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Volt/Var Control for Power Grids With Connections of Large-Scale Wind Farms: A Review

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ABSTRACT Large-scale wind farms (LSWFs) have become a popular form of exploiting abundant wind energy. However, the integration of LSWFs presents challenges to the volt/var control (VVC) of power grids. In this regard, various VVC methods for power grids with connections of LSWFs have been proposed from different viewpoints. This paper provides a comprehensive review on VVC for power grids with connections of LSWFs. First, the challenges presented by LSWFs to VVC are investigated with regard to the uncertainty of power flow and voltage, conflicts of VVCs among interconnected power grids, operation of discrete devices, voltage stability, and reactive power market. Second, an overview on current research regarding VVC methods for LSWFs connected power grids is presented, where the VVC methods are classified into three categories: decentralized VVC, centralized VVC, and hierarchical VVC. The three categories of VVC methods are analyzed and compared in terms of their advantages, disadvantages, and applications. In addition, drawbacks of current research are concluded. Finally, to overcome the drawbacks presented in current research, this paper provides directions for future research, including event-triggered VVC methods, big data techniques, reactive power markets, energy storage systems, and VSC-based HVDC.

INDEX TERMS Volt/var control, power grids, large-scale wind farms, event-triggered, big data techniques, reactive power market.

I. INTRODUCTION

Wind power generation has been developing rapidly in recent years. According to a global wind report by the Global Wind Energy Council [1], the global total capacity of wind power reached 486.8 GW at the end of 2016, including the 54.6 GW of new capacity that was added in 2016. In recent years, there has been an increase in both the number and capacity of wind farms. Large-scale wind farms (LSWFs) and LSWF bases/clusters on the order of GW in size are either under construction or in planning in several countries [2]–[6].

Volt/var control (VVC) determines the control strategies of various devices, such as the automatic voltage regulators in generators, on-load tap changers, and shunt capacitors/reactors, which are used to regulate the reactive power and voltage of the target power grids [7]. It is essential for the safe, stable and economic operation of power grids. However, the connection of LSWFs to the grid creates challenges for VVC. The intermittent and fluctuating output of wind farms and the long-distance transmission are two important issues which should be fully considered when using VVC. Specifically, the challenges brought by LSWFs to VVC are as follows: 1) increasing the uncertainty of power flow and voltage, 2) intensifying the conflicts of VVCs among interconnected power grids of different hierarchies/regions, 3) increasing the operation of discrete VVC devices, 4) reducing the voltage stability and 5) complicating the reactive power market. Those challenges are further discussed in this paper.

The traditional VVC methods should be improved to adapt to situations involving LSWFs. Many countries have implemented specific grid codes for wind farms, where the technical requirements on VVC are described [8]–[10]. Further, many studies have been conducted to investigate the issues raised by VVC for power grids with connections of LSWFs. This paper focuses on the VVC methods in steady states, and the scope of VVC surveyed in this paper is a scheme to control reactive power and voltage over power grids. A comprehensive review on the existing research discussing such studies is presented in this paper. Furthermore, some directions for future research are proposed.

The rest of the paper is organized as follows. First, the challenges presented by LSWFs to VVC are discussed. Second, a comprehensive overview of VVC methods for power grids with connections of LSWFs is presented. Third, directions for future research are provided. Lastly, conclusions are made.

II. CHALLENGES PRESENTED BY LSWFS TO VVC

In this section, the challenges presented by LSWFs to VVC are discussed.

A. INCREASING THE UNCERTAINTY OF POWER FLOW AND VOLTAGE

The significant uncertainty of wind power output, which results from the inherent intermittence and fluctuation of wind speed, is one of the most difficult problems for VVC. For instance, according to data from 18 wind farms in the Jiuquan Wind Power Base, there is a ten percent probability that the power output changes at an hourly rate of 5%-10% [11]. Another instance comes from the Republic of Ireland, where the wind power output fell 74% in four hours on 5 and 6 November, 2003 [12]. In extreme weather conditions, such as storm fronts, a severe change of wind power output could occur in a short time. As the New York Independent System Operator observed, the wind power output ramped up from 26% to 61% over 30 minutes and then ramped down to 5% over 10 minutes as a storm front passed by on 10 June, 2008 [13]. The intermittence and fluctuation of wind power output leads to a fast change of active power flows in power grids, and thus causes a fast change of reactive power and voltage. With the great uncertainty of wind power, a traditional VVC based on a deterministic power flow and a fixed control period cannot operate effectively, and may even worsen the voltage quality and reactive power distribution.

B. INTENSIFYING THE CONFLICTS OF VVCS AMONG INTERCONNECTED POWER GRIDS

The integration of LSWFs intensifies the conflicts of VVCs among interconnected power grids. LSWFs are usually far away from load centers. Massive amounts of wind power are frequently delivered to remote load centers via long transmission lines. As Fig. 1 shows, the outputs of LSWFs are delivered from the sending grid to the receiving grid. The long-distance transmission of wind power expands the influence of random wind power on VVC to the sending grid, receiving grid and other connected grids. The transmission of large amounts of wind power increases the variation of the operation conditions over the interconnected power grids, and thus increases the difficulty of coordination for the VVCs among different hierarchical/regional power grids. A VVC oscillation could occur among interconnected hierarchical/regional power grids if the VVCs in those hierarchical/regional power grids are uncoordinated [14], [15].

C. INCREASING THE OPERATION OF DISCRETE VVC DEVICES

The transmission of large amounts of random wind power inevitably leads to a significant fluctuation of the reactive

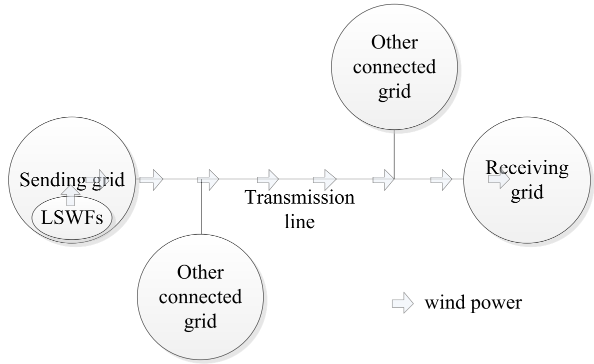

FIGURE 1. Transmission of wind power in an interconnected power grid.

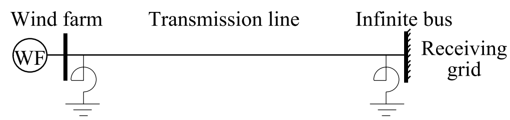

FIGURE 2. Simulation system.

power consumption in transmission lines and increases the operation of discrete VVC devices, which are the devices that can only be regulated at discrete steps for VVC. Currently, extra high voltage (EHV) and ultra-high voltage (UHV) AC/DC transmission lines are being used or under construction to deliver GWs of wind power to remote load centers [16]–[19]. The reactive power consumption of an EHV/UHV transmission line changes significantly as the power being transmitted changes. A simulation study conducted on a system shown as Fig. 2 demonstrates the change of reactive power consumption with the transmitted power of a 500 km UHV AC transmission line. The parameters of the transmission line come from Zhang *et al.* [20], the reactive power output of the wind farm is zero, the shunt reactor the line is equipped with is set to an 85% compensation rate, and the receiving grid is considered as an infinite bus and provides reactive power compensation to the line. The result is shown in Fig. 3, where the transmission line has a significant change of reactive power consumption as the transmitted power changes. For DC transmission, line commutated converters (LCCs) are usually used to transmit large power. The reactive power consumption of the rectifier is 30%-50% of the transmitted power, and the consumption of the inverter is 40%-60% in LCC based HVDC [21]. Therefore, significant fluctuation of wind power will lead to significant fluctuation of reactive power consumption in both AC and DC transmission lines. The significant reactive power consumption fluctuation requires frequent regulation of VVC devices. Continuous VVC devices, which are the devices that can be regulated continuously for VVC, such as STATCOM and SVC, are suitable for frequent regulation. However, continuous devices are only equipped in certain important buses with limited capacity due to their high cost. The common devices for VVC are discrete devices, such as fixed HV shunt reactors, switchable low voltage (LV) shunt reactors and

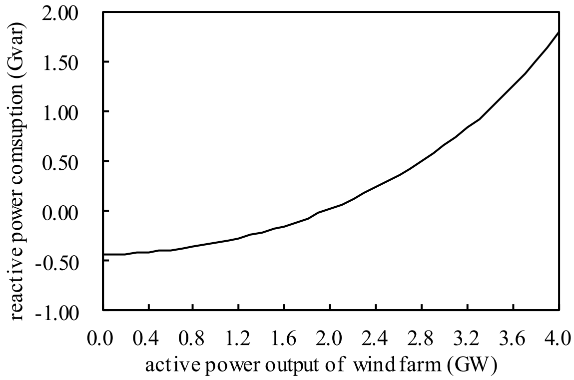

FIGURE 3. Reactive power consumption of a 500 km UHV AC transmission line.

