A distributed AC power grid with wind farms using ADMM-based active and reactive power control

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Abstract:

A distributed active and reactive power control (DARPC) strategy based on the alternating direction method of multipliers (ADMM) is proposed for regional AC transmission system (TS) with wind farms (WFs). The proposed DARPC strategy optimizes the power distribution among the WFs to minimize the power losses of the AC TS while tracking the active power reference from the transmission system operator (TSO), and minimize the voltage deviation of the buses inside the WF from the rated voltage as well as power losses of the WF collection system In this study, a two-stage reactive power optimization method based on the alternating direction method of multipliers (ADMM) algorithm is proposed for achieving optimal reactive power dispatch in wind farm-integrated distribution systems. Unlike existing optimal reactive power control methods, the proposed method enables distributed reactive power flow optimization with a two-stage optimization structure. Furthermore, under the partition concept, the consensus protocol is not needed to solve the optimization problems. In this method, the influence of the wake effect of each wind turbine is also considered in the control design. Simulation results for a mid-voltage distribution system based on MATLAB verified the effectiveness of the proposed method.

Keywords: Two-stage optimization, Reactive power optimization, Grid-connected wind farms, Alternating direction method of multipliers (ADMM).

1.0 INTRODUCTION

Wind power has been continuously developing due to the increasing demand of renewable energy and low-carbon energy policy With the wind power penetration increasing, the wind power fluctuations and the interaction between largescale wind farms (WFs) and power systems have introduced several technical challenges, e.g., the optimal power allocation, voltage regulation and coordination for the AC transmission system (TS) with WFs a multi-period OPF model was formulated to minimize the operating cost in the grid with offshore WFs. In [1], an OPF-based optimal generation schedule was proposed to minimize the total system cost and operate the system securely with wind power. In an extended OPF model was used to minimize the generation cost of thermal units and wind units in the power system with WFs. In [2], a multi-objective stochastic OPF model was formulated to reduce the operating cost, emission and enhance the voltage stability in the power system with significant wind penetration. In an optimal reactive power dispatch strategy based on OPF was proposed to minimize the voltage stability index in a wind power integrated power system. For the WF control, the conventional strategy is the proportional distribution (PD) control scheme. The active and reactive power references of wind turbines (WTs) are proportionally distributed according to the available wind power, which is easy to implement [3]. However, the PD control scheme cannot achieve optimal power distribution inside the WF. Several optimization-based dispatch methods have been developed to overcome the disadvantage of the PD scheme and achieve better control performance of the WF. In an optimal power dispatch method was proposed to reduce the production cost and maximize the active power production of the WF. The ADMM-based optimization methods have been widely used in the WF optimal control In [4], an ADMM-based two-tier active and reactive power control scheme was proposed to achieve the optimal voltage regulation inside the WF cluster. In, an ADMM based voltage control method was proposed for the large-scale WF cluster to coordinate the reactive power output among several WFs and WTs inside each WF. In [5], a model predictive control method based on ADMM was proposed to minimize voltage deviations and reactive power output fluctuations of WTs inside WFs. In an ADMM-based optimal active power control method was proposed for synthetic inertial response of large-scale WFs. The aim is to minimize the differences in the rotor speed of the WTs and the wind energy loss.

2.0 RELATED WORKS

Haishu et al. **[6]** proposed a comprehensive optimization model of ADN combining dynamic reconfiguration and reactive power optimization. Ping et al. **[7]** proposed a two-stage reactive power and voltage optimization method. In the first stage, the reconstruction scheme and the operation state of slow action equipment were determined, and in the second stage, the influence of fast action equipment on RDG random output was adjusted. Guowei et al. **[8]** used energy storage for day ahead and intraday voltage optimization of distribution network and realized voltage optimization by limiting the energy storage power range in the day ahead and adjusting the port output in real-time in intraday. Considering the influence of photovoltaic, Wei et al. **[9]** proposed a multi-time scale optimization control method for photovoltaic grid-connected distributed generation system, which aimed at minimizing the expected value of operation cost and carries out reactive power optimization of the distribution network in long timescale and short timescale. Further considering the influence of load characteristics on voltage, Zhiqiang et al. **[10]** carried out reactive power optimization in two stages: day-ahead optimization and realtime optimization and added the correction of the day-ahead optimization in the day. At the same time, considering the uncertainty of new energy and flexible load, double timescales (1-hour level and 15-minute level) **[11]** were proposed, which used the traditional on-load voltage regulating transformer on-load tap changer and shunt capacitor for hour level voltage optimization and used the reactive power output of new energy units for 15-minute level to control the voltage deviation of nodes. Xu et al. **[12]** applied network reconfiguration to the AC/DC power grid, which can optimize the power flow distribution of the distribution system and improve the economy. Further considering the temporal and spatial imbalance of the net load of the distribution network, Wang et al. **[13]** took the light abandonment, load loss, and minimum switching cost as the goal and divided the period according to the load timing characteristics; the multiperiod and multilevel reconfiguration scheme of active distribution network was obtained.

