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Coordination Strategy of Large-Scale DFIG-based Wind Farm for Voltage Support with High Converter Capacity Utilization

Zhen Dong, Zhongguo Li, Lingyu Du, Yixing Liu, Zhengtao Ding, *Senior Member, IEEE*

Abstract—Due to the long-distance transmission, external grid cannot effectively support the access point voltage (APV) of the large-scale wind farm (WF), which thus entails DFIG-based WF to provide its ancillary services on reactive power generation. Considering factors of limited down-sized converter capacity, various operating modes of wind turbines (WTs), and the large pressure of large-scale WF communication on the central governor, this paper proposes a distributed active power and reactive power coordination scheme for APV support. A reactive power self-allocation scheme is developed and operated in each WT for reactive power dispatch. Based on the mechanism of distributed consensus control and aligning with the principle of preferential and proportional utilization of spare reactive power capacity (RPC), the proposed method collaborates the rotor side converters and the grid side converters of all WTs but without the necessity of knowing the total RPC. Further, in case that the total RPC is insufficient for the demand, a coordinating factor for RPC extension is generated to weaken the active power. Through a current-enforced PQ coordinating loop, it guarantees a high utilization of converter capacity as well as an exact compensation on the reactive power imbalance, which thereby reduces the wind power curtailment for the RPC release. Several case studies verify the effectiveness of the proposed method.

Index Terms—Access point voltage support, active power and reactive power coordination, converter capacity extension, DFIG wind turbine, large-scale wind farm control.

ABBREVIATIONS

APV	Access Point Voltage
CRS	Constant Rotor Speed
DFIG	Doubly Fed Induction Generator
GSC	Grid Side Converter
MPPT	Maximum Power Point Tracking
PAC	Pitch Angle Control
ROC	Rotor Over-Speeding Control
RP&AP	Reactive Power and Active Power
RPC	Reactive Power Capacity
RPD	Reactive Power Demand
RPSA	Reactive Power Self-Allocation
RSC	Rotor Side Converter
WF	Wind Farm
WT	Wind Turbine

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I. INTRODUCTION

WITH higher penetration of wind energy in power systems, most wind plants nowadays are required to be configured with voltage or reactive power control [1]. Particularly, for large-scale WF locating at remote areas, external grid is not able to provide a satisfactory APV support due to the long-distance transmission [2, 3]. Meanwhile, considering the additional construction and maintenance costs needed to install reactive power compensation equipment and the requirements of timely dynamic responses, it is preferable for converter-based WFs to provide ancillary services on reactive power generation with their idle converter capacities [4, 5].

The DFIG-based WT, which is equipped with down-size-designed RSC and GSC, has been widely applied in wind power generation system due to the favorable performance and economic prospects. Meanwhile, the limited converter capacity of DFIG-based WF entails a dedicated capacity distribution on active power and reactive power for wind power generation as well as APV support. Basically, the active power generated by WTs under a specific wind speed and a specific operating mode occupies a certain amount of converter capacity. Then, the RPC is the sum of the remaining RSC and GSC capacities [6]. If APV support is taken as a priority, when the RPD is larger than the current RPC, part of wind power generation need to be abandoned, and the operating point is driven to move along the converter capacity curve in the direction of decreasing active power until the RPD is met. In this realm, a so-called coordinated active and reactive power control is needed [7, 8] and two points are of particular importance: *i*) an accurate curve for description on the maximum converter capacity; *ii*) a proper distribution and control scheme on power trajectory migrating alongside the capacity curve for a high converter utilization.

A converter capacity is physically constrained by the permitted rotor and stator current [9]. *PQ* curve is an widely applied approach for describing the converter capacity, which can be derived from the steady-state phasor model with current constraints enforced. It can serve as the distribution principle, directly determining the active and reactive power setting points, or using the reactive power capacity obtained as the power controller limit [8, 10]. However, when current constraints are transformed from the current frame to the power frame, inaccuracy possibly occurs due to different levels of model simplifications [11]. As a result, the derived *PQ* curve cannot match the corresponding current constraints

well, which means the actual converter capacity may be underestimated (resulting in a lower utilization) or overestimated (resulting in a compromised tracking performance due to the saturation [12]). As an alternative way, putting both modeling and control under the dq frame, excitation current for reactive power can be strictly limited by directly using current constraints (thus realizing a theoretically full converter capacity), whilst the difficulty is that how to bridge the current frame operation with the designed reactive power allocation [13].

