reliability [62], the WPG facility's life span [57], the WPG facility's active power production [57], and the WPG facility's reactive power support error [66]. The objective functions are commonly optimized using solvers such as particle swarm optimization [56,57,59,64,65], the alternating direction method of multipliers [54,58], the soft actor-critic algorithm [52], quadratic programming [53], and the grey wolf optimizer [66].

The reactive power produced by the WTGs is controlled using centralized, distributed, and decentralized controllers [52,54,58,67,68]. Centralized controllers calculate and allocate reactive power setpoints to each WTG based on optimized objective function solutions [52,54,57,62]. However, distributed controllers enable each WTG to determine its reactive power setpoint based on local operating conditions and the operating conditions of neighboring WTGs [58,67,68]. On the other hand, decentralized control enables each WTG to independently control the reactive power support it provides at its terminals based on local operating conditions [68].

The curtailment of WTGs' active power production can be utilized to improve the reactive power support that WPG facilities provide to the power system [66,67]. However, this approach contravenes some grid codes because their P-Q capability requirements necessitate that WPG facilities provide the required maximum reactive power support while operating at maximum active power production (see Fig. 1). In addition, reducing the active power produced by WPG facilities can cause the power system frequency to decrease, which can cause underfrequency load shedding protection schemes to operate [69].

4. Grid integration transformer on-load tap changer control

4.1. *Transformer on-load tap changer operation*

Transformers with OLTCs are used to regulate the power system voltage and to control reactive power flows [70–73]. These transformers regulate the voltage level at their secondary side bus [74,75]. Wind power generation facilities use transformers with OLTCs to connect the MV collector networks to the power system's HV network. Unlike transformers with off-load tap changers, transformers with OLTCs change the tap position while energized to regulate the controlled bus voltage level. Fig. 3 presents a block diagram of a transformer with an OLTC. The OLTC relay implements settings for the controlled bus voltage setpoint and voltage bandwidth. The relay also implements time delay settings that delay the tap changer before it performs a tapping action to restore the voltage to be within the specified bandwidth. The motor drive receives a signal from the relay for the tap position to move either up or down, depending on whether the MV bus voltage level exceeds the upper or lower voltage bandwidth setting.

The relationship between the transformer HV and MV bus voltages is given by Eq. (9). The grid integration transformer winding turns ratio and the impact of tapping on the winding turns ratio are described by Eqs. (10) and (11). The winding turns ratio is inversely proportional to the transformer's MV bus voltage. To regulate the MV bus voltage, the OLTC alters the winding turns ratio by tapping down to increase the bus voltage or tapping up to reduce the bus voltage.

$$V_2 = \frac{V_1}{a} - Z_T I_2 \tag{9}$$

$$a = \frac{n_1}{n_2} \tag{10}$$

$$a = a_0 + n\Delta a \tag{11}$$

where V_1 and V_2 are the transformer HV and MV bus voltages, respectively, a is the transformer winding ratio, n_1 and n_2 are the transformer

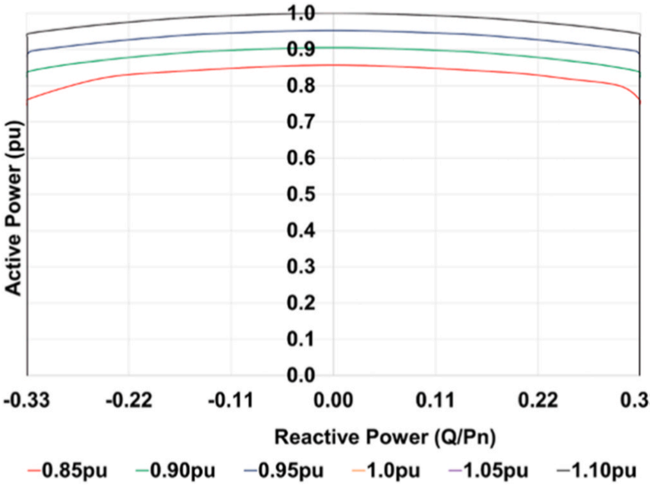

Fig. 2. Wind turbine generator P-Q capability curve showing active power and reactive power capacity voltage dependency.

HV and MV winding turns, Z_T is the impedance of the transformer, I_2 is the transformer MV current, a_0 is the transformer nominal tap position turns ratio, n is the current tap position, and Δa is the change in the transformer winding ratio due to a single tapping operation.

4.2. On-load tap changer control strategies

The transformers used for grid integration in WPG facilities regulate the global voltage level of the MV collector network [76,77]. This allows WTGs to operate within their continuous operating voltage limits, enabling them to maximize the reactive power support they can provide [76,78]. The active and reactive power capacities of the WTGs are affected by the voltage level at their terminals (see Fig. 2). A reduction in the terminal voltage reduces their capacity [76,77,79].