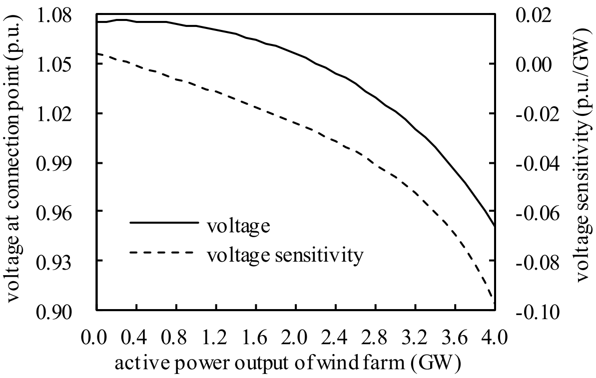

FIGURE 4. Voltage and voltage sensitivity at the connection point of a 500 km UHV AC transmission line.

capacitors [22], and filters (for HVDC). Therefore, the fluctuant reactive power consumption caused by LSWFs will result in frequent regulation of the discrete devices, which is harmful because excessive regulation shortens the life expectancy of the devices and increases maintenance cost.

D. REDUCING THE VOLTAGE STABILITY

The connection of LSWFs results in voltage stability problems. LSWFs are typically connected to a weak grid, which is indicated by a low short circuit ratio (SCR) [23], [24]. Wind power on the order of GWs size presents a great challenge to transmission infrastructures [25]. Congestion would occur in transmission lines due to large amounts of wind power. In case of low SCR and heavy loading, the voltages at the buses along the transmission lines are very sensitive to power changes. Fig. 4 shows the voltage and voltage sensitivity to the change of the active power output of a wind farm at the connection point of a 500 km UHV AC transmission line. The SCR at the connection point is 1.93. As shown in Fig. 4, the voltage decreases faster and faster as the active power output of the wind farm increases. A case study indicates that voltage collapse will occur at a relatively high voltage level in a system delivering large quantities of wind power [23]. Therefore, LSWFs reduce voltage stability and may cause voltage collapse.

E. COMPLICATING THE REACTIVE POWER MARKET

LSWFs bring economic and technical problems to the reactive power market. The participation of LSWFs in reactive power market presents challenges to payment and cost allocation. Double-fed induction generator (DFIG) or permanent magnet synchronous generator (PMSG) based wind farms can provide reactive power to power systems [26], [27]. From this perspective, the owner of the wind farm should be paid for providing reactive power ancillary service. However, the volatility of wind power increases the demand of flexible reactive power regulation. From this perspective, the owner of the wind farm is required to pay a part of the cost of reactive power ancillary service. Therefore, it is necessary to present reasonable rules for payment and cost allocation in reactive power market involving LSWFs. Besides, the volatility of wind power greatly increases uncertainty of reactive power market clearing. Reactive power market clearing is the process to determine the market equilibrium prices, at which the quantity of the reactive power that reactive power demanders are willing and able to buy exactly balances the quantity that reactive power providers are willing and able to sell [28], [29]. The design of the framework of reactive power market clearing, including the mathematical models used in reactive power market clearing and the time intervals of market clearing process, has to address the issues resulting from the uncertainty of wind power. In conclusion, LSWFs complicate reactive power market in both economic and technical aspects.

III. OVERVIEW OF CURRENT RESEARCH

Various VVC methods have been proposed to cope with the influences of connection of LSWFs. An overview of current research discussing VVC methods for power grids with connections of LSWFs is presented in this section. It should be noted that the LSWFs in this section refer to wind farms or wind farm clusters whose capacity amounts to or above 100 MW, since only a few studies investigate wind farms in the GW range with regard to VVC.

As shown in Fig. 5, according to the control architecture, the VVC methods can be classified into three categories:

1) Decentralized VVC: Local volt/var controllers receive local or partial information of power system states (e.g., wind power, active power load and reactive power load) and decide the control inputs (e.g., voltage references of PV buses, reactive power output reference of wind farms, and control instructions of reactive power compensators) of the local devices for VVC.
2) Centralized VVC: A central volt/var controller receives all the information of power system states and decides the control inputs of all the devices for VVC in the system.
3) Hierarchical VVC: Multiple volt/var controllers are organized in a hierarchical structure. All the controllers can receive partial or all information of power system states. The control inputs are divided into disjoint groups and decided by the controllers at different

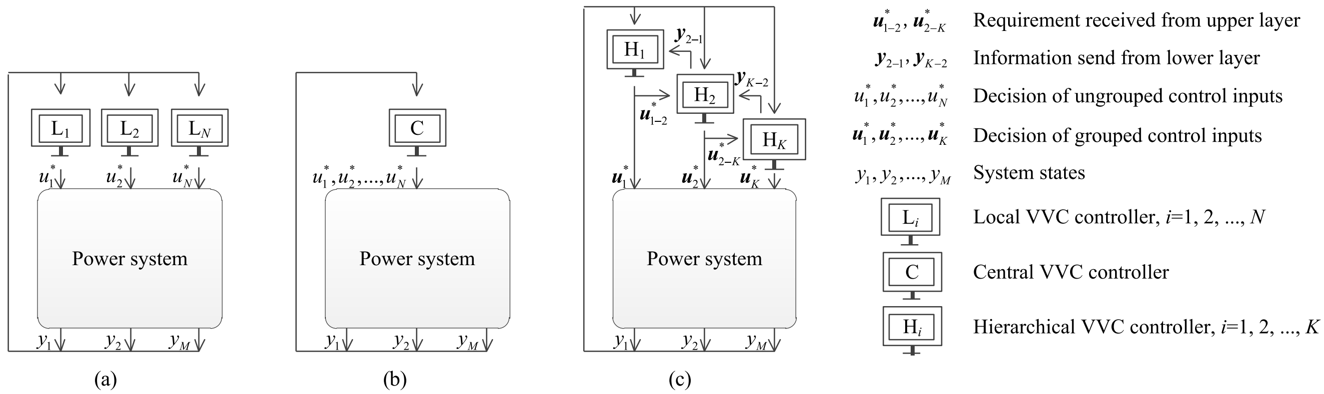

FIGURE 5. VVC architecture. (a) Decentralized VVC. (b) Centralized VVC. (c) Hierarchical VVC.

layers. The controller at a lower layer complies with the decision made by the controller at the upper layer. There are usually two ways to realize this: The first way is the controller at the lower layer adjusts its control inputs at a high frequency while the controller at the upper layer does it at a low frequency. The other way is the controller at the lower layer fulfills the requirements received from the controller at the upper layer and sends necessary information to the controller at the upper layer.

It is worth mentioning that researchers are paying attention to distributed VVC. Similar to decentralized VVC, the control inputs are decided by local volt/var controllers in distributed VVC. The difference between distributed VVC and decentralized VVC is that each local VVC controller in distributed VVC can exchange information with the others, while the VVC controllers in decentralized VVC cannot. However, to the best of the authors' knowledge, most studies on the VVC for power grids with connections of LSWFs are focused on decentralized VVC, centralized VVC and hierarchical VVC, and few studies have utilized distributed VVC.

A. DECENTRALIZED VVC

According to the control criteria, decentralized VVC can be divided into three parts: local power factor or reactive power control, local voltage control, and remote voltage control. Local power factor or reactive power control is used to regulate the power factor or reactive power at a local bus within its limits or according to a set point. Local voltage control is used to regulate voltage at a local bus within limits or according to a set point. Remote voltage control is used to regulate the voltage at the selected bus according to a voltage set point.

The relationships between current research in decentralized VVC and the challenges investigated in Section II are explained as follows, where the labels of (A)-(E) represent that the conclusion is related to the challenge listed in Section II.A to Section II.E, respectively.

Decentralized VVC cannot make complete observation of the power system's states and lacks cooperation of different local controllers; thus, it cannot make decisions from the perspective of the whole system. Therefore, it cannot address the problems of uncoordinated VVC among interconnected power grids (B) and reactive power market (E). Local power factor or reactive power control takes the reactive power output or power factor of a wind farm as control criterion [32]–[35], thus reduces the uncertainty of the reactive power output of the wind farm (A). However, the reactive power output cannot be adjusted according to voltage, and large voltage variations may happen [34]. Unlike local power factor or reactive power control, Local/remote voltage control takes the voltage at the target bus as control criterion [33], [35]–[44]. It performs better to maintain voltage profiles (A). In addition, it is reported in [35] that local voltage control is better than local power factor control to avoid voltage collapse (D). None of these papers pays attention to the operation time of discrete devices (C).