From the whole WF point of view, the large amount of dispersed WT's collaborate with each other for RPD support. Accounting for the various wind velocities brought by the different geographical environments, WT's operating in different operating modes take up different converter capacities. In this case, treating all WT's uniformly and using an aggregated model for whole WF description are no longer appropriate [14, 15]. Accordingly, the conventional uniform reactive power allocation scheme entails that WT's with relatively low RPC encroach too hastily their own active power capacities before the entire RPC of the wind farm is used up, resulting in unnecessary loss of the total active power production. Whereas a desirable dispatch principle is that the entire WF prioritizely uses the existing RPC of both RSC and GSC, allocating reactive power tasks according to the required RPD and RPC of each WT. If it is still insufficient, WT's simultaneously and dynamically reduce active power output to further release RPC.

The large-scale WF with numerous WT's presents a spatially wide-area-distribution characteristics. Centralized structure requires to have large long-distance interactions with the remotely penetrative WT's, which thus brings much more severe communication pressure and the extreme reliance on the central controller [16]. In the other words, centralized control becomes overwhelmed since WT's have been widely dispersed in physical layer while the communication in information layer is still centralized. In contrast, the distributed control has its advancements for such large-scale multi-agent situations, which achieves the consistency between the information layer and the physical layer [17]. In this case, there is only limited-distance communication with adjacent neighbors for cooperation, rather than large amounts of communication with the remote controller, thus avoiding the above problems of centralized framework. Under the distributed framework, [18] proposes a coordination control for WT's participating in system primary control. [14] extracts the kinetic energy for active power regulation. [19] takes both WT's and STATCOMs into consideration for WF voltage control. [20] investigates the voltage control of WF under different frameworks and illustrates the superiority of distributed control over the centralized methods w.r.t. robustness to communication delay, voltage disturbance rejection, etc.

However, the absence of global information due to distributed architecture limits the functional implementation of existing distributed methods, e.g., [14, 18–20] separately consider the active power sharing or reactive power sharing but without taking the coordination problem into consideration. In particular, to date, few papers have mentioned how to

implement an autonomous cooperation of all the WT's' available converter capacities for power allocation under the full-range load. As for the proposed method, apart from retaining merits of distributed framework, the state-of-the-art is that, through a self-determined control of each WT, the systematical cooperative control among WT's and between the RSC and GSC therein is realized simultaneously to meet different levels of RPD. Furthermore, coordination between active and reactive power sharing is achieved with high converter utilization for an effective APV support even under the extremely-heavy load. The contribution can be specified into the following twofolds:

- 1) A novel RP & AP coordination strategy is proposed to ensure that each WT is capable of undertaking the assigned RPD beyond its existing RPC. It removes the power loop limit, and updates RPC through the current constraint. Further, employing the difference between reactive power reference and the updated RPC, a cooperating factor is constructed, aiming at dynamically adjusting and exerting the active power when RPD is larger than the original RPC. Through deloading operation, the reduced active power can exactly provide the extra RPC for RPD compensation. The proposed algorithm does not rely on the accuracy of the PQ curve and guarantees a high utilization of the converter capacity during the whole period of RP & AP coordination.
- 2) Under the premise of an effective RP & AP coordination strategy, further, a reactive power self-allocation (RPSA) scheme is developed covering varying levels of RPD. The proposed allocation scheme is realized distributedly in each local controller of WT's rather than the central controller of the WF. Each WT directly determines the individual reactive power setting points according to the RPC of their own RSC and GSC and parameters exchanged with the neighbors, while eliminating the procedures of data collection, computation and reactive power dispatch of WF's central engine. Through parallel computing, the algorithm ensures a proportional RPD sharing, and further, a simultaneous depletion of reactive power and activation of the RP & AP coordination strategy if RPD further increases, thereby avoiding unnecessary wind curtailment.

The remainder part is arranged as follows. In Section II, a brief introduction on RPC and RPD is given, and thereafter the relationship is analyzed with some principles summarized. Section III presents the proposed method, which includes an overall description on WF architecture, AP & RP coordination strategy for WT control and RPSA. Case studies and comparison results are provided in IV, followed by the conclusion in Section V.