Multiple control strategies have been developed to regulate the global voltage level of WPG facilities' MV collector networks using grid integration transformers' OLTCs. These control strategies use conventional, adaptive, and coordinated controllers. Conventional control typically implements a centralized controller with static voltage setpoints and fixed voltage bandwidth settings [76–78]. The reactive power support that WPG facilities can provide to the power system is improved by implementing transformer OLTC settings that keep WTGs operating within their continuous operating voltage limits [78]. The main advantage of conventional control is the ease of determining and implementing the static setpoints. However, this approach may prematurely limit the reactive power that WTGs can provide due to inadequate regulation of their terminal voltage levels [76,77].

Centralized control strategies that adaptively control the operation of OLTCs have been used to improve the reactive power support that WPG facilities provide to the power system [76,77]. These control strategies adapt the tap changer voltage setpoint during operation to improve the MV collector network's voltage regulation [76,77]. The adaptive control of OLTCs can improve the reactive power support WPG facilities provide to the power system, however, the controller can also increase the frequency of tap changer operations [76,77], which reduces its lifespan.

The tapping of OLTCs can be reduced using centralized control strategies that coordinate their operation with the reactive power produced by WTGs and shunt reactive power devices [79–82]. These control strategies coordinate the operation of the devices by optimizing single-objective and multi-objective functions [79,80,83]. The objective functions considered include the WPG facility's POC voltage deviation [79], the WPG facility's MV collector network voltage deviation [79,80], shunt capacitor bank (SCB) switching [80], tap changer operation [80,83], active power losses in the WPG facility [81–83], and the static synchronous compensator (STATCOM) reactive power margin [79,80]. These objective functions are optimized using solvers such as model predictive control [79], mean–variance mapping optimization [83], and the interior-point optimizer [82]. The transformers' OLTCs provide global voltage regulation for the MV collector network, while the shunt reactive power devices supplement the reactive power produced by the WTGs [79]. The coordinated operation of the devices can reduce active power losses and tap changer operation [79,81,83]. Reducing active power losses can improve the energy levels that WPG facilities export to the power system.

5. Shunt reactive power device control

5.1. Shunt reactive power device capacity

Shunt reactive power devices are integrated into the power system to provide reactive power support for voltage regulation [84–86]. These devices control the voltage by injecting and absorbing reactive power into the power system. These devices are also integrated into WPG facilities to improve their reactive power capacity [30,37,32]. Devices integrated into WPG facilities include SCBs, shunt reactors (SRs), STATCOMs, static var compensators (SVCs), and synchronous condensers (SynCons) [30,31,32], [87,88]. The devices are integrated at the MV bus of the grid integration transformers in WPG facilities as shown in Fig. 4.

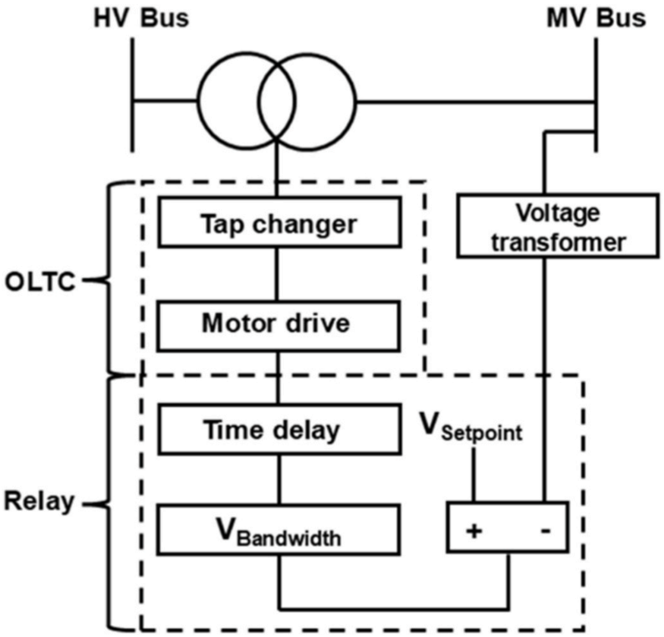

Fig. 3. Transformer on-load tap changer block diagram showing the tap changer and relay integration.

In WPG facilities, SRs and SCBs are integrated to absorb and inject reactive power, respectively. The reactive power absorption support from SRs is governed by Eq. (12), and their reactance is given by Eq. (13).

$$Q_{SR} = \frac{V^2}{X} \tag{12}$$

$$X = 2\pi fL \tag{13}$$

where Q_{SR} is the reactive power absorbed by the SR, V is the SR terminal voltage, X is the SR inductive reactance, f is the frequency, and L is the SR inductance.