1) LOCAL POWER FACTOR OR REACTIVE POWER CONTROL

The power factor of a wind farm output can be expressed as

$$\cos\varphi = \frac{P}{\sqrt{P^2 + Q^2}} \tag{1}$$

where $\cos\varphi$ is the power factor of the wind farm output, P is the active power output from the wind farm and Q is the reactive power output from the wind farm. It can be inferred that when a constant power factor is adopted to regulate the reactive power output of wind farm, the wind farm output has a fixed proportion of the reactive power output to the active power output.

Owners of wind farms tend to operate the wind power at a constant power factor or reactive power within the ranges required by grid codes [8]–[10], such as zero reactive power output. DFIGs and PMSGs can be controlled to regulate power factor or reactive power output, while fixed speed induction generators (FSIGs) cannot. For DFIG-based wind farms, constant power factor or reactive power control can be achieved by regulating the q-axis current of the rotor-side converts of DFIGs, and for PMSG-based wind farms, it can be achieved by regulating the q-axis current of the grid-side converts of PMSGs [30], [31]. For FSIG-based wind farms, it can be achieved by regulating reactive power compensators equipped in wind farms [32]. Some studies considering LSWFs are also based on the assumption that the outputs of wind farms have constant power factors or constant reactive power outputs [32]–[35]. Xu *et al*. [33] provided control strategies of wind farms, STATCOM and HVDC for a case of integrating an offshore wind farm and oil & gas installations by LCC based HVDC system. The reactive power output of the wind power was set as zero. To offer a reference for the development of offshore wind farms in Taiwan, Wang *et al*. [34] analyzed voltage variation brought by large-scale offshore wind farm in Taiwan Power System. The power factors of the outputs of all the wind turbine generators (WTGs) were set at a specific value. To quantify the impacts of wind farms on voltage, Zhang *et al*. [32] proposed a statistical method to assess the voltage deviation at the point of common coupling between the wind farm and the grid, where the wind farm operated under constant power factor control. Both the wind power and the grid Thevenin equivalent impedance were formulated by discrete probabilistic models. In order to assess the voltage security of power system, Ma *et al*. [35] proposed a method to construct voltage stability boundary of power system with connection of a DFIG based wind farm. Constant power factor control was used as one of the control strategies for the wind farm.

Although it is easy to implement local power factor or reactive power control and assess its performance, it is unable to adjust reactive power output according to the variation of voltage. It is indicated that local power factor or reactive power control can lead to large voltage variation [34]. Besides, the set point of reactive power or power factor is usually made arbitrarily and is hard to achieve an optimal control.

2) LOCAL VOLTAGE CONTROL

A method for voltage control is to keep the voltage at the target bus as a constant. Ma *et al*. [35] compared the voltage stability boundary under constant voltage control of DFIG wind farm with that under constant power factor control, and illustrated that constant voltage control is better than constant power factor control in avoiding voltage collapse. When wind farms are connected with LCC based HVDC, constant voltage control is required at the AC side of the rectifier for commutation, while LCC has no ability for AC voltage control and requires support from other VVC devices. Xu *et al*. [33] and Bozhko *et al*. [36] used STATCOMs to provide a constant commutation voltage. To coordinate the control of wind farms and LCC based HVDC in the situation that a stiff AC voltage source is not available, Xiang *et al*. [37] analyzed the interactions between a wind farm and LCC based HVDC, and designed a controller for the wind farm to provide constant commutation voltage as well as retaining optimal power tracking capability. For the DC voltage control in LCC based HVDC, the inverters were commonly operated to maintain constant DC voltage [33], [36], [37]. Recently, voltage source converter (VSC) based HVDC has been deployed to connect wind farms. VSC has the ability to independently generate reactive power for AC voltage support. Xu *et al*. [38] developed control strategies of VSC based HVDC and wind farms to provide smooth operation during wind power variations. Xu and Yao [39] studied different voltage control and power dispatch strategies to demonstrate the flexibility of multi-terminal VSC based HVDC system for integrating large offshore wind farms. Both of them utilized VSCs to maintain the voltages at the AC sides of VSCs. Constant voltage control can provide firm voltage support. However, when multiple voltage sources are in a close electrical proximity, applying constant voltage control can lead to an unstable control due to the error of voltage measurement [40].

An alternative to constant voltage control is Q-V characteristic based control. Q-V characteristic can be divided into two parts: Q-V characteristic of a voltage controller, and Q-V characteristic of a power system. The Q-V characteristic of a voltage controller is the relation between the reactive power set point and the measured voltage, and the Q-V characteristic of a power system is the relation between reactive power injection and voltage at a target bus. An illustration of Q-V characteristic based control is shown as Fig. 6, where the solid line segments are the pre-set Q-V characteristic of the voltage controller of a voltage source, the dashed line is the Q-V characteristic of the power system, $Q_{\min}$ and $Q_{\max}$ are the limitations of reactive power output of the voltage source, and V_{ref} is the voltage set point. The reactive power set point of the voltage sources is determined by the intersection point of the Q-V characteristics of the voltage controller and the power system, i.e., point A. With Q-V characteristic based control, the voltage can be maintained at a point around V_{ref}. Q-V characteristic based control is helpful in coordinate the voltage control of multiple voltage sources in a close electrical proximity. To demonstrate this advantage, Miller *et al*. [40] provided an analysis and a field test of Q-V characteristic based control for wind farms in close proximity and indicated that it can coordinate the reactive power outputs of the wind farms without the requirement of communication between the wind farms, while constant voltage control may not find a equilibrium point for the reactive power outputs of wind farms due to the error of voltage measurement. However, Hau *et al*. [41] noted the voltage oscillation problem in a situation where wind farms applying Q-V characteristic based control were connected in parallel, and suggested a reduction of the controllers' dynamics or a reduction of the required reactive power to improve stability of the dynamic process of control.

In context of VSC based HVDC connection, I-V characteristics based control is commonly used for the grid-side converters to control DC voltage. Like the Q-V characteristic, the I-V characteristic consists of the I-V characteristic of a voltage controller and that of a power system. The I-V characteristic of a voltage controller is the relation between the current set point and the measured voltage, and that of a power system is the relation between current injection

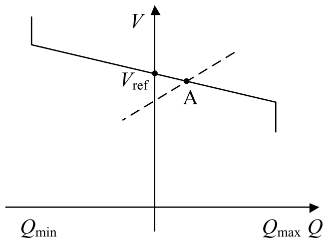

FIGURE 6. Illustration of Q-V characteristic based control.

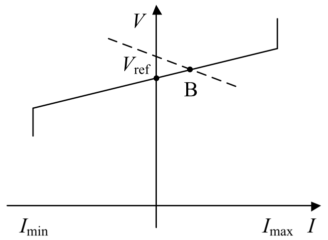

FIGURE 7. Illustration of I-V characteristic based control.

and voltage at a target bus. As Fig. 7 shows, the solid line segments and the dashed line are the I-V characteristics of the voltage controller and the power system, respectively, $I_{\min}$ and $I_{\max}$ are the limitations of the current of the converter, and V_{ref} is the voltage set point. And the current set point of the converter is determined by point B. Xu and Yao [39], Wang *et al.* [42] analyzed the performances of various I-V characteristics on multi-terminal VSC based HVDC and verified that I-V characteristic based control is flexible and effective on DC voltage control and power dispatch of multiple VSCs. Egea-Alvarez *et al.* [43] focused on the design of the I-V characteristic based control and the building of a scaled test platform of multi-terminal VSC based HVDC.

Local voltage control is better than local power factor or reactive power control for voltage regulation at local bus. However, in most situations, the set point of voltage is made arbitrarily. Therefore, local voltage control is incapable to achieve an optimal reactive power dispatch.

3) REMOTE VOLTAGE CONTROL

Kim *et al.* [44] applied remote voltage control for wind farm to support the voltage at a remote bus. To exploit the available reactive power capacity for instant voltage recovery, they determined the slope of the Q-V characteristic for each WTG in real time, considering the different output of WTGs resulting from the wake effect.

With a well selected bus, remote voltage control is helpful for maintaining the voltages in a regional power grid. However, like local voltage control, the set point of voltage is usually made arbitrarily. Therefore, remote voltage control is hard to achieve an optimal reactive power dispatch.

4) ADVANTAGE, DISADVANTAGE AND APPLICATION OF DECENTRALIZED VVC

Decentralized VVC is simple and easy to implement. It does not require complicated computation and system-wide communication. However, it only takes local reactive power, local voltage or remote voltage as control criteria, and cannot consider the challenges presented by LSWFs from a system-wide perspective. It is hard for decentralized VVC to achieve an optimal control due to the lack of full observation of system states and information exchange between local controllers. In practice, decentralized VVC is used for simple VVC when computation and communication capability in the power system is low.