II. ANALYSIS ON RPC AND RPD

A. RPC

The converter capacity of DFIG is determined by RSC and GSC. For RSC, the active and reactive power capacity is constrained by the maximum rotor current I_{r_max} , the maximum stator current I_{s_max} as well as the maximum rotor voltage. Considering that the rotor speed range is always bounded to

Fig. 1. RPC of DFIG under different operating modes.

avoid conflicting against the maximum rotor voltage, a current-enforced RPC is expressed as [11]:

$$Q_{R_min} = - \left\{ U_s^2 I_{s_max}^2 - \frac{(P + R_r \frac{U_s^2}{X_m^2} + (R_r + sR_s) I_{s_max}^2)^2}{(1-s)^2} \right\}^{\frac{1}{2}} \quad (1)$$

$$Q_{R_max} = -U_s^2/X_s + \left\{ \frac{(X_m U_s I_{r_max})^2}{X_s^2} - \frac{P^2}{(1-s)^2} \right\}^{\frac{1}{2}}, \quad (2)$$

where P is the active power; U_s is the stator voltage; R_s and R_r are the stator and the rotor resistance, respectively; X_s and X_m are the stator and the mutual reactance; s is the slip.

Similarly, the RPC of GSC is

$$\{Q_{G_max}, Q_{G_min}\} = \pm \{S_{GSC}^2 - s^2 P^2 / (s-1)^2\}^{\frac{1}{2}}, \quad (3)$$

where S_{GSC} is the capacity of GSC, which is usually designed as one third of the DFIG rated capacity for the active power flow generated from the rotor side.

Combining (1)-(2) with (3), the RPC of DFIG under different operating modes can be presented as Fig. 1 shows. The relationship between P and s is established as follows [21]: MPPT mode when $P < 0.75$ p.u. (thus s and P is one-to-one correspondence following MPPT curve); CRS mode at $s = s_{min} = -0.2$ when $P \in [0.75, 1]$ p.u.; PAC mode for suppressing a constant active power at $P = 1.0$ p.u.

B. RPD

Large-scale WF transmits active power to the grid through high-voltage transmission over long distances, which makes APV unable to be compensated through the external grid, so self-compensation from the WF side is encouraged. The RPD to maintain the APV within a proper level can be calculated by [22]:

$$Q_D = - \{ U_{APV}^2 U_G^2 / X_L^2 - P_w^2 \}^{\frac{1}{2}} + U_{APV}^2 / X_L, \quad (4)$$

where U_{APV} and U_G are the voltage of access point and external grid, respectively. X_L is the reactance of the transmission line, and P_w is the generated wind power of the WF.

RPC of WF and RPD can be depicted in the same figure to illustrate the relationship when using RPC for APV support. As shown in Fig. 2, Q_{D1} - Q_{D3} describe different

Fig. 2. The relationship between RPC and RPD.

Fig. 3. PQ curve for ROC-prioritized operation under a given wind velocity.

RPD corresponding to different values of APV, of which $U_{APV1} < U_{APV2} < U_{APV3}$. Due to the different operating modes under various wind velocities, the situation can be divided into several cases.

1) *RPD within RPC of RSC (Case (i))*: As Q_{D1} shows, it is within the RPC of RSC even when $P = 1.0$ p.u. under high wind velocity, indicating that the existing RPD is sufficient enough for the decoupled power control with no interacted actions required.

2) *RPD within the sum RPC of RSC and GSC (Case (ii))*: If Q_D increases from Q_{D1} to Q_{D2} , RPC of RSC cannot meet the RPD at high wind velocity due to the occupation of the generated active power. Compared with reducing the active power via deloading operation, the participation of GSC is preferred, since Q_{D2} is still within the sum RPC of RSC and GSC.

3) *RPD outside the sum RPC of RSC and GSC (Case (iii))*: When Q_D is up to Q_{D3} , RPD with high active power generation is outside the RPC and requires an active participation of active power control. Accounting for the operating mode, for $P > 0.75$ p.u., since the rotor speed has reached its upper limit, employing PAC is the only choice, and then the operating point will migrate alongside PQ curve corresponding to $s = -0.2$ until reaching the intersection. Whilst for $P < 0.75$ p.u., the choice is more flexible since both ROC and PAC can be applied for deloading operation. ROC harvests less wind power with higher rotor speed away from MPPT point, while higher rotor speed can relax the original RPC. As the enlarged part of Fig. 2 shows, assuming that the current operating point is A and point B represents the operating point at the maximum ROC-based deloading

Fig. 5. Control diagram of AP & RP Coordination scheme.