The reactive power injection support from SCBs is governed by Eq. (14), and their susceptance is given by Eq. (15).

$$Q_{SCB} = V^2 B_C \tag{14}$$

$$B_C = \frac{1}{2\pi fC} \tag{15}$$

where Q_{SCB} is the reactive power injected by the SCB, V is the SCB terminal voltage, B_C is the SCB susceptance, f is the frequency, and C is the SCB capacitance.

Based on Eqs. (12) and (14), the reactive power support from SRs and SCBs is static and cannot be varied. Additionally, it decreases as their terminal voltage level drops. This characteristic does not negatively impact the performance of SRs because they are switched out of service when their terminal voltage reduces to improve the power system voltage. However, the performance of SCBs is negatively impacted because they are integrated to improve the voltage level, but become less effective when the voltage at their terminals decreases.

Dynamic shunt reactive power devices such as STATCOMS, SVCs and SynCons are integrated to provide reactive power support that can be varied. The reactive power support from STATCOMs is given by Eq. (16).

$$Q_{STATCOM} = \frac{V_{MV}^2 - V_{MV}V_{STATCOM}}{X_T} \tag{16}$$

where V_{MV} is the voltage at the STATCOM transformer MV bus, $V_{STATCOM}$ is the voltage at the STATCOM terminals, and X_T is the STATCOM transformer reactance.

The reactive power injection and absorption support from SVCs is given by Eqs. (17) and (18), respectively. The thyristor controlled SRs in SVCs provide controllable reactive power absorption support, while the SCBs provide reactive power injection support. The use of SCBs causes the reactive power injection support from SVCs to decrease when the voltage at their terminals reduces.

$$Q_{C\_SVC} = -B_C V^2 \tag{17}$$

$$Q_{R\_SVC} = (B_{Lmax} - B_C)V^2 \tag{18}$$

where B_C is the SCB susceptance, B_{Lmax} is the thyristor controlled SR susceptance, and V is the SVC terminal voltage.

The SynCon provides reactive power support that can be varied using a DC source by under exciting or over exciting the field winding to absorb or inject reactive power, respectively. The reactive power support the SynCon provides is given by Eq. (19).

$$Q_{SynCon} = \frac{V_{MV}\left(V_{SynCon} - V_{MV}\right)\cos\Theta}{X_T} \tag{19}$$

where V_{MV} is SynCon transformer MV bus voltage, V_{SynCon} is the SynCon terminal voltage, X_T is the SynCon transformer reactance, and Θ is the voltage angle displacement between the SynCon transformer MV and LV buses.

5.2. Shunt reactive power device control strategies

The reactive power support that WPG facilities provide to the power system is commonly supplemented using STATCOMs [32,89]. However, SCBs, SRs, SVCs, and SynCons are also integrated into WPG facilities to improve their reactive power capacity [30,31,32], [87,90]. Some studies have used centralized conventional controllers to manage the operation of shunt reactive power devices such as SCBs, SRs, STATCOMs, and SVCs [30,61,32,90]. Conventional controllers use static settings to control shunt reactive power devices. Wind power generation facilities use SRs to improve the global voltage regulation of their MV collector networks by absorbing the reactive power injected by the cable system, enabling the facilities to increase the reactive power they can absorb from the power system [30,61]. Shunt reactors only absorb reactive power and cannot control the amount they absorb, whereas STATCOMs and SVCs are integrated into WPG facilities to provide variable reactive power absorption and injection support [37,61,32]. These devices eliminate the reactive power deficit between the required support and what the WPG facilities can provide to the power system by supplementing the facilities' reactive power capacity [61]. Conventional control of shunt reactive power devices can result in suboptimal reactive power support from WPG facilities due to uncoordinated reactive power production.

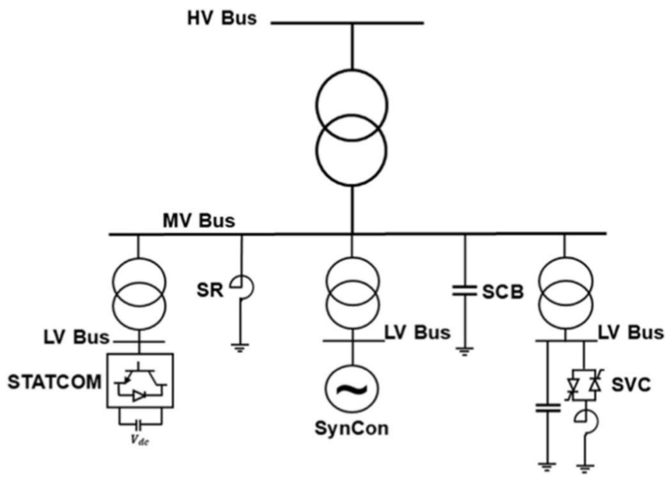

Fig. 4. Shunt reactive power device integration in wind power generation facilities MV collector bus.