B. CENTRALIZED VVC

Centralized VVC adjusts control inputs periodically from a system-wide perspective. Generally, the control task is formulated as a constrained programming model, which are expressed as:

$$\begin{aligned} &\min \boldsymbol{f}(\boldsymbol{x}, \boldsymbol{u}) \\ &\text{s.t. } \boldsymbol{h}(\boldsymbol{x}, \boldsymbol{u}) = \boldsymbol{0} \\ &\quad\;\; \boldsymbol{g}(\boldsymbol{x}, \boldsymbol{u}) \leq \boldsymbol{0} \end{aligned} \tag{2}$$

where, $\boldsymbol{x}$ are the state variables (e.g., voltage magnitudes of PQ buses, and voltage angles of PQ buses and PV buses), $\boldsymbol{u}$ are the control variables (e.g., voltage magnitudes of PV buses, reactive power output of wind farms, control instructions of reactive power compensators, and tap ratios), $\boldsymbol{f}(\boldsymbol{x}, \boldsymbol{u})$ are the objective functions (e.g. active power loss, and total voltage deviation), $\boldsymbol{h}(\boldsymbol{x}, \boldsymbol{u})$ are the equality constraints (e.g., power flow constraints), and $\boldsymbol{g}(\boldsymbol{x}, \boldsymbol{u})$ are the inequality constraints (e.g., limits of voltage, limits of reactive power output of wind farms, limits of reactive power compensators, and limits of tap ratios). Optimization algorithms, such as interior point method (IPM) and genetic algorithm (GA), are usually used to search optimal solution to the model [45].

The relationships between current research in centralized VVC and the challenges (A)-(E) investigated in Section II are explained as follows:

Centralized VVC makes system-wide observation and decides control inputs periodically. References [17], [46]–[50], and [60] decide the control inputs based on the measured value of wind power or wind speed directly in each control period to deal with the change of wind power (A). However, the uncertainty of wind power within each control period still influences the performance of VVC. Shortening the control period can reduce the uncertainty of wind power within each control period, but it will increase the computation burden of controller and operation of discrete devices. In order to mitigate the influences of the uncertainty of wind power within each control period (A), [51]–[53] and [59] use prediction values of wind power, and [54]–[58] utilize probability distribution of wind power, in the VVC models. In order to prevent the discrete devices from excessive regulation (C), [51]–[53] take the operation cost of discrete devices as an objective function or a part of an objective function. To avoid voltage instability (D), [55] and [57] formulate voltage stability as an objective function, while [52], [53], and [56] formulate voltage stability as a constraint in the optimal models for VVC. With regard to reactive power market (E),

[57] proposes a multi-objective model to compromise system payment and voltage security margin, and [58] discusses the reactive power cost for WTGs. Although current research in centralized VVC has addressed some challenges presented by LSWFs, it has not studied the coordination of VVC among interconnected power grids (B).

According to the time of executing optimization calculation, centralized VVC are divided into on-line optimization and off-line optimization.

1) ON-LINE OPTIMIZATION

On-line optimization executes optimization calculation in each control period to decide optimal control inputs.

Wilch *et al.* [46] and Pappala *et al.* [47] applied an adaptive particle swarm optimization (PSO) algorithm to minimize the active power loss of a simple radial power grid connected with an offshore wind farm. They demonstrated that the adaptive PSO algorithm was robust enough to obtain optimal solutions. Aside from the commonly used VVC devices, the switchable cables were considered as controllable VVC devices. Kumar *et al.* [48] presented an ORPD model, where the L-index was used to formulate the objective function, to enhance voltage stability utilizing the reactive power of a wind farm and other reactive power resources. And they used trust region method to search optimal solution. To determine the voltage and reactive power set points in a long EHV AC cable transmission line connecting an offshore wind farm, Lauria and Schembari [17] regarded a symmetrical current profile as the condition for maximum active power transmission capacity and near-minimum loss of the AC cable transmission line. Based on the condition of a symmetrical current profile, they obtained the voltage set points for nodes connecting wind farms and the required compensations for other nodes by a modified power flow algorithm. The proposed method is simple and can be applied in a radial power grid. Considering the economic operation of multi-terminal HVDC systems connected with large offshore wind farms, Aragüés-Peñalba *et al.* [49] proposed an optimum voltage control method to obtain the optimum voltages of grid-side VSCs for minimum losses of the HVDC systems. They determined the voltages at the DC sides of grid-side VSCs using IPM. The proposed method can reduce the active power loss without further important investments. However, they did not consider the active power losses of VSCs. Aragüés-Peñalba *et al.* [50] included the active power losses of VSCs in the objective function. However, the uncertainty of wind power within each control period, which would influence the performance of the optimization, is not addressed in these works [17], [46]–[50].

One way to address the uncertainty of wind power within each control period is to utilize wind power (or wind speed) prediction. To deal with the uncertainty of wind power and its prediction, Pappala *et al.* [51] proposed a deterministic scenario method and a stochastic tree method, where the wind power was forecasted by an artificial neural network. The objective function was formulated as a sum of the values of transformer operation cost and active power loss corresponding to a set of predicted wind power. The deterministic scenario method was performed on a single wind power prediction scenario. Furthermore, the stochastic tree method was performed on several wind power prediction scenarios to cope with the uncertainties in the wind power forecast. El-Araby [52] proposed a day-ahead ORPD method considering the volatility of wind power and the errors of wind power forecast. He formulated the objective function as the total cost including cost of energy losses and operation cost of reactive power compensators in a day with the hourly forecasted wind power, and considered voltage stability margin in the constraints. Hourly forecasted wind power, and its relevant scenarios which were sampled from a normal distribution representing the wind power forecast errors, were used to formulate constraints. To cope with the voltage stability problem caused by fluctuant wind power, Yang *et al.* [53] proposed an optimal dispatch strategy for a wind farm cluster considering the static voltage stability by introducing the up-fluctuation factor, down-fluctuation factor, and the wind power prediction value into the constraints of voltage stability margin. The operation cost of discrete devices was taken as a part of the objective function. Apparently, the accuracy of the wind power (or wind speed) forecast plays an important role in the effectiveness of these methods [51]–[53]. This accuracy is difficult to guarantee because of the great uncertainty surrounding wind power.

Another way to consider the uncertainty of wind power within each control period is to utilize a stochastic characteristic model of wind power (or wind speed). Taghavi *et al.* [54] proposed a stochastic optimal reactive power dispatch (ORPD) model to concern the uncertainty of wind power and loads. They used the Weibull distribution for the wind speed. To diminish the computation burden while retaining accuracy, they applied a point estimate method (PEM) for solving the stochastic problem. In addition, they utilized a discrete PEM to cope with the fact that there is no common probability density function for wind power. To compromise the objective of economic operation and voltage stability, Mohseni-Bonab *et al.* [55] proposed a multi-objective ORPD model for active power loss minimization and voltage stability index minimization, which considered the uncertainty of wind power and load. They presumed the wind power fell into one of five scenarios, which are generated with wind speed having a Rayleigh distribution, and formulated the objective functions as the expected value corresponding to these five scenarios, then used the ε-constraint method to create the Pareto set, and then used the fuzzy satisfying approach to select the best compromise solution. The proposed model was solved by SNOPT and SBB solvers in a GAMS environment. Mohseni-Bonab *et al.* [56] formulated objective functions as the expected value of active power losses and operation & maintenance costs for wind farms corresponding to a set of wind power and load scenarios, and they dealt with the voltage stability problem as a constraint of L-index. Weibull distribution and Normal distribution are used for wind speed and load, respectively. To address the issues of reactive power market clearing, Kargarian and Raoofat [57] proposed a stochastic multi-objective market model to compromise system payment and voltage security margin. They presumed the wind speed had a normal distribution and fell into one of thirteen scenarios, and formulated objective functions as expected values. In the study, the wind farm consisted of fixed speed WTGs and did not take part in the reactive power dispatch. To develop the reactive power ancillary services of wind farm, Ullah *et al*. [58] discussed reactive power cost models for variable speed WTGs with different grid codes and then integrated the wind farm's reactive power capability into the short-term system operation. They used a normal distribution for the wind speed. The methods in [54]–[58] require detail information of the probability distribution of wind power, which may be hard to obtain.

On-line optimization is helpful in achieving safe, stable and economic operation of power grids with connections of LSWFs. However, in order to cope with the fluctuation of wind power, the optimization calculation should be executed using a short control period or considering multiple wind power scenarios simultaneously, which will lead to a computation problem.

2) OFF-LINE OPTIMIZATION

To avoid complicated computation in each control period, off-line optimization is proposed. In off-line optimization, optimization calculations are executed for most system states before the controller is put into operation. Then control rules representing the relation between optimal solutions and system states are generated by dealing the results of the above optimization calculations. In each control period, the controller makes decision of control inputs based on the control rules and needs not solve the optimization problem. An illustration is shown in Fig. 8 to compare off-line optimization with on-line optimization.