Fig. 6. Illustration on operating point trajectories under different control constraints. (a) Power trajectories. (b) Rotor current trajectories.

a stable DC-Link voltage while q axis is for reactive power regulation. Besides, pitch angle actuator (PAA) is employed for the balance of the decreased electrical active power and mechanical power. Here, $u_{gd_com} = u_{sd} + \omega_s L i_{gq}$ and $u_{gq_com} = u_{sq} - \omega_s L i_{gd}$ are for the purpose of decoupling. The stator-field-oriented control is adopted for RSC control, and $u_{rd_com} = -\omega_r \sigma L_r i_{rq}$, $u_{rq_com} = \omega_r \sigma L_r i_{rd} + \omega_r L_m |\psi_s| / L_s$ [23]. The limit in reactive power loop is transferred to the current loop and determined by i_{rq} through (7). Then $Q_{R_cap_d}$ is constructed by i_{rd_cap} using (5). P_{R_c} is generated by the error of Q_R and $Q_{R_cap_d}$ through a PI controller, of which the upper and lower limits are set as 0 and $-P_{R_ref}$, respectively. For convenience, the PI controller is called coordinating controller and P_{R_c} is the coordinating factor.

When Q_{R_ref} is less than the initialized reactive power capacity Q_{R_cap} , P_{R_c} will be limited at 0 with no effect on P_{R_ref} . Accordingly, i_{rd_ref} will not reach the dynamic limit and dq -axis control is fully decoupled. For Q_{R_ref} larger than Q_{R_cap} , as shown in the enlarged part of Fig. 6 (a), the PQ curve shown in blue is depicted by (1)-(2), while the red curve where points C and D are located represents the PQ curve that is strictly determined by the current constraint shown in Fig. 6 (b). We take point O as the initial operating point, comparing the operating point migration under different PQ curves when facing the same RPD Q_d . If the blue PQ curve is applied, the power trajectory is O-A-B, while using the red PQ curve is O-A-C-D. From the active power point of view,

the extension of PQ curve reduces ΔP_R of the active power curtailment. However, from system control perspective, since the direct expression of PQ curve in red is unavailable, the scheme realization is transferred to the rotor current frame. As Fig. 6 (b) shows, the control objective is to drive the rotor current trajectory to migrate alongside O-A-C-D.

The mechanism is as follows: when the operating point moves to point C in Fig. 6 (b), Q_R cannot track Q_{R_ref} due to the d -axis current limit. Luckily, it is able to trigger the action of coordinating controller once the transient state of Q_R goes beyond $Q_{R_cap_d}$ and then i_{rq_ref} is weakened. Since q axis always has enough margin for i_{rq} tracking i_{rq_ref} , the decreasing i_{rq} prompts the increase of the dynamic d -axis current limit i_{rd_cap} from point C to point D in Fig. 6 (b), releasing more Q_R through the d -axis power and current loop as well as more $Q_{R_cap_d}$ through the proposed control loop (as the red arrowed loop shows in Fig. 5). This procedure will not end until $Q_{R_cap_d} = Q_R = Q_{R_ref}$, indicating that the converter capacity released by the reduced active power exactly compensates the remaining RPD.

C. RPSA

Depicting the individual states of the i th WT with subscript i , the allocation principle of proposed RPSA for WF with N WTs is as follows:

If the total RPC of RSC is larger than RPD Q_d , only $Q_{R_ref,i}$ is allocated while $Q_{G_ref,i}$ is kept as zero. Each WT determines the reactive power reference of RSC according to the proportional principle or fair load-sharing principle[24], which is expressed as

$$Q_{R_ref,i} = \frac{Q_d Q_{R_cap,i}}{\sum_{i=1}^N Q_{R_cap,i}}, \quad \text{for } Q_d \leq \sum_{i=1}^N Q_{R_cap,i}. \quad (8)$$

Similarly, we get

$$Q_{R_ref,i} = \frac{Q_d Q_{R_cap,i}}{\sum_{i=1}^N (Q_{R_cap,i} + Q_{G_cap,i})},$$

$$Q_{G_ref,i} = \frac{Q_d Q_{G_cap,i}}{\sum_{i=1}^N (Q_{R_cap,i} + Q_{G_cap,i})},$$

for $\sum_{i=1}^N Q_{R_cap,i} < Q_d < \sum_{i=1}^N (Q_{R_cap,i} + Q_{G_cap,i})$; (9)

$$Q_{R_ref,i} = \frac{Q_d (Q_{R_cap,i} + Q_{G_cap,i})}{\sum_{i=1}^N (Q_{R_cap,i} + Q_{G_cap,i})} - Q_{G_cap,i},$$

$$Q_{G_ref,i} = Q_{G_cap,i},$$

for $Q_d \geq \sum_{i=1}^N (Q_{R_cap,i} + Q_{G_cap,i})$. (10)