3.0 DISTRIBUTED VOLTAGE OPTIMIZATION CONTROL SCHEME

The distributed voltage optimization control scheme is realized based on ADMM and partitioning. The interactive information only includes the state of the coupling branch, which reduces the demand for data transmission. A parallel computing architecture can be adopted, and when the number of nodes increases, it has good scalability

Concept of ADMM-based optimization method:

The ADMM is an algorithm that is intended to blend the dual ascent decomposability with the superior convergence properties of the method of multipliers The algorithm solves problems in the form:

$$\min f(x) + g(z) \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ (1)$$

s.t Ax +Bz = C

As in the method of multipliers the Augmented Lagrangain is formed As Follows

$$Lp\ (x,z,y) = f(x) + g(z) + Y^{T}\ (Ax+ BZ= C)+\frac{\rho}{2}||Ax + Bz - c||^{2}$$

ADDM Consists of the Iterations

$$x^{k+1} := \arg\min_{x} L_{\rho}(x, z^k, y^k)$$

$$z^{k+1} := \arg\min L_{\rho}(x^{k+1}, z, y^k)$$

$$y^{k+1} := y^k + \rho(Ax^{k+1} + Bz^{k+1} - c) \quad \text{………………………………………. (2)}$$

algorithm coupling constraints. That is, the constraints with the consideration of area partition are as follows:

ADMM-based grid optimization scheme

To make the partition problem equivalent to the original problem, the state variables of the coupling branch in each adjacent region must be equal. Therefore, the grid optimization objective can be decomposed into the distributed coordination calculation of sub-optimization problems in each region. The distributed reactive power optimization control model based on partition coordination is as follows:

$$\min \sum_{i=1}^{n_{area}} f_i(x_{grid,i}) = \sum_{i=1}^{n_{area}} P_{grid,i}^{loss} \quad \text{……………………………………….(4)}$$

where i represents the ith partition in the network, ij n , {1, 2, , } = Λ area . xgrid,i represents the set of all state variables in the ith region, x PQUQ grid i i mn i mn i m i m , , , ,, = {, ,,} WF , where m and n represent the number of grid nodes, mn N , ∈ i . Pi,mn and Qi,mn are the active and reactive power from node m to node j in the ith region, respectively. Ui,m is the voltage of node m, and Qi m WF , is the reactive power produced by the WF connected to node m.

The constraints of this optimization problem are primarily considered from the power flow constraints, the safe operating condition of the power grid, the reactive power capacity constraints of the WFs, and ADMM

$$P_{i,mn} = \sum P_{nk} - \frac{P_{i,mn}^2 + Q_{i,mn}^2}{V_{i,m}^2} R_{i,mn} - P_{i,n}^{load} + P_{i,n}^{WF} \quad \text{…………………………………… (4)}$$

$$Q_{i,mn} = \sum Q_{nk} - \frac{P_{i,mn}^2 + Q_{i,mn}^2}{V_{i,m}^2} X_{i,mn} - Q_{i,n}^{load} + Q_{i,n}^{WF}$$

$$V_{i,n}^2 = V_{i,m}^2 - 2(R_{i,mn}P_{i,mn} + X_{i,mn}Q_{i,mn}) \quad \text{……………………………………… (5)}$$

$$V_{i,n}^2 = V_{i,m}^2 - 2(R_{i,mn}P_{i,mn} + X_{i,mn}Q_{i,mn}) + (R_{i,mn}^2 + X_{i,mn}^2)\frac{P_{i,mn}^2 + Q_{i,mn}^2}{V_{i,m}^2} \quad \text{……………………………………………………….. (6)}$$

$$\left|Q_{i,m}^{WF}\right| \leqslant Q_{i,m}^{WF\ \max} = \sqrt{\left(S_{i,m}^{WF}\right)^2 - \left(P_{i,m}^{WF}\right)^2} \quad \text{………………………………………… (7)}$$

$$X_i = X_j \quad \text{………………………………………………………………… (8)}$$

where i is the ith region in the grid, i n = {1, 2, , } Λ area , and m, n, and k are the mth, nth, and kth nodes in the grid, respectively; mnk N , , {1, 2, , } = Λ . The optimization problem of the entire system is decomposed into a coordinated calculation of sub-optimization problems of narea regions.