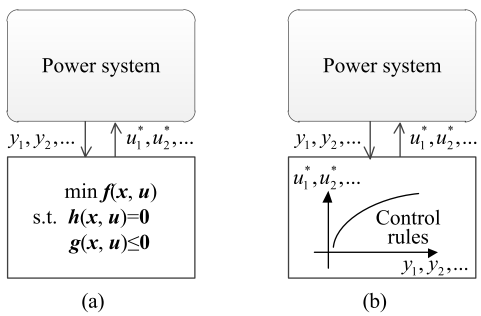

FIGURE 8. Illustration of on-line optimization and off-line optimization. (a) On-line optimization. (b) Off-line optimization.

To reduce computation burden in each control period, Sakamuri *et al*. [59] constructed an offline Reference Voltage Lookup Table by optimization for minimal loss of an offshore AC grid with a cluster of wind farms for most system states. The table was used to select voltage set point according to wind speed. They also proposed a reactive power dispatch method for WTGs, wind farms and wind farm clusters based on the ratio of the participation factors and the available reactive power. Sáiz-Marín *et al*. [60] proposed a method to determine the reactive power outputs of wind farms and on-load tap changers in order to minimize the active power loss by data mining, which is the process in databases to discover and reveal previously unknown, meaningful and useful patterns. They built a database of optimal scenarios, and selected and defined a set of explanatory variables. Based on the database of optimal scenarios, they obtained the relationships between the optimal control inputs (reactive power outputs of wind farms and tap ratio of a transformer) and the explanatory variables, using the regression rules and the classification trees, respectively. In real-time control, the control inputs were decided according to the values of the explanatory variables and the above relationships. Data mining method is attractive because of its analytical expression of optimal setting of VVC devices, which is helpful to avoid complicated computation. However, the research on this subject is quite preliminary and much more work should be conducted.

Off-line optimization can reduce computation burden in real-time optimal control greatly and is attractive in the situation involving fast changing system states resulting from LSWFs. However, the control rules can be very complicated and difficult to reveal in a large power system.

3) ADVANTAGE, DISADVANTAGE AND APPLICATION OF CENTRALIZED VVC

The contributions of the works in centralized VVC can be summarized in Table I and II.

Centralized VVC can control all the available VVC devices in a power system optimally. It can be used to cope with various challenges presented by LSWFs to VVC from a system-wide perspective. However, it requires high capacity of computation and communication.

Despite the advantage of centralized VVC in system-wide optimization, it has two limitations. First, it is inflexible to coordinate different device characteristics. It controls discrete and continuous devices in the same control period, which has little consideration on different regulation characteristics between discrete and continuous devices. Second, it is inflexible to coordinate different objectives between the transmission system and wind farms. A wind farm has its own control objectives, and some of them may conflict with the control objectives of the transmission system. It is complicated for centralized VVC, which uses one programming model, to deal with different control objectives between the transmission system and the wind farm. In some situations, a wind farm keeps information confidential and has autonomy in operating its control devices, which hinders centralized VVC.

In practice, centralized VVC is used for system-wide optimal reactive power dispatch, when the computation and communication capacity in the power system is sufficiently high and the central controller can obtain whole information of system states and control all available VVC devices.

TABLE 1. Contributions to VVC models.

Reference	Contribution
[46] [47]	Considered switchable cables as controllable devices.
[48]	Used L-index to formulate the objective function to improve voltage stability.
[17]	Regarded a symmetrical current profile as an optimal condition of the AC cable transmission line.
[49] [50]	Proposed optimal voltage control model for multi-terminal HVDC.
[51]	Formulated the objective function was as the sum of the values of transformer operation cost and active power loss corresponding to a set of predicted wind power, and Proposed a deterministic scenario method and a stochastic tree method to deal with the uncertainty of wind power and its prediction.
[52]	Formulated the objective function as the total cost including cost of energy losses and operation cost of reactive power compensators in a day with the hourly forecasted wind power, and considered voltage stability margin in the constraints.
[53]	Took operation cost of discrete devices as a part of the objective function, and introduced the up-fluctuation factor, down-fluctuation factor, and the wind power prediction value into the constraints of voltage stability margin.
[55]	Formulated the objective functions as the expected value of active power loss and L-index corresponding to a set of wind power scenarios generated with wind speed having a Rayleigh distribution.
[56]	Formulated objective functions as the expected value of active power losses and operation & maintenance costs for wind farms corresponding to a set of wind and load scenarios. Weibull distribution and Normal distribution are used for wind speed and load, respectively.
[57]	Formulated objective functions as the expected value of system payment and voltage security margin corresponding to a set of wind speed scenarios generated from a normal distribution.
[58]	Discussed reactive power cost models for variable speed WTGs with different grid codes and then integrated the wind farm's reactive power capability into the short-term system operation.

C. HIERARCHICAL VVC

Hierarchical VVC makes decisions of control inputs periodically in a hierarchical structure from a system-wide perspective. Hierarchical VVC has multiple programming models to consider different objectives or constraints as described in (3), where the subscripts represent the index of different layers. These models are managed by a hierarchical architecture. The models in lower layers comply with the decisions made from the models in upper layers.

$$\begin{aligned}
&\min \boldsymbol{f}_1(\boldsymbol{x}_1, \boldsymbol{u}_1)\\
&\text{s.t. } \boldsymbol{h}_1(\boldsymbol{x}_1, \boldsymbol{u}_1) = \mathbf{0}\\
&\quad\ \boldsymbol{g}_1(\boldsymbol{x}_1, \boldsymbol{u}_1) \le \mathbf{0}\\
&\min \boldsymbol{f}_2(\boldsymbol{x}_2, \boldsymbol{u}_2)\\
&\text{s.t. } \boldsymbol{h}_2(\boldsymbol{x}_2, \boldsymbol{u}_2) = \mathbf{0}\\
&\quad\ \boldsymbol{g}_2(\boldsymbol{x}_2, \boldsymbol{u}_2) \le \mathbf{0}\\
&\dots\\
&\min \boldsymbol{f}_n(\boldsymbol{x}_n, \boldsymbol{u}_n)\\
&\text{s.t. } \boldsymbol{h}_n(\boldsymbol{x}_n, \boldsymbol{u}_n) = \mathbf{0}\\
&\quad\ \boldsymbol{g}_n(\boldsymbol{x}_n, \boldsymbol{u}_n) \le \mathbf{0}
\end{aligned} \tag{3}$$

TABLE 2. Contributions to solution methods.

Reference	Contribution
[17]	Proposed a modified power flow algorithm.
[54]	Utilized a discrete PEM to solve a stochastic reactive power dispatch model.
[55]	Used the ε-constraint method to create the Pareto set, and then used the fuzzy satisfying approach to select the best compromise solution.
[59]	Constructed an offline Reference Voltage Lookup Table for voltage set point selection, and proposed a reactive power dispatch method for WTGs, wind farms and wind farm clusters.
[60]	Proposed a method to set the reactive power outputs of wind farms and on-load tap changers by data mining.

The relationships between current research in hierarchical VVC and the challenges (A)-(E) investigated in Section II are explained as follows:

Similar to centralized VVC, hierarchical VVC adjusts control inputs periodically and considers prediction and probability distribution of wind power in the optimal model for VVC [61], [62], [24], to mitigate the influences of the uncertainty of wind power (A). In addition, [61] uses hierarchical VVC to coordinate the regulation of discrete devices and continuous devices. Specifically, they regulate discrete devices using a long control period to avoid excessive regulation of discrete devices (C), and regulate continuous devices using a short control period to cope with the variation of wind power (A). A similar approach is applied in [62]. To avoid voltage instability, [61] takes voltage stability margin as an objective function in the second layer (D). Current research in hierarchical VVC has not considered the coordination of VVC among interconnected power grids (B) and reactive power market (E).

The differences between hierarchical VVC and centralized VVC are shown in Table III. Compared with centralized VVC, hierarchical VVC can set different control periods for discrete devices and continuous devices and thus is flexible to coordinate different device characteristics. As shown in Fig. 9(a), a long control period helps to reduce the regulation of discrete devices in centralized VVC; however, the heavy variation of wind power brings large influence to the performance of centralized VVC. In contrast, as shown in Fig. 9(b), a short control period can mitigate the influence of the change of wind power by regulating the VVC devices in a short time; however, it will cause excessive regulation of discrete devices. To solve such contradiction, hierarchical VVC regulates discrete devices using a long control period to avoid excessive regulation of discrete devices, and regulates continuous devices using a short control period to cope with the variation of wind power, as shown in Fig. 9(c). In addition, hierarchical VVC can use controllers at different layers to execute control tasks of the transmission system and wind farms, and thus coordinate different objectives between the transmission system and wind farms. In the situation that a wind farm has privacy of information and autonomy in operating its control devices, hierarchical VVC is also applicable.