Since all the sum items in (8)-(10) are unavailable due to the distributed mechanism, the distributed protocol is developed as

$$\begin{aligned}
k_{l,i} &= 1/k_{c,i} \\
\dot{k}_{c,i} &= \alpha \left(\frac{Q_{cap,i}}{Q_d/N} - k_{c,i} \right) - \beta \sum_{j=1}^N a_{ij} (k_{c,i} - k_{c,j}) - z_i \\
\dot{z}_i &= \alpha \beta \sum_{j=1}^N a_{ij} (k_{c,i} - k_{c,j}), \quad (11)
\end{aligned}$$

with initial condition $\sum_{i=1}^N z_i(0) = 0$; a_{ij} is determined by the communication topology, see [25, 26] for more information; $k_{c,i}$ and $z_{c,i}$ are parameters exchanged with neighbors; α and β are the coefficients responsible for the convergence speed, satisfying $\alpha, \beta > 0$.

To prove that the $k_{c,i}$ converges to $\mathbf{1}_N^T Q_{cap}/Q_d$, it is equivalent to show

$$e_i \triangleq k_{c,i} - \mathbf{1}_N^T Q_{cap}/Q_d \quad (12)$$

converges to zero. For the ease of analysis, we introduce a transformation variable δ_i as

$$\delta_i = z_i - \alpha \frac{Q_{cap,i}}{Q_d/N} + \alpha \mathbf{1}_N^T Q_{cap}/Q_d. \quad (13)$$

It then follows that

$$\begin{aligned}
\dot{e}_i &= -\alpha e_i - \beta \sum_{j=1}^N a_{ij} (e_i - e_j) - \delta_i \\
\dot{\delta}_i &= \alpha \beta \sum_{j=1}^N a_{ij} (e_i - e_j). \quad (14)
\end{aligned}$$

Let the augmented state variables of the network be $e = [e_1, \dots, e_N]^T$, $\delta = [\delta_1, \dots, \delta_N]^T$. Thus, the compact form of (14) can be obtained as

$$\begin{aligned}
\dot{e} &= -\alpha e - \beta \mathcal{L} e - \delta \\
\dot{\delta} &= \alpha \beta \mathcal{L} e, \quad (15)
\end{aligned}$$

where $\mathcal{L}$ is the Laplacian matrix associated with the communication graph. Equivalently, we have

$$\begin{bmatrix} \dot{e} \\ \dot{\delta} \end{bmatrix} = \Psi \begin{bmatrix} e \\ \delta \end{bmatrix} \quad (16)$$

where $\Psi = \begin{bmatrix} -\alpha I_N - \beta \mathcal{L} & -I_N \\ \alpha \beta \mathcal{L} & \mathbf{0}_N \end{bmatrix}$. Therefore, the rest of the proof is to demonstrate that Ψ is stable. Now, we introduce the following transformation

$$\begin{bmatrix} p \\ q \end{bmatrix} = \mathcal{T}_1 \mathcal{T}_2 \begin{bmatrix} e \\ \delta \end{bmatrix} \quad (17)$$

where

$$\mathcal{T}_1 = \begin{bmatrix} I_N & \mathbf{0}_N \\ \alpha I_N & I_N \end{bmatrix}, \mathcal{T}_2 = \begin{bmatrix} \mathcal{T}_3^T & \mathbf{0}_N \\ \mathbf{0}_N & \mathcal{T}_3^T \end{bmatrix}, \mathcal{T}_3 = \begin{bmatrix} r \\ R \end{bmatrix}^T \quad (18)$$

with $r = \frac{1}{\sqrt{N}} \mathbf{1}_N$, $r^T R = 0$, $R^T R = I_{N-1}$ and $R R^T = I_N - r r^T$. Let us regroup the variables, p and q , by partitioning them as $p = [p_1, p_{2:N}^T]^T$ and $q = [q_1, q_{2:N}^T]^T$. Then, we have

$$\begin{bmatrix} \dot{p}_1 \\ \dot{q}_1 \end{bmatrix} = \Psi_1 \begin{bmatrix} p_1 \\ q_1 \end{bmatrix}, \quad \Psi_1 = \begin{bmatrix} 0 & -1 \\ 0 & -\alpha \end{bmatrix}; \quad (19)$$

$$\begin{bmatrix} \dot{p}_{2:N} \\ \dot{q}_{2:N} \end{bmatrix} = \Psi_2 \begin{bmatrix} p_{2:N} \\ q_{2:N} \end{bmatrix}, \Psi_2 = \begin{bmatrix} -\beta R^T \mathcal{L} R & -I_{N-1} \\ 0 & -\alpha I_{N-1} \end{bmatrix}. \quad (20)$$

