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Active and reactive power coordinated optimal dispatch in active distribution network based on model predictive control

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Abstract. With the proliferation of the distributed energy resources (DERs), the scheduling and control of the distribution network have become more complicated. To cope with the uncertainty nature of distributed generation, a multi-timescale optimal dispatch method in active distribution network (ADN) based on the model predictive control (MPC) is proposed in this paper. First, based on MPC, a hierarchical scheduling framework for ADN is established, including long-timescale stage, and short-timescale stage. Then, via coordinated control of various resources in the ADN, i.e., distributed generators, energy storage, capacitor banks and OLTC transformer, the impact of intermittent renewable energy and load forecast errors can be reduced. Finally, considering the coupling characteristics of active and reactive power in the ADN, a joint active and reactive power optimization model is proposed to further reduce the network loss. Numerical simulation on a modified IEEE-33 distribution network system verifies the correctness and superiority of the proposed scheduling approach.

1. Introduction

The large-scale integration of distributed energy resources (DERs) has increased the control complexity of the distribution network operates [1], [2]. On the one hand, the prediction error of DERs may lead to the non-optimality of the scheduling results. Therefore, the network operator needs to consider the prediction errors explicitly [3], [4]. On the other hand, DERs can bring bi-directional power flow in the distribution network (DN), which may result in security issues such as line congestion and over-voltage [5]. To cope with the challenge brought by the increasing penetration of DERs, researchers proposed the concept of an active distribution network (ADN) [6], aiming to control these DERs actively and reduce their negative impact on the DN.

Based on the feature that the prediction accuracy of renewable energy sources (RESs) accelerates with the decrease of the predicted timescale [8], [9], the optimal scheduling scheme is modified step by step to diminish the dominance of the random flux of RESs [10]. In [11], a multi-timescale active power scheduling method for the large-size wind power grid connection is proposed, which realizes the step-by-step correction of wind power(WP) prediction error. According to the characteristic that the prediction error of wind power decreases gradually with timescale shortening [12], a coordinated formulation strategy of multi-stage unit commitment scheduling method considering WP generation is proposed. By coordinating and optimizing unit commitment in all timescale, the cost of power generation including wind power generation can be reduced. Considering that with the continuous subdivision of timescale, the forecast accuracy of WP and load is continuously improved, the

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coordinated control between wind power units and conventional units is realized to maximize the consumption of wind power [13], [14]. Based on the latest power prediction information, [15] builds closed-loop optimal control, which corrects the scheduling deviation caused by prediction errors timely, to guarentee the security and stability of the ADN and maximize its operation benefit.

Connecting a large number of DG has changed the original power flow and energy structure of the ADN [16], and have a certain impact on the system voltage stability and network loss. In [17], the multi-agent system is used in the voltage/var optimization problem for the distribution network. It shows that the usage of DERs for reactive power compensation leads to the great decrease in the electric energy losses, and proves the quickness and the effectiveness of the proposed algorithm. However, only reactive power is considered in this method, which is not complete for the ADN. Different from the transmission network, the line resistance is close to the reactance in the distribution network, which leads to the strong coupling between active and reactive power. Therefore, it is not complete and comprehensive to conduct a unilateral active/reactive power optimization analysis based on the traditional theory of active and reactive power for comprehensive energy in a power system is established in [18], which takes the minimum total generation overall charge of the distribution system and the minimum active power losses of the network as the objective function and solves the optimal comprehensive benefits solution.

To address the above issues, based on the model predictive control (MPC) technique, this paper proposes a coordinated control method of active and reactive power dividing the control process into long-timescale and short-timescale. Optimal dispatch problem at different timescale performs separate MPC for their respective control objective and control variables. The long timescale is derived from the day-ahead 24-hour prediction of RESs and load. The multi steps rolling optimization approach is adopted to optimize the active and reactive output of each controllable device. The short timescale is derived from the optimized results of the longer timescale and ultra-short-term forecast of RESs. In the short-timescale optimal scheduling problem, the incremental power output of active/reactive devices is optimized with a rolling horizon. The overall goal of the proposed method is to reduce network loss and ensure the safety and economic operation of the ADN, which can make the distribution system operator handle the fluctuation and randomness of RESs and loads more effectively and actively.

2. MPC-based active-reactive power coordination dispatch model

A multi timescales joint optimal dispatching method is proposed in this paper. In the long timescale, 1h is taken as the time resolution, the network losses is selected as the optimization objective, and the scheduling plan of the future 24h period is optimized. In the short timescale, taking RESs short-term rolling forecast as a benchmark, and long-timescale optimal operation value as reference, distribution system operator scrolls to calculate active power increment of the next 15 min. However, only the first control instruction of the optimal control sequence can be executed.

2.1. Objective function

2.1.1. Long timescale. The optimization control variables include active and reactive output of RESs, charging/discharging power of energy storage, compensation capacitor tap position, the output of static var compensator and the OLTC tap ratio. Taking the current operation state as the initial value, RES and load demand forecast data as input variables, ΔT as the resolution and minimum network loss as the optimization goal, scroll to solve the active and reactive regulating resources' output for the coming time $M\Delta T$.