TABLE 3. Differences between hierarchical VVC and centralized VVC.

Category	Number of Controllers	Control period	Control variables
Centralized VVC	Single controller	Single control period	A controller decides all control inputs
Hierarchical VVC	Multiple and hierarchical controllers	Control periods differ from layer to layer	Each Controller decides partial control inputs

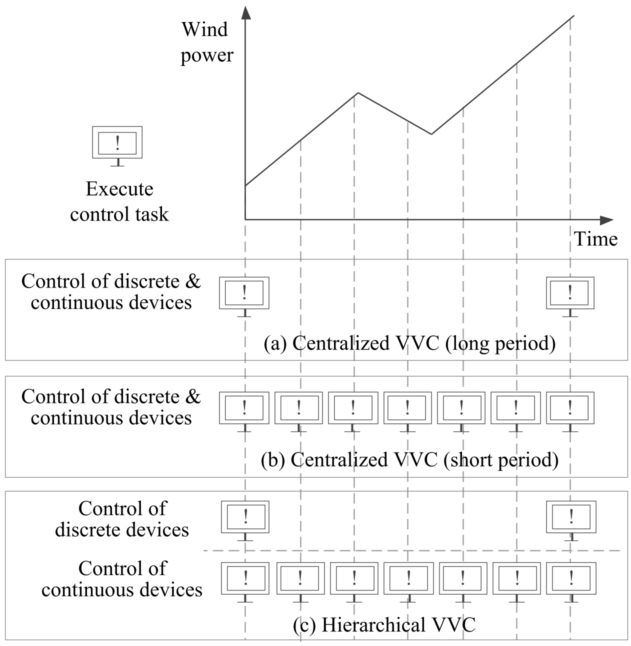

FIGURE 9. Comparison of centralized VVC and hierarchical VVC regarding the control of discrete and continuous devices.

By using hierarchical VVC, the control of the wind farm can be achieved by a controller at wind farm side, and other controllers need not to obtain detailed information of the wind farm and control VVC devices equipped in the wind farm.

One of the goals of hierarchical VVC is to coordinate discrete devices and continuous devices for VVC. To achieve such coordination, Liu and Wang [61] proposed a two-tier control strategy. In the first tier, they determined the control strategy of the discrete devices by considering the switching time of the discrete devices. Several sequential forecasting wind power scenarios were used in this tier. In the second tier, they provided the control strategy of the continuous devices for each scenario considering a static voltage stability margin. Similarly, Cui *et al.* [62] proposed a two-stage stochastic ORPD model. In the first stage, the decisions of the reactive power compensators were made for the objective to minimize the operation cost of the compensators and the expected energy loss. In the second stage, the decision of the generator terminal voltages and the tap ratios were made for minimal active power loss.

Another goal of hierarchical VVC is to coordinate different objectives between the transmission system and wind farms. To achieve such coordination, Guo *et al.* [24] presented a two-layer hierarchical automatic voltage control method. At the upper layer, a system-wide voltage controller was used to decide an optimal distribution of reactive power and voltage among the transmission system. A security-constrained optimal power flow (SCOPF) based preventive control method was proposed for N$-$1 scenarios to mitigate the cascading trip risk. At the lower layer, a wind-farm voltage controller was used with three control modes: 1) to maintain the terminal voltages of the WTGs within limits, 2) to regulate the wind farm's voltage at the high voltage bus to trace the set point given by the controller at the upper layer, and 3) to substitute the dynamic reactive power reserve with slower reactive power sources. The second mode was used to fulfill the requirements received from the upper layer, and the third mode was performed under the constraint of such requirements.

Hierarchical VVC has all the advantages of centralized VVC. Besides, hierarchical VVC is flexible to coordinate different regulation characteristics between discrete devices and continuous devices, and is flexible to coordinate different objectives between the transmission system and wind farms. However, the design and the implementation of hierarchical VVC are more complicated than those of centralized VVC. Hierarchical VVC also requires high capacity of computation and communication. In practice, hierarchical VVC is used for system-wide optimal reactive power dispatch considering coordination of different regulation characteristics between discrete devices and continuous devices or coordination of different objectives between the transmission system and wind farms, when the computation and communication capacity in the power system is sufficiently high.

D. SUMMARY OF CURRENT RESEARCH

1) COMPARISON OF DECENTRAILIZED, CENTRALIZED AND HIERARCHICAL VVC

Table IV provides the case parameters of current research in terms of the control period, wind farm capacity, and tested power grid. Table V provides the VVC models currently being used in the research in terms of the mathematical model, objective, and solution method.

Based on Tables IV and V, the challenges of each category of VVC methods are described as follows:

- Decentralized VVC focuses on the local power factor or reactive power, local voltage, and remote voltage with regard to objective. It pays no attention to system-wide objectives, such as active power loss of the power system, and operation cost of the power system. The system-wide problems brought by LSWFs to VVC remain unsolved in decentralized VVC. A challenge

TABLE 4. Case Parameters of current research.

Reference	Control period	WF Capacity (MW)	Tested power grid
Decentralized VVC			
[33]		500	2-terminal system
[34]		403.2	161 kV Taichung city power grid
[32]		300	20/33/135/400 kV 13-bus system
[35]		1260	IEEE 39-bus system
[36]		≈ 1000	490 kV 2-terminal system
[37]		≈ 910	400 kV 2-terminal system
[38]		300	± 150 kV 2-terminal system
[39]		1000	500 kV 4-terminal system
[40]		--	230 kV network around eastern Wyoming
[41]		100	--
[42]		1800	± 320 kV 4-terminal system
[43]		600	300 kV 4-terminal system
[44]	0.1 sec	100	154 kV 4-bus radial system
Centralized VVC			
[46]	--	400	150 kV 4-bus radial system
[47]	--	400	150 kV 4-bus radial system
[48]	--	327.6	220/400 kV 79-bus Indian system
[17]	--	2000	400 kV 5-bus radial system
[49]	--	200, 400	± 80 kV 4-terminal system and 7-terminal system
[50]	--	1000	± 400 kV 6-terminal system
[51]	15 min	400	33/150 kV 6-bus radial system
[52]	1 hour	≈ 100	IEEE 14-bus system
[53]	15 min	1780.5	110 kV Radial system
[54]	--	621	Modified IEEE 14-bus system
[55]	--	250	IEEE 57-bus system
[56]	--	113, 800	IEEE 30-bus system and modified IEEE 118-bus system
[57]	--	115.5	IEEE 14-bus system
[58]	10 min	300	130/220/400 kV Cigre-32 system
[59]	5-30 min	800	Hybrid system with a 33/155 kV 23 bus AC network, a ±320 kV 2-terminal DC network and a 220/400 kV AC network
[60]	--	514, 250	132 kV 21-bus and 9-bus networks within the Spanish power system
Hierarchical VVC			
[61]	1 hour at upper layer, 15 min at lower layer	246	110 kV 14-bus radial system
[62]	1 hour at upper layer, 15 min at lower layer	260	IEEE 118-bus system
[24]	--	2379	220 kV Zhangbei Wind Power Base

of decentralized VVC is how to achieve system-wide optimization with partial or local information of power system states.

- Centralized VVC has to solve optimization problems, which are usually modeled as NLP or MINLP. It requires high computation capacity to solve those optimization problems within a rational time. A challenge of centralized VVC is how to improve calculation efficiency for optimal reactive power dispatch in large-scale power systems with uncertain wind power.
- Hierarchical VVC also faces the challenges of solving NLP and MINLP. Besides, hierarchical VVC needs to coordinate multiple controllers at different layers. The control periods and control objectives differ from layer to layer. A unique challenge of hierarchical VVC is how to design the coordination of controllers at different layers, such as to select control periods and to define interactions of controllers at different layers.

Table VI provides a comparison of decentralized VVC, centralized VVC, and hierarchical VVC in terms of advantage, disadvantage, application, and challenge.

2) DRAWBACKS OF CURRENT RESEARCH

Although current research has proposed various VVC methods for power grids with connections of LSWFs, there are several drawbacks, which can be concluded as follows:

- In terms of time, the control periods of centralized VVC and hierarchical VVC are either not heavily detailed or not mentioned at all. However, the control period is a critical parameter that affects the computation cost, communication cost, operation cost and performance of the VVC as the random wind power changes the power flow and voltage frequently. However, it is not a key issue for decentralized VVC.
- In terms of spatiality, the power grids discussed are relatively simple; few publications have studied VVC in a large grid with several interconnected hierarchical/regional power grids. As a matter of fact, the reactive power and voltage in the interconnected hierarchical/regional power grids are influenced by the LSWFs. Moreover, centralized optimization algorithms are not suitable for large power grids, because the computation

TABLE 5. VVC models of current research.