Note that the eigenvalue of $R^T \mathcal{L} R$ are the same as the positive eigenvalues of the Laplacian matrix $\mathcal{L}$. Thus, the eigenvalues of Ψ_1 are 0 and $-\alpha$, and those of Ψ_2 are $-\alpha$ with multiplicity $N-1$ and $-\beta \lambda_i(\mathcal{L})$ with $\lambda_i(\mathcal{L}), i = 2, \dots, N$ being the i th smallest eigenvalue of $\mathcal{L}$. Since the null-space spanned by Ψ is the consensus space, i.e., $(I_N, -c I_N)$, for some constant $c \in \mathbb{R}$, due to the connectivity of the graph, we have e_i converges to zero exponentially, and consequently $k_{c,i}$ converges to $\mathbf{1}_N^T Q_{cap}/Q_d$. Moreover, the exponential convergence rate is given by $\min\{\alpha, \beta \lambda_2(\mathcal{L})\}$. As a result, considering a WF with large numbers of WTs, the convergence speed can be adjustable by tuning α and β , or by optimizing the communication topology such that the second smallest eigenvalue of $\mathcal{L}$ is maximized.

In (11), k_l can act as the reactive power utilization indicator: $k_l(\infty) > 1$ if Q_d is overloaded; $k_l(\infty) \leq 1$, otherwise. Then, RPSA can be realized by augmenting (11) in the proposed Algorithm 1. The pseudo code of the proposed Algorithm 1 during each dispatch is as follows.

Algorithm 1: RPSA

Input: Q_d

Output: $Q_{R_ref,i}; Q_{G_ref,i}$

- 1: initialize $Q_{R_cap,i}$ and $Q_{G_cap,i}$;
 - 2: compute $Q_{tot_cap,i}$;
 - 3: initialize $Q_{cap,i}$ separately using $Q_{R_cap,i}$, and $Q_{tot_cap,i}$;
 - 4: call (11) to calculate $k_{l_R,i}$ and $k_{l_tot,i}$ in parallel;
 - 5: **if** $k_{l_R,i}(\infty) < 1$ **then**
 - $Q_{R_ref,i} = Q_{R_cap,i} k_{l_R,i}$; $Q_{G_ref,i} = 0$;
 - else if** $k_{l_R,i}(\infty) > 1$ **and** $k_{l_tot,i}(\infty) < 1$ **then**
 - $Q_{R_ref,i} = Q_{R_cap,i} k_{l_tot,i}$;
 - $Q_{G_ref,i} = Q_{G_cap,i} k_{l_tot,i}$;
 - else if** $k_{l_tot,i}(\infty) > 1$ **then**
 - $Q_{R_ref,i} = Q_{tot_cap,i} k_{l_tot,i} - Q_{G_cap,i}$;
 - $Q_{G_ref,i} = Q_{G_cap,i}$.
-

IV. CASE STUDY

A 150MW WF composed of 100*1.5 MW GE WTs is employed and connected to the external grid through a 200-kilometer transmission line ($X_L = 1.65 \times 10^{-3} \text{H/km}$). WT parameters can be found in [21]. Every 20 WT is regarded as an identical unit sharing the same wind velocity and thus the WF is divided into 5 agents, as shown in Fig. 7. A ring topology is chosen for mutual communication considering simplicity and robustness [27], corresponding to $\mathcal{L} = \begin{bmatrix} 2 & -1 & 0 & 0 & -1; & -1 & 2 & -1 & 0 & 0; & 0 & -1 & 2 & -1 & 0; & 0 & 0 & -1 & 2 & -1; & -1 & 0 & 0 & -1 & 2 \end{bmatrix}$. For convenience, in RPSA, the initial state of k_c is randomly set around 1 as [0.8, 0.9, 1.0, 1.1, 1.2, 1.3], and z is set as 0. Considering the execution of RPSA and the interval control, the time delay for each dispatch is set as 100ms [28]. Besides, if not specifically marked, unmarked units of the ordinates in all figures below are defaulted as p.u..