To optimize the reactive power that WPG facilities provide to the power system, control strategies that coordinate the reactive power produced by STATCOMs, SCBs, and SynCons with that produced by the WTGs are used [51,87,89,91]. The reactive power produced by WPG facilities is coordinated using single and multi-objective functions [62,91,92]. The optimized objective functions include the WPG facility's active power losses [51,87,89,93], the WPG facility's POC voltage [51], the WTGs' terminal voltage deviation from reference [89,91], [93–96], the WTGs' reactive power margin [89,94,95], the WPG facility's reactive power margin [89], the SCB's reactive power support [31], and the STATCOM's reactive power support [91,93,96]. These objective functions are optimized using solvers such as Gurobi [51], the Tabu search algorithm [94], particle swarm optimization [89,91,97], interior point optimizer [93], gradient projection [95], genetic algorithm [96], and the artificial fish swarm algorithm [87].

The control strategies are based on centralized and distributed controllers. Centralized control implements a single controller to optimize the reactive power support from the WTGs and shunt reactive power devices [51,89,91,94]. Alternatively, distributed control implements a two-stage strategy, in which one stage uses integrated shunt reactive power devices to regulate the global MV collector network voltage level of the WPG facility, and the other stage controls the WTGs' terminal voltages to minimize voltage deviation [98]. Within the WPG facility, each WTG communicates with its neighboring WTGs to determine the appropriate reactive power support required to regulate its terminal voltage [98,99]. The benefit of centralized control over distributed control is that the reactive power from the WPG facility to the power system can be optimized to reduce the size of the integrated shunt reactive power device [32,91,93].

It is common practice when coordinating the reactive power produced by WTGs and shunt reactive power devices to give priority to one device and use the other to supplement reactive power support when a deficit occurs [31,94,96,100]. Wind turbine generators are normally used as the primary source of reactive power support, while shunt reactive power devices are used to supplement reactive power support when the WTGs reach their capacity limits [32,94,96,100]. However, shunt reactive power devices can also be used as the primary source of reactive power support, with WTGs supplementing the reactive power demand [92,96].

Coupling STATCOMs with SCBs [31,82,97] and STATCOMS with SynCons [87] to create hybrid shunt reactive power compensators utilizes the devices advantages, while reducing their limitations. Hybrid shunt reactive power compensators reduce the capacity of the individual devices, resulting in optimizing the solution's cost. Moreover, these hybrid configurations exploit the fast response of dynamic reactive power devices such as STATCOMs and SynCons, along with the cost competitiveness of static devices such as SCBs [31,97].

6. Discussion

6.1. Regional grid codes reactive power capability requirements

Reactive power support from WPG facilities is crucial for power system voltage regulation. Grid codes from different regions specify different reactive power and power factor requirements. As shown in Table 4, WPG facilities in Africa are required to provide the widest reactive power range, between 33% and 48% of active power capacity.

This corresponds to a power factor range of 0.95 to 0.90. On the other hand, Asian grid codes require WPG facilities to provide between 20% and 33% of active power capacity as reactive power support, corresponding to a power factor range of 0.98 to 0.95. In contrast, European grid code requirements are more uniform, typically limiting reactive power capacity to 33% of active power capacity. This corresponds to a power factor of 0.95. These differences in reactive power and power factor ranges between African, Asian, and European grid codes reflect regional power system characteristics. African power systems are characterized by long, lightly loaded transmission lines that require larger reactive power support for voltage regulation.

To align grid code compliance testing procedures from multiple jurisdictions, the IEC TS 63102 standard details procedures that should be followed when testing the compliance of WPG facilities and photovoltaic (PV) systems [101]. The test procedures are based on simulations, on-site testing, and compliance monitoring [101]. The standard is unique in that its procedures focus on testing facilities rather than individual WTGs or inverters. It outlines procedures for testing grid code compliance related to frequency withstand capability, reactive power control, active power control, fault ride-through, and power quality [101].

The IEC standards are commonly developed for testing WTGs [102,103]. The IEC 61400-21-1 standard provides procedures for testing WTGs' electrical characteristics, including active power control, reactive power control, fault ride-through withstand capability, and power quality [102]. This standard is utilized during prototype testing to demonstrate the WTGs capabilities against grid code requirements. In addition to electrical characteristics, the IEC 61400-26-1 standard provides procedures for analyzing WTGs availability based on time and energy production metrics [103]. The WTGs' availability is determined using operational states such as in service, out of service, and non-operational [103]. Wind turbine generator availability informs the performance of WPG facilities and impacts energy production.