Table 1: Procedure of ADMM-based optimization algorithm of the grid

Step 1	Initialization: divide the WF into n_{areaWF} regions
Step 2	Optimization: solve the optimization problem in each region
Step 3	Communication: exchange coupling information with adjacent regions
Step 4	Update: calculate the global variable yWF,i and dual variable λWF,i
Step 5	Evaluation: determine whether it is satisfied with the convergence condition yt yt WF i, , WF i (1) ( ) + − ≤ε. If yes, output Qj WT as the reactive power dispatch command for each WF; otherwise, go to Step 2.

4.0 SIMULATION RESULTS

A distribution network (IEEE 33 bus system) with five WFs, with each WF having two feeders and 2 × 2 MW DFIG-based WTs connected to each feeder is used for validating the performance of the proposed strategies. The parameters of the DFIG-based WF can be found in and the other parameters that are used in simulations are listed in Table

Table 2: Parameters used in the simulation

Parameters	Value
Rated WF Power	8 MVA
Step 3	10 kV
Step 4	2
Step 5	4
Step 6	7,11,15,20,25

Control strategies:

Because the consensus ADMM algorithm is one of the key optimization methods based on ADMM adopted among recent articles, this paper primarily adopts three control strategies to conduct comparative simulations, as shown in the table below. Strategy A is the proposed two stage optimization algorithm, and Strategies B and C are consensus control of the grid and WFs, respectively.

Which are dispatched with the reactive power commands according to the consensus protocol of the utilization ratio among the WFs in the grid and WTs in the WF, respectively.

Table 3: Control strategies adopted for comparison

Strategies	Description
Rated WF Power	The proposed two-stage optimization algorithm
Strategy B	Consensus control of the grid
Strategy C	Consensus control of the WFs

Assume that the coupling region of the grid and the WFs are as shown in Figs 1,2. respectively. Considering the reactive power scheduling command issued by the TSO to be 1.55 p.u., the reactive power output assigned to each WF is shown

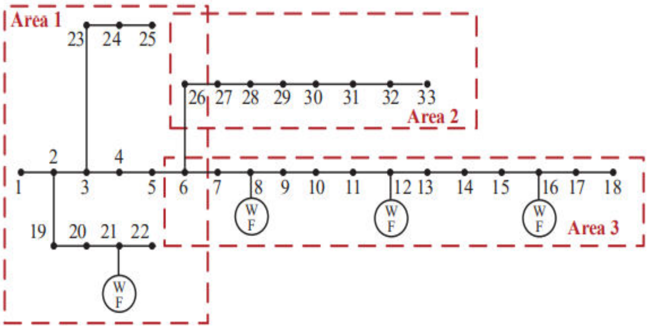

Fig 1: Grid structure with partition

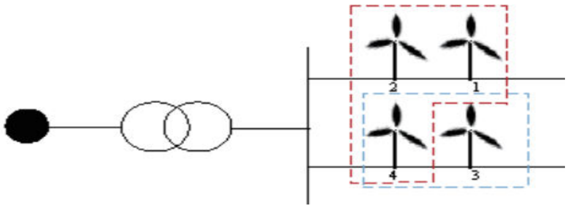

Fig 2: WF structure with partition

Table 4: Reactive power output assigned to each WT in the WF

Node number	WT number	Reactive power output (p.u.)
7	1, 3	0
	2, 4	0.02
11	1, 3	0.0121
	2, 4	0.0779
15	1, 3	0.0046
	2, 4	0.0704
20	1, 3	0
	2, 4	0.065
25	1, 3	0.2296
	2, 4	0.2954

Distributed optimization is an iterative process. During each iteration, neighboring regions exchange coupling branch states. Communication times are positively correlated with optimization problem solving times. In the proposed algorithm, when the convergence conditions are set as $\varepsilon = 10^{-4}$, both grid and wind farm sides can achieve convergence within 70 iterations under a parallel computing structure, which meets the reactive power dispatch requirements.

Conclusion:

In this study, we present a two-stage distributed reactive power output optimisation control approach that takes wake effects into account for WFs, and we show that this method is both effective and reasonable. Information privacy is adequately preserved by the proposed method since no information outside of the coupled region is shared across areas. The proposed optimization framework simultaneously achieves the goals of tracking TSO control commands, optimizing reactive power output of WFs at the distribution network level, and optimizing fan output at the WF level. The performance and convergence of the proposed method were verified via simulations considering the IEEE 33-bus and 4 × 2 MW WF systems. However, this study only discussed the response of the distribution network and WF sides to the TSO dispatching commands. The dynamic response of the proposed method under variable wind speed conditions and the autonomous response under voltage fluctuation conditions should be considered in future studies

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