Fig. 7. Configuration of the tested system.

Fig. 8. Comparison on RSC response using different methods. (a) Reactive power. (b) Rotor current. (c) Active power. (d) Pitch angle.

A. Case 1: Comparison on Utilization of RPC

In the first step, in order to verify the high utilization of the proposed AP & RP coordination strategy for RSC, it is compared with other two PQ -curve based methods applied in [10] (Method A) and [13] (Method B), where Method A is a fixed RPC determined by assuming a steady-state condition. The capacity is unchanged for a specified P_R even for dynamic evaluations, while Method B is derived from circuital expressions and the capacity is dynamically determined using the updated values for P_R and s . The APV support is solely undertaken by RSC with the reactive power reference of GSC always kept at zero. The wind velocity of the

entire wind farm is uniformly set as 11 m/s. The APV target is set to 1.0 p.u. The system initially operates in active power reference control with $Q_R = 0$, and 113.3 Mvar inductive load was suddenly added at 10 s. Fig. 8(a)-(d) respectively presents the responses of RSC reactive power, rotor current, active output and pitch angle. Because RPD exceeds the existing RPC, the three methods enter the AP & RP coordination stage successively around 11 s, where the proposed method is the latest (the later entry time indicates the higher utilization of RPC). Further, it can be seen that due to the same load on access point, the three methods have very little difference in the performance of reactive power (Fig. 8(a)), and the small difference comes from the RPDs corresponding to the active power at different curtailment levels. However, from the perspective of active power, the proposed method obviously reduces the weakening of active power (Fig. 8(c)). This is because compared with the other two methods, the proposed method has a high rotor current utilization much closer to the limit (Fig. 8(b)), thus broadening the PQ capacity boundary. The extracted converter capacity reduces the active power curtailment, which also corresponds to smaller pitch angles (Fig. 8(d)).

B. Case 2: System Response under Different Loads

In this case study, the control objective is to maintain U_{AP} at 1.03 p.u. once the APV drops below 0.97 p.u., the wind velocities for each group are set as [13.2 12.0 10.8 9.6 8.4] m/s, and the active power references are set according to the MPPT curve as [0.93 0.72 0.53 0.37 0.25] p.u., respectively. 58.3 Mvar, 91.7 Mvar, 125 Mvar inductive loads are given separately to cover three cases discussed in Section II. The simulation results are shown in Fig. 9. In Case (i), the responses of $k_{L,R}$ and $Q_{R,ref}$ for dispatch, the output reactive power of RSC and the frequency and voltage responses of APV are presented. The converged value of each $k_{L,R,i}$ is smaller than 1, indicating that only RSC is needed to be activated for APV support when 58.3 Mvar is given at 1s. As Q_R tracks the self-allocated value $Q_{R,ref}$, U_{AP} is stable around 1.03 p.u. In Case (ii), as the load absorbs 91.7 Mvar, $k_{L,R,i}$ converge at 1.314 while $k_{L,tot,i}$ converge at 0.842. The participation of GSC eases the burden of RSC and fastens the voltage recovery. In Case (iii), the terminal values of $k_{L,tot,i}$ are larger than 1, indicating the active power curtailment is required. GSC remains at the maximum reactive power capability (c), and the remaining tasks are left to RSC. As Q_R increases, AP & RP Coordination is activated at around 5 s.

C. Case 3: System Response under Wind Velocity Change and Load Change

Setting the objective value of U_{AP} as 1 p.u., system originally operates at load absorbing 91.7 Mvar. Wind velocity is changed from [13.2 12.0 10.8 9.6 8.4] m/s to [13.2, 12.0, 12.0, 10.8, 10.8] m/s at 10 s, and then the load is reduced to 41.7 Mvar at 20 s. Fig. 10 shows the responses of active power P_R , the coordinating factor $P_{R,c}$, reactive power from RSC Q_R and GSC Q_G , and frequency and voltage of access point. The

Fig. 9. System response under different RPD. Case (i) RPD within RPC of RSC. Case (ii) RPD within RPC. Case (iii) RPD outside RPC.

change of wind velocity suddenly increases the active power production (Fig. 10 (a)) and decreases the according RPC. Facing increased RPD and changed RPC, RPSA rearranges the reactive power allocation of each agents, where agents with increased active power (WT3, WT4 and WT5) undertake reduced reactive power tasks (Fig. 10 (c)). Due to the heavily decreased RPC, system migrates from Case (ii) to Case (iii), which can be seen from Fig. 10 (b) and (d). AP & RP Coordination guarantees a great balance between RPC and RPD, and thus U_{AP} maintains at 1 p.u. with little fluctuation

Fig. 10. System response under wind velocity change and load change. (a) Active power. (b) Coordinating factor. (c) Reactive power of RSC. (d) Reactive power of GSC. (e) Access point frequency and voltage.