6.2. Shunt reactive power devices performance

When WPG facilities cannot meet reactive power requirements, shunt compensation devices are integrated. Table 5 compares the reactive power compensation devices commonly used to supplement reactive power. Switched SCBs and SRs are low cost solutions and provide slow response due to mechanical switching. In contrast, SVCs, STATCOMs, hybrid STATCOM–SCB, and hybrid STATCOM–SynCon shunt reactive power devices provide faster, continuous, and variable reactive power support. However, these devices are costly.

Reactive power compensation devices present integration challenges that should be considered during selection. Shunt capacitor banks can introduce series resonance, creating a low impedance path for harmonic currents, while SRs can cause high inrush currents and transient over voltages during switching. In weak power systems, SVCs and STATCOMs can experience controller instability, leading to oscillatory behavior. Hybrid reactive power devices offer a promising balance between cost and performance, but typically have a larger footprint than single technology devices.

6.3. Reactive power control structures

Wind power generation facilities use centralized, distributed, and decentralized control strategies to manage the operation of the grid integration transformers' OLTCs, shunt reactive power devices, and WTGs. Fig. 5 shows the reactive power control structures and the devices they control. Centralized controllers implement hierarchical control using facility level and device level controllers. These controllers utilize a facility wide communication medium to exchange signals with devices and to coordinate their operation. However, centralized controllers are slow due to communication and computation delays and operate with low tolerance to controller and communication failures.

Table 4
Regional wind power generation facilities reactive power capacity and power factors range from grid codes in Africa, Asia and Europe.

Ref	Region	Reactive power capacity range	Power factor range
[29], [39–41]	Africa	$\pm 0.33 \times P_n$ to $\pm 0.48 \times P_n$	±0.95 to ±0.90
[42–44]	Middle East	$\pm 0.20 \times P_n$ to $\pm 0.33 \times P_n$	±0.98 to ±0.95
[27,28,45]	Europe	$\pm 0.33 \times P_n$	±0.95

Distributed and decentralized controllers do not implement hierarchical control and rely only on device level controllers. Distributed controllers utilize a localized communication medium to coordinate the operation of adjacent devices. This control structure improves resilience to controller and communication failures and reduces communication delays, but it cannot provide facility wide reactive power coordination. On the other hand, decentralized controllers do not use a communication medium and rely on controllers that operate independently. This control structure is robust, and controller failure affects only the controlled device. However, the lack of communication between devices prevents coordination and can cause controller hunting due to conflicting control instructions.

6.4. Classification of control strategies

Fig. 6 classifies control strategies used in WPG facilities and the devices they control. Centralized control structures include conventional, adaptive, and coordinated reactive power controllers [76,32]. Conventional control [37,78,32,104] and coordinated control [56,81,89] are used to control the operation of the grid integration transformers' OLTCs with the reactive power produced by WTGs and shunt reactive power devices in WPG facilities. In contrast, adaptive control manages only the tapping of grid integration transformers' OLTCs, and does not coordinate their operation with other devices [76,77]. On the other hand, distributed control is based on the coordinated control of WTGs and shunt reactive power devices [58,98,99], while decentralized control manages the reactive power support WTGs provide [68].

Most control strategies use centralized controllers to manage the reactive power produced by WPG facilities. This can be attributed to commercially available power system simulation tools that provide generic power plant controllers based on centralized control. This makes it convenient for researchers and engineers to modify these controllers when developing new control strategies.

Table 6 summarizes the response time, benefits, and limitations of the control strategies. Conventional control strategies are commonly used to manage the reactive power support that WPG facilities provide to the power system. These controllers are versatile and simple to implement; however, they can be slow due to communication delays, and their settings are applied as static values. In contrast, adaptive and coordinated controllers improve reactive power production by adapting and coordinating, respectively, the operation of multiple devices. Adaptive controllers are faster because they continuously adapt the grid integration transformers' OLTC operation, whereas coordinated controllers are slower because they coordinate multiple devices during operation and are therefore impacted by high computational burden and

Table 5

Comparison of shunt reactive power devices based on cost, response speed and reactive power support range.

Ref.	Device	Cost	Response time	Reactive power range
[88, 90]	SCB	Low	Slow	• Static reactive power injection.
[30]	SR	Low	Slow	• Static reactive power absorption.
[61, 32, 88]	SVC	Moderate	Moderate	• Dynamic reactive power injection and absorption.
[91, 93, 95, 96]	STATCOM	High	Fast	• Dynamic reactive power injection and absorption.
[31, 82, 97]	Hybrid STATCOM-SCB	Moderate	Moderate	• Dynamic and static reactive power injection and absorption.
[87]	Hybrid STATCOM-SynCon	High	Fast	• Dynamic reactive power injection and absorption.

communication delays. Interoperability between control strategies that manage the same devices is feasible; however, control strategies that manage different devices have limited interoperability and may lead to suboptimal reactive power control.