Reference	mathematical model [a]	objective [b]	Solution method
Decentralized VVC			
[33]		RPG, VM	Constant RPG, Constant V
[34]		PF	Constant PF
[32]		PF	Constant PF
[35]		PF, VM	Constant PF, Constant V
[36]		VM	Constant V
[37]		VM	Constant V
[38]		VM	Constant V
[39]		VM	Constant V, I-V
[40]		VM	Q-V
[41]		VM	Q-V
[42]		VM	I-V
[43]		VM	I-V
[44]		VM	Q-V
Centralized VVC			
[46]	MINLP	APL	Adaptive PSO
[47]	MINLP	APL	Adaptive PSO
[48]	LP	SVS	Trust region method
[17]	NLP	APTC, APL	Modified power flow
[49]	NLP	APL	IPM
[50]	NLP	APL	IPM
[51]	MINLP	OC, APL	PSO
[52]	MINLP	ELC, OC (SVS constrained)	Benders decomposition,
[53]	NLP	VM, DRPR, OC (SVS constrained)	IPM
[54]	Fuzzy LP	APL	PEM
[55]	MINLP	APL, SVS	ε-constraint method, Fuzzy satisfying approach, SNOPT and SBB solvers
[56]	MINLP	APL, O&MC (SVS constrained)	ε-constraint method, Fuzzy satisfying approach, SNOPT and SBB solvers
[57]	NLP	SP, SVS	--
[58]	NLP	SP	--
[59]	NLP	APL, VM	IPM, Participations factors
[60]	--	APL	Data mining
Hierarchical VVC			
[61]	MINLP	VM and OC at upper layer, VM and SVS at lower layer	Non-dominated Sorting Genetic Algorithm II (NSGA-II)
[62]	MINLP	OC and APL at upper layer, APL at lower layer	Hybrid GA-IPM, PEM
[24]	NLP	APL and APG at upper layer, VM and DRPR at lower layer	Benders decomposition

[a]LP = linear programming, NLP = nonlinear programming, MINLP = mixed-integer nonlinear programming.
[b]PF = power factor, RPG = reactive power generation, VM = voltage magnitude, APL = active power loss, APTC = active power transmission capacity OC = operation cost, DRPR = dynamic reactive power reserve, SVS = static voltage stability, ELC = energy loss cost, O&MC = operation & maintenance cost, SP = system payment, APG = active power generation.

time grows exponentially as the size of the power grid increases [63].

- In terms of objective, the objectives considered in most studies are active power loss and voltage magnitude. The voltage stability problem has not been thoroughly studied. Another drawback is that payment for reactive power ancillary services have not been considered in most studies, which is not suitable in deregulated electricity markets involving various market participants.

IV. FUTURE RESEARCH

Considering the overview of the current research on VVC methods for power grids with connections of LSWFs, several possible directions for future research are listed as follows.

A. EVENT-TRIGGERED VVC METHODS FOR POWER GRIDS WITH CONNECTIONS OF LSWFS

Aside from the local regulation of reactive power and voltage, the VVC methods used in practice are mostly triggered by time. For the time-triggered VVC methods, the superior controllers periodically generate and send commands to the inferior controllers. The time-triggered VVC methods may not be capable of responding to the change of power flow and voltage, as the wind power output may change greatly within a control period. A short control period helps to improve the performance of VVC in dealing with rapid changes in power flow and voltage; however, it would also increase the computation burden, communication burden, and require further regulation of discrete devices. Moreover, the strategy involved in using time-triggered VVC methods usually remains the same even while facing different situations and

TABLE 6. Comparison of decentralized VVC, centralized VVC and hierarchical VVC.

Category	Advantage	Disadvantage	Application	Challenge
Decentralized VVC	• Simple and easy to implement • Does not require complicated computation and system-wide communication	• Cannot consider the challenges presented by LSWFs from a system-wide perspective • Hard to achieve an optimal control due to lack of full observation of system states and lack of information exchange between local controllers	Simple VVC when computation and communication capability in the power system is low	How to achieve system-wide optimization with partial or local information of power system states
Centralized VVC	• Can achieve a system-wide optimization • Can cope with various challenges presented by LSWFs to VVC from a system-wide perspective	• Requires high capacity of computation and communication • Inflexible to coordinate different device characteristics • Inflexible to coordinate different objectives between the transmission system and wind farms	System-wide optimal reactive power dispatch, when the computation and communication capacity in the power system is sufficiently high and the central controller can obtain whole information of system states and control all available VVC devices	How to improve calculation efficiency for optimal reactive power dispatch in large-scale power systems with uncertain wind power
Hierarchical VVC	• Has all advantages of centralized VVC • Flexible to coordinate different device characteristics • Flexible to coordinate different objectives between the transmission system and wind farms	• Requires high capacity of computation and communication • Complicated to design and implement	System-wide optimal reactive power dispatch considering coordination of different regulation characteristics between discrete devices and continuous device or coordination of different objectives between the transmission system and wind farms, when the computation and communication capacity in the power system is sufficiently high	• How to improve calculation efficiency for optimal reactive power dispatch in large-scale power systems with uncertain wind power • How to design the coordination of controllers at different layers

the method is not easily adapted to different objectives in the context of LSWFs connection.

The event-triggered methods provide a flexible mechanism for the VVC in power grids integrating intermittent and fluctuant wind power. The event-triggered methods are triggered by predefined events rather than time. Under the event-triggered methods, control tasks are executed only when necessary [64]. Besides, the responses of the event-triggered methods can be flexible according to the event detected. Fig. 10 shows the differences between time-triggered methods and event-triggered methods, where t is a constant control period of time-triggered methods. The event-triggered methods have been utilized in dissipative control [64], state estimation [65], [66], fault detection [67], stabilizing control [68], etc. These literatures have demonstrated the event-triggered methods are effective and more efficient in utilizing control task execution capabilities than the time-triggered methods. The primary problem to apply event-triggered methods to VVC is to define the VVC events. Event-triggered methods were adopted in the hybrid automatic voltage control [69]–[71], where the events consisted of voltage quality events, voltage stability events, and economic operation events. However, the voltage stability events and economic events were defined with the aid of optimization algorithms. Thus, the computation and communication problems that are present in the time-triggered VVC methods mentioned before are also obstacles to the hybrid automatic voltage control. Zhang *et al.* [72] and Li *et al.* [73] provided the analytic expression of optimal reactive power dispatch in a transmission line. Chen *et al.* [74] proposed a slack optimal control method to optimally set the tolerance band of gateway reactive power based on the analysis of network characteristics for a radial distribution network. These studies give direction for

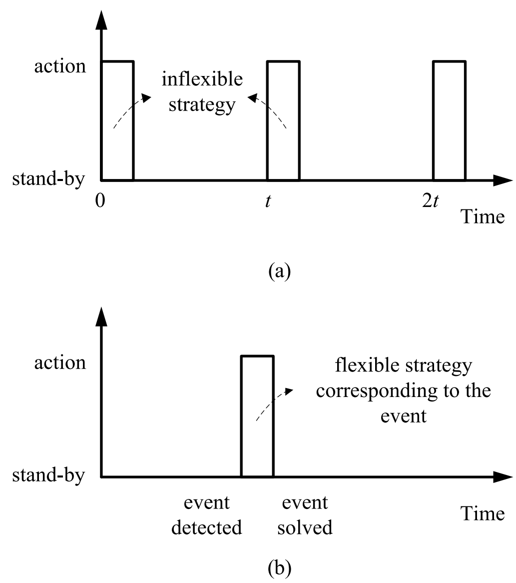

FIGURE 10. Illustration of time-triggered method and event-triggered method. (a) Time-triggered method. (b) Event-triggered method.

defining VVC events without using optimization algorithms. However, more research should be conducted for cases where the power grids are larger and more complicated than a simple transmission line and a radial network.

The event-triggered method is recommended for the VVC in power grids with connections of LSWFs. First, a rational category of VVC events should be discussed in the context of the connection of LSWFs. The category should cover most control tasks of VVC. Second, an effective and computationally efficient method for detecting VVC events has to be proposed. Specifically, indices and their thresholds should be constructed to determine whether the control task should be executed. The detection of VVC events is required to be rapid to cope with the challenge presented by the great uncertainty of wind power. Third, strategies for different VVC events should be presented.

The key points for future research of event-triggered VVC methods for power grids with connection of LSWFs are summarized as follows: 1) the categorization of VVC events considering different objectives (such as active power loss, voltage stability and operation cost) and different objects (such as AC/DC transmission systems and wind farms) under the influences of LSWFs, 2) methods for rapidly defining and detecting the VVC events without complicated computation, and 3) different strategies corresponding to different VVC events.