(Fig. 10 (e)). At 20 s, the sharply reduced RPD drives the system from Case (iii) to Case (i). Since the remaining RPC of RSC is larger than RPD, both Q_G and $P_{R,c}$ turn back to zero and the active power generation returns to MPPT mode.

D. Case 4: Comparison under Communication Line Failure

A comparison study with other two methods is presented in Fig. 11, where CM, DM and PDM are respectively abbreviated for centralized method, distributed method and the proposed distributed method. For a fair comparison, all of the three methods are based on the fair load-sharing principle. Setting the same condition with Case 3, 91.7 Mvar load is given at 5s. Communication line disconnection (for CM, it is between WT3 and the central controller, while for DM and PDM, it is between WT2 and WT3.) happens at 8s. Then, wind velocity increases to [13.2, 12.0, 12.0, 10.8, 10.8] m/s at 10 s. Fig. 11 shows the responses of access point voltage U_{AP} , the total reactive power $Q_{R,tot}$ and total active power $P_{R,tot}$. It can be seen that in the first 8s, three methods have the same response. Once line fault happens, WT3 with CM has to stop its service, resulting in a reduction of reactive power as well as active power (Fig. 11(b) and (c)). As the shrunken RPC cannot support the previous RPD, U_{AP} starts to drop Fig. 11(a). While WF with DM or PDM operates normally since WT3 is still connected with the system through the chain communication

Fig. 11. WF responses under communication line fault.

line, corresponding to $\mathcal{L} = [2 \ -1 \ 0 \ 0 \ -1; -1 \ 1 \ 0 \ 0 \ 0; 0 \ 0 \ 1 \ -1 \ 0; 0 \ 0 \ -1 \ 2 \ -1; -1 \ 0 \ 0 \ -1 \ 2]$. As wind rises at 10s, the increasing active power crowds out the space of reactive power, so the reduced RPC cannot further support the original RPD. $Q_{R,tot}$ with CM continuously goes down and $Q_{R,tot}$ with DM begins to drop as well due to the lack of coordination with active power $P_{R,tot}$, leading to the decrease of U_{AP} . In comparison, PDM maintains its APV support through a certain amount of wind curtailment, keeping U_{AP} constant.

E. Case 5: System Response under WT Failure

With the same wind velocity of Case 2, the system maintains U_{AP} at 1 p.u. when loading 41.7 Mvar. Then, WT5 fails at 15s and is removed from the system dispatch. Because of this, the communication topology of WF changes from a loop connection to a chain connection, corresponding to $\mathcal{L} = [1 \ -1 \ 0 \ 0; -1 \ 2 \ -1 \ 0; 0 \ -1 \ 2 \ -1; 0 \ 0 \ -1 \ 1]$. It can be seen from Fig. 12 that the output of active and reactive power dips to zero, and there is a short-term drop on the frequency of access point, while the active power output of other WTs remains unchanged. Since the increase of other WTs' reactive power output compensates the gap in time, the APV restores to 1 p.u. after a small sag.

V. CONCLUSION

This paper proposes a distributed architecture for the DFIG-based wind farm to provide access point voltage support with less wind power curtailment. Under the unknown relationship between the total reactive power capacity and reactive power demand, a reactive power self-allocation scheme operated in each wind turbine is responsible for the reactive power allocation on rotor side converter and grid side converter, based on the principle of preferential use on spare converter capacity. An active power and reactive power coordination scheme is developed for a heavier reactive power demand. It further extracts the converter capacity through the intervention of the maximum rotor current, and coordinates the distribution of active and reactive power while always maintaining the maximum utilization on converter capacity. The proposed

Fig. 12. System response under WT5 failure. (a) Active power. (b) Reactive power of RSC. (c) Access point frequency and voltage.

control scheme ensures the effective support for different levels of reactive power demand and maintains a relatively high wind power yield.

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