A limitation of these control strategies is that they can lead to excessive tap changer operation, potentially shortening its lifespan. This reduced the tap changer reliability due to frequent malfunctions. Shorter maintenance intervals are used to improve the tap changer reliability; however, this increases maintenance costs, leading to increased equipment lifecycle costs.

6.5. Reactive power coordination algorithms performance

Table 7 summarizes the algorithms used to optimize the reactive power support that WPG facilities provide to the power system. They are categorized into classical, metaheuristic, and machine learning based algorithms, and the devices they control are highlighted. Metaheuristic algorithms can find global or near global solutions, but have slow convergence speeds, making them unsuitable for real time reactive power control. Classical algorithms converge faster, enabling real time reactive power control. However, these algorithms are most effective for convex problem formulations, whereas reactive power optimization in WPG facilities is non-convex, and may have multiple optimal solutions. Machine learning based algorithms are best suited for real time reactive power control, but require training data to be effective and efficient.

6.6. Research gaps and focus areas for the future

The increased integration of WPG facilities into the power system requires them to provide reactive power support for voltage regulation and reliable system operation. Optimizing the reactive power support from these facilities requires advanced control strategies. The review conducted in this paper has identified several research gaps in the existing literature on wind power generation reactive power control:

(1) Wind power generation facilities produce variable active power, and this variability can be mitigated by integrating either battery energy storage systems or photovoltaic systems to create hybrid facilities. Current grid codes specify reactive power support requirements for single technologies, and do not consider hybrid facilities. However, hybrid facilities may have operating regimes that do not exist in single technology facilities. Identifying these operating regimes and their impact on the reactive power support from hybrid facilities can assist in developing future grid code requirements for these facilities.

(2) The application of hybrid control structures is limited in the literature, making their benefits unclear. Additionally, comparative analyses of centralized, distributed, decentralized, and hybrid control structures are needed to highlight their suitability for reactive power control in WPG facilities.

(3) Classical and metaheuristic algorithms are widely used for reactive power optimization in WPG facilities; however, the application of machine learning based algorithms remains limited. There is a need for machine learning based reactive power control strategies that enable real time control capabilities.

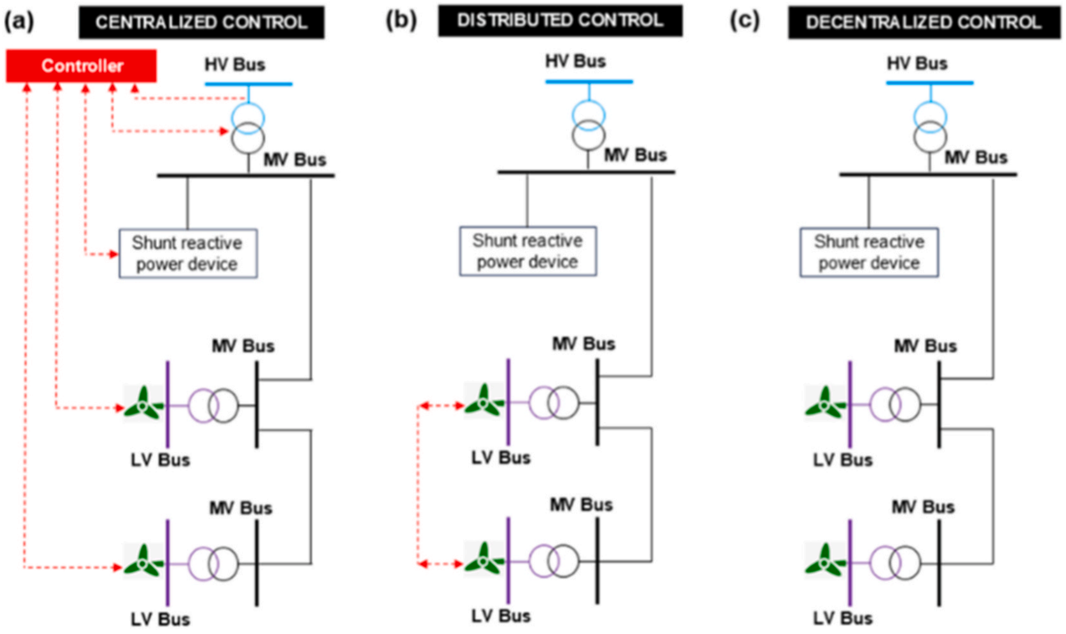

Fig. 5. Control structures used to operate a WPG facility's grid integration transformer's on-load tap changer, shunt reactive power device and wind turbine generators: (a) centralized control, (b) distributed control, (c) decentralized control.