B. APPLICATION OF BIG DATA TECHNIQUES TO VVCS FOR INTERCONNECTED POWER GRIDS

Optimization algorithms have difficulties in the application to VVC for large power grids [75]. The performance of the algorithms is greatly influenced by the dimensions and the initial set points of the optimization model for VVC, and the set parameters of the algorithms. The dimensions can be reduced by performing optimization algorithms for VVC for each hierarchical/regional power grid separately rather than for a whole interconnected power grid. However, the related research commonly ignores the regulation of reactive power and voltage in external power grid (i.e., other connected hierarchical/regional power grids), which is not conducive to the coordination of VVCs for interconnected power grids. In the case that conflicts of VVCs among interconnected power grids are intensified by LSWFs, a VVC oscillation may happen.

Big data techniques have a great potential to improve the performance of the optimization of VVCs for interconnected power grids. ''Big Data are high-volume, high-velocity, and/or high-variety information assets that require new forms of processing to enable enhanced decision making, insight discovery and process optimization [76].'' Big data are emerging and have been studied in a large number of fields [77]. Since power systems have been in operation, massive amounts of data have been collected and stored. The data of power systems have all the features of big data [78]. There are many techniques for analyzing big data, such as association rule learning and cluster analysis [79]. Some research has been conducted for preliminary discussions on the use of big data techniques in power systems, such as demand side energy management [80] and load forecasting [81], [82]. However, few publications have discussed application of big data techniques to VVC.

Future researchers can apply big data techniques to the optimization of VVC. Big data techniques can be used in two ways when combined with the optimization of VVC: by improving the performance of optimization algorithms [83], and by modeling the reactive power and voltage regulation behaviors of external power grids. Big data techniques provide measures to analyze the information produced by VVC. Data mining technique can be used to analyze the history information of VVC to produce initial solutions which are near the optimal solution. Data clustering techniques can be utilized to identify clusters of individuals, and thus eliminate redundant individuals, in order to reduce computational burden of optimization algorithms [84]. Each individual presents a potential solution in the processes of population-based algorithms [83]. Another application of data clustering techniques is to adjust parameters of the algorithms, such as the crossover and mutation probabilities of GA, in order to improve convergence rate and prevent premature convergence [85]. The history information of individuals, which are produced in the processes of the algorithms, can be helpful to detect whether an area contains a local optimum [86]. It is recommended to conduct further research on the fusion of big data techniques and optimization algorithms. Besides, data mining method offers a method to model the behavior of VVC of external power grids, when the optimization of VVC is performed for a hierarchical/regional power grid separately. Such modeling can predict the VVC behaviors, i.e., the regulation of VVC devices, of the external power grids, and thus provides more accurate account of the interaction between the target power grid and the external power grids. Therefore, it is helpful to the coordination of VVCs for interconnected power grids.

The key points for future research on the application of big data techniques to VVCs for interconnected power grids are summarized as follows: 1) combination of big data techniques and optimization algorithms, such as using big data techniques to set initial points close to the optimal solution and adjust parameters to get better performance, and 2) modeling the reactive power and voltage regulation behaviors of external power grids using big data techniques, when optimization algorithms are performed in VVC for a hierarchical/regional power grid separately, to improve VVC coordination and avoid VVC oscillations.

C. DESIGN OF REACTIVE POWER MARKET CONSIDERING PARTICIPATION OF LSWFS

Neglecting to consider the issue of payment for reactive power ancillary services harms the benefit provided by reactive power providers, which will lead to a passive response to the needs of VVC. Regarding the connection of LSWFs, it is necessary to study the economic and technical issues of VVC resulting from the participation of LSWFs in reactive power market. However, most of the VVC methods reviewed in Section III did not consider these issues.

A well designed reactive power market is needed to address the economic and technical issues presented by LSWFs to VVC. Currently, a general thought is that the transmission system operators (TSOs) should pay for reactive power compensation to the generation plants which provide reactive power ancillary services [57], [87]–[90]. However, as mentioned in Section II, the reactive power and voltage of transmission systems are influenced by LSWFs. The needs of VVC result from not only load demand but also LSWFs. In other words, LSWFs increase the demand of flexible reactive power regulation. Owners of LSWFs are also responsible for payment for reactive power ancillary services. The duties of LSWFs' owners and TSOs to VVC should be clearly discussed and introduced into the cost allocation for reactive power ancillary services. Besides, considering that LSWFs can also provide reactive power ancillary service, a rational expected payment function (EPF) should be presented for the reactive power provided by LSWFs. The EPF for reactive power is the relationship between the reactive power provider's expectation of payment and the provided reactive power [91]–[93]. The EPF for reactive power is one of the most important knowledge in reactive power market; however, few literatures have discussed the EPF for reactive power provided by LSWFs. For reactive power market clearing, the uncertainty of wind power should be considered to schedule the reactive power regulation and reserve.

As a future research direction, it is suggested to design a proper reactive power market considering the participation of LSWFs. It is necessary to determine the duties of LSWFs' owners and TSOs to VVC. For this purpose, a quantitative assessment is required to evaluate the influences of LSWFs and transmission systems on the demand of VVC. Furthermore, a compelling method to assign cost of VVC to LSWFs' owners and TSOs should be presented. Considering the capacity of LSWFs to provide reactive power, a rational EPF for such reactive power is required. In addition, it is required to design a framework of reactive power market clearing to cope with the challenges resulting from the uncertainty of wind power, in the aspects of mathematical models and time intervals.

The key points for future research in the design of the reactive power market, considering participation of LSWFs, are summarized as follows: 1) assessment of the duties on VVC of market participants including owners of LSWFs and TSOs, 2) methods to assign the cost of reactive power ancillary services to the market participants, 3) EPF for the reactive power provided by LSWFs, and 4) frameworks for the reactive power market clearing considering the uncertainty of wind power.

D. OTHER RELATED TECHNOLOGIES

Energy storage systems (ESSs) are one of the best solutions to mitigate the inherent intermittence and fluctuation of wind power, thus mitigating the corresponding variation of power flow and voltage in power grids. In addition, ESS is usually an excellent VVC resource. There is a wide application of ESSs in power grids with wind farm connections, such as active power dispatching [94]–[96] and voltage support [97]. Although ESS has numbers of attractive benefits, several problems such as capacity, capital investment, life span and practical difficulties hamper the viable construction of large-scale ESS [98]. A comprehensive assessment of the merits of ESS is needed to support decision-making for the allocation of ESS in the context of VVC with LSWF connections. In operation, VVC schemes to exploit the abilities of ESS in active/reactive power regulation while maintaining the life span need deeper studies, where a proper modeling of large-scale ESS is required.

VSC based HVDC is another technology that can improve the reactive power and voltage characteristics in the transmission of power from LSWFs. VSC based HVDC has the advantage of flexible active/reactive power decoupling control. Currently, the Xiamen Flexible HVDC Project in China is of the largest capacity HVDC projects in the world. [99]. VSC based HVDC is a good choice for delivering large amounts of wind power considering its ability to enact VVC. As mentioned in Section III, the studies about the VVC of VSC based HVDC focused on local voltage control [38], [39], [42], [43] and control in the DC grids [49], [50] regarding the connections of LSWFs. The potential of VSC based HVDC to support reactive power compensation and voltage regulation for AC power grids should be further studied and tested in AC/DC hybrid power grids with connections of LSWFs.

V. CONCLUSION

VVC is challenged by the connection of LSWFs to the grids. In this paper, the influences of LSWFs on VVC are investigated, and VVC methods for power grids with connections of LSWFs are reviewed. Many VVC methods for power grids with connections of LSWFs have been studied with different approaches, which are placed into categories of decentralized VVC, centralized VVC and hierarchical VVC in this paper. However, there are drawbacks, which are listed as follows:

1) The control periods of VVC have never been clearly discussed. Nonetheless, it is a critical issue affecting the computation cost, communication cost, operation cost and performance of VVC as the uncertainty of wind power changes the power flow and voltage frequently.
2) Few publications have studied VVC in a large grid with several interconnected hierarchical/regional power grids, where the reactive power and voltage in the interconnected regional power grids are influenced by LSWFs.
3) Static voltage stability has not been thoroughly studied, and payment for reactive power ancillary services has not been considered in most studies.

Regarding the drawbacks, guidelines for future research are provided as follows: 1) event-triggered VVC methods for power grids with connections of LSWFs, 2) application of big data techniques to VVCs for interconnected power grids, 3) design of reactive power market considering the participation of LSWFs, and 4) studies and field tests of large-scale ESSs and large-scale VSC based HVDC on VVC for power grids with connections of LSWFs.

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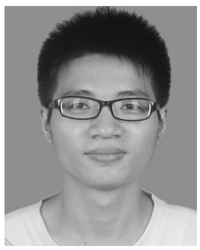

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