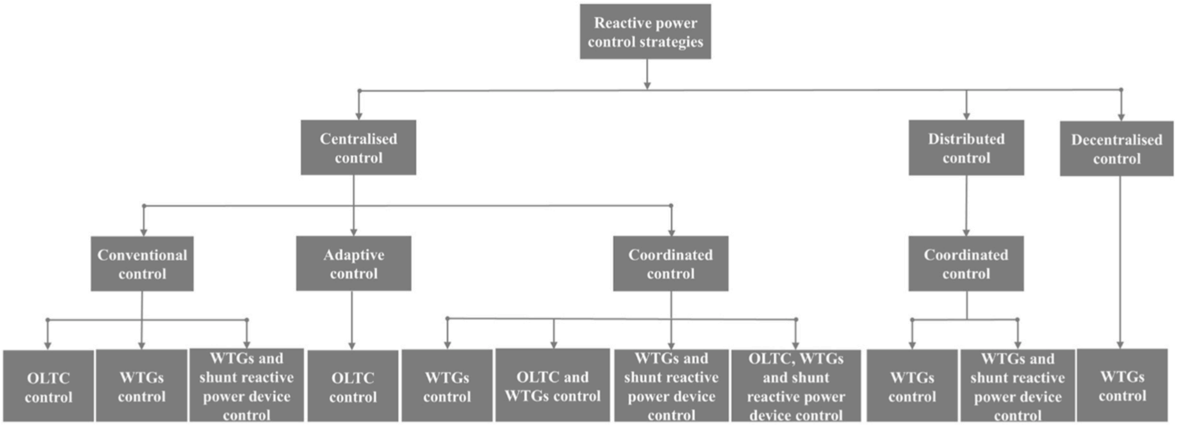

Fig. 6. Control strategies classification into centralized, distributed and decentralized control structures.

Table 6
Benefits and limitations of wind power generation facilities reactive power support improvement strategies focusing on conventional, adaptive and coordinated reactive power control.

Ref.	Controller	Response	Benefits	Limitations
[76–78]	Tap changer conventional control	Slow	- Easy implementation.	- Determining the best tap changer voltage and bandwidth setpoints can be difficult.
[104,105]	WTGs conventional control	Moderate	- Apportions the reactive power support required at the POC to each WTG to ensure they do not overload.	- The WTGs' reactive power capacity can be limited prematurely by their terminal voltage due to a lack of adequate global MV collector network voltage regulation. - Uncoordinated reactive power production from the WTGs can result in the WPG facilities providing suboptimal reactive support.
[30,37,32,88]	WTGs and shunt reactive power devices conventional control	Slow	- Easy implementation.	- Can result in suboptimal reactive power support from WTGs and shunt reactive power devices. - A larger than necessary shunt reactive power device may be required.
[76,77]	Tap changer adaptive control	Fast	- Quick controller reaction time.	- Can result in excessive tap changer operation.
[55,62], [57–59], [63–65], [67, 68]	WTGs coordinated control	Slow	- Optimally distributes the required reactive power support among the WTGs.	- May not maximize the reactive power support WTGs provide due to a lack of global MV collector network voltage regulation.
[31,51,87,89, 94,97–99]	WTGs and shunt reactive power device coordinated control	Slow	- Improved regulation of WTGs' terminal voltages and the global MV collector network voltage. - Can result in reduced shunt reactive power device capacity due to coordinated reactive power production.	- Complex controller implementation. - Slower controller performance due to the coordinated operation of multiple devices.
[83]	Tap changer and WTGs coordinated control	Slow	- Can reduce tap changer operation. - Can reduce the facility's active power losses.	- The WPG facility's reactive power support can be limited if the WTGs have inadequate capacity.
[80–82]	Tap changer, WTGs, and shunt reactive power device coordinated control	Slow	- Tap changer and integrated shunt reactive power device provide global voltage control for the MV collector network. - The shunt reactive power device supplements the reactive power support from the WTGs - WTGs provide local voltage control within the MV collector network. - Can reduce tap changer operation. - Can reduce the facility's active power losses.	- Complex controller implementation. - Slower controller performance due to the coordinated operation of multiple devices.

(4) There is a lack of studies that perform comparative analyses of classical, metaheuristic, and machine learning based control strategies to evaluate their performance based on criteria such as tap changer operation, shunt reactive power device operation, and compliance with grid code requirements. Such studies would help identify control strategies that provide better optimization, while enabling WPG facilities to achieve grid code requirements.

To address these research gaps, future studies should focus on two main areas. First, investigating the reactive power support envelopes of hybrid facilities based on the technologies they use. These studies will identify the hybrid facilities' operational boundaries to inform the development of their grid code requirements. Second, developing and validating machine learning based hybrid control strategies that combine centralized and distributed control structures to improve the reactive power capacity of WPG facilities. These novel control strategies should balance facility wide coordination with controller response suitable for real time applications. Their performance should be validated against centralized, distributed, and decentralized control strategies to determine their suitability for reactive power control. Additionally, comparative analyses with classical and metaheuristic optimization algorithms should be conducted to assess their impact on tap changer and shunt reactive power device operation. For practical deployment, the reactive power capability of WPG facilities employing new control strategies should be benchmarked against grid code requirements.

Table 7

Comparison of algorithms used to optimize the reactive power support wind power generation facilities provide to the power system, and the devices they control.

Classification	Ref.	Optimization algorithm	Controlled Devices	Convergence speed	Real time control
Classical Algorithms	[53]	Quadratic programming	• WTGs	• Moderate convergence speed. • Can get stuck in local optimal solutions.	• Suitable for real time reactive power control, but may be limited by the WPG facility's problem formulation being non-convex.
	[54,58]	Alternating direction method of multipliers	• WTGs		
	[95]	Gradient projection	• WTGs		
	[51]	Gurobi optimizer	• WTGs and STATCOM		
	[79]	Model predictive control	• WTGs, STATCOM and OLTC		
	[82,93]	Interior point optimizer	• WTGs, STATCOM and OLTC • WTGs, OLTC and hybrid STATCOM-SCB reactive power device		
Metaheuristic Algorithms	[59,61,64,89,91,97,106]	Particle swarm optimization	• WTGs • WTGs and OLTC • WTGs and STATCOM • WTGs and hybrid STATCOM-SCB reactive power device	• Slow convergence speed. • Efficient at finding global and near global solutions.	• Not suitable for real time reactive control due to slow convergence speed.
	[92,96]	Genetic algorithm	• WTGs and STATCOM		
	[94]	Tabu search	• WTGs and STATCOM		
	[66]	Grey wolf optimizer	• WTGs		
	[87]	Artificial fish swarm algorithm	• WTGs and hybrid STATCOM-SynCon reactive power device		
	[83]	Mean-variance mapping optimization	• WTGs and OLTC		
Machine Learning	[52]	Soft actor-critic algorithm	• WTGs	• Require data to train the model.	• Suitable for real time control.

7. Conclusion

The increasing penetration of WPG facilities into power systems places the onus on these facilities to provide reactive power support to assist with regulating the system voltage. This review paper presents grid code requirements from selected countries in Africa, Asia, and Europe to identify compliance requirements as well as regional reactive power capability and power factor ranges. In addition to reactive power support requirements, some grid codes also specify the time that WPG facilities are allowed to take to reach new voltage, reactive power, and power factor setpoints. Furthermore, some grid codes require WPG facilities to operate within specified tolerances after reaching a new setpoint. Current grid codes do not consider the requirements for hybrid facilities, leaving a gap in their compliance assessment.

An extensive review of control strategies developed to improve the reactive power support WPG facilities provide to the power system is also presented. These control strategies are classified into centralized, distributed, and decentralized structures, and their performance in terms of response time is analyzed along with their benefits and limitations to identify areas for improvement. Current control strategies are not implemented using hybrid control structures. Moreover, they are mostly optimized using classical and metaheuristic algorithms. As a result, they can cause excessive operation of the grid integration transformer OLTC, and they can have slow response. These limitations highlight a need for better performing control strategies.

It is recommended that future studies should focus on developing reactive power capability envelopes for hybrid facilities to assist in creating the requirements they should achieve to integrate into the power system. Additionally, machine learning based hybrid control strategies are proposed to improve the reactive power support WPG facilities provide during real time operation. These control strategies should be validated using classical and metaheuristic based control strategies, and their performance should be benchmarked against grid code requirements to ensure application in real world WPG facilities. The proposed research direction can produce novel reactive power control solutions to optimize reactive power support from WPG facilities to enable their increased penetration into the power system.

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All authors have been personally and actively involved in substantive work leading to the manuscript and will hold themselves jointly and individually responsible for its content.

Declaration of generative AI and AI-assisted technologies in the manuscript preparation process

During the preparation of this work, the author(s) used ChatGPT and Grammarly in order to improve grammar and spelling. After using this tool/service, the author(s) reviewed and edited the content as needed and take(s) full responsibility for the content of the published article.

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The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

No data was used for the research described in the article.

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