To guarantee the economy of the overall system operation reducing network losses, the optimization objective of the longer timescale is to minimize the network loss of distribution network, i.e.

$$\min F = \min \sum_{t=t_0}^{t_0 + M\Delta T} \sum_{i=1}^n \sum_{j \in u(i)} r_{ij} \tilde{I}_{ij,t}$$
(1)

2113 (2021) 012056 doi:10.1088/1742-6596/2113/1/012056

$$\tilde{I}_{ij,t} = F(K_{ij,t}, H_{i,t}^{c}, P_{i,t}^{ch}, P_{i,t}^{dis}, Q_{i,t}^{DG}, Q_{i,t}^{SVC})$$
(2)

whereas t_0 indicates the starting time of rolling optimization under longer timescale, u(i) is a set of all the line that point to node *i*, r_{ij} represents the resistance of the transmission line *ij*, $\tilde{I}_{ij,t}$ is the square of the current amplitude on the transmission line *ij* at time periods *t*, K_{ij} is the tap position of on-load tap-changer transformer, $H_{c,i,t}$ represents the current tap position of the capacitor bank, $P_{ch,i,t}$ and $P_{dis,i,t}$ are the charging and discharging power of the energy storage device respectively, $Q_{DG,i,t}$ is the reactive power output of distributed generators, and $Q_{SVC,i,t}$ is the reactive power output of the static var compensator.

2.1.2. Short timescale. The optimal objective is still to minimize the operating network losses of the distribution network, but the time horizon is shortened from 24h to period. In addition, the regulation plan of compensation capacitor and OLTC has been determined in the optimized scheduling under the long timescale, so the optimized scheduling under the short timescale will not be changed.

To address the random fluctuations of RESs output and load demand, prevent voltage from exceeding the limit and guarantee the secure operation of the system and keep consistent with the overall optimization trend of the longer timescale, the optimization control of the shorter timescale still takes the minimization of network losses as the objective.

$$\min F = \min \sum_{i=1}^{t_0+N\Delta t} \sum_{i=1}^{n} \sum_{i\in u(i)} r_{ii} \tilde{I}_{ij,t}$$
(3)

$$\tilde{I}_{ij,t} = F(P_{ch,i,t}^{T1} + \Delta P_{i,t}^{ch}, P_{i,t}^{dis,T1} + \Delta P_{i,t}^{dis})$$
(4)

$$Q_{i,t}^{DG,T1} + \Delta Q, Q_{i,t}^{SVC,T1} + \Delta Q_{i,t}^{SVC})$$

$$(5)$$

whereas N indicates the optimization horizon, $P_{j,t}^{ch,T1}$, $P_{j,t}^{dis,T1}$, $Q_{j,t}^{SVC,T1}$ are the reference of the charging and discharging active power of the energy storage and the reactive power of the distributed generators and the static var compensator solved by the long timescale optimization at the time *t* respectively.

2.2. Constraints

2.2.1. Power flow model. According to the characteristics of the radial network, the power flow equation is expressed in the form of Distflow in this paper (see [19]).

$$\sum_{i\in\alpha(j)} (P_{ij,t} - \tilde{I}_{ij,t}r_{ij}) + P_{j,t} = \sum_{k\in\beta(j)} P_{jk,t}$$
(6)

$$\sum_{i\in\alpha(j)} (Q_{ij,t} - \tilde{I}_{ij,t} \mathbf{x}_{ij}) + Q_{j,t} = \sum_{k\in\beta(j)} Q_{jk,t}$$

$$\tag{7}$$

$$k_{ij,t}^2 \widetilde{U}_{j,t} = \widetilde{U}_{i,t} - 2(r_{ij}P_{ij,t} + x_{ij}Q_{ij,t}) + (r_{ij}^2 + x_{ij}^2)\widetilde{I}_{ij,t}$$
(8)

$$\widetilde{U}_{i,t}\widetilde{I}_{ij,t} = P_{ij,t}^2 + Q_{ij,t}^2$$
(9)

where $\alpha(j)$ indicates the set of all the nodes that point to node j, $\beta(j)$ is the set of all the nodes that point to node j, $P_{ij,t}$ and $Q_{ij,t}$ are the active and reactive output at the head point of transmission branch ij, $P_{j,t}$ and $Q_{j,t}$ are the injection of active and reactive power, r_{ij} and x_{ij} represent the resistance and reactance of the transmission line branch, $\tilde{I}_{ij,t}$ represents the current amplitude square of transmission branch ij, and $\tilde{U}_{i,t}$ is the voltage amplitude square of bus i.

2.2.2. Distribution network safety limits.

$$I_{ij,t} \le I_{ij}^{\max} \tag{10}$$

$$U_i^{\min} \le U_{i,t} \le U_i^{\max} \tag{11}$$

where I_{ij}^{max} is the maximum limitation of current amplitude on the branch ij, U_i^{min} and U_i^{max} are the upper and lower limitation of voltage amplitude at bus *i* respectively.

2113 (2021) 012056 doi:10.1088/1742-6596/2113/1/012056

2.2.3. Distributed generators.

$$P_{DG,i,t} = P_{DG,i,t}^{pre} \tag{12}$$

$$Q_{DG,i,t}^{\min} \le Q_{DG,i,t} \le Q_{DG,i,t}^{\max}$$
(13)

$$Q_{DG,i,t}^{\max} = -Q_{DG,i,t}^{\min} = \sqrt{S_{DG,i}^2 - \left(P_{DG,i,t}^{pre}\right)^2}$$
(14)

where $P_{DG,i,t}^{pre}$ represents the predicted active power output of distributed generators, $Q_{DG,i,t}^{max}$ and $Q_{DG,i,t}^{min}$ are the upper/lower reactive power output limits respectively, while $S_{DG,i}$ is the inverter's nominal rated power.

2.2.4. Static Var Compensator.

$$Q_{SVC,i}^{\min} \le Q_{SVC,i,t} \le Q_{SVC,i}^{\max}$$
(15)

whereas $Q_{SVC,i}^{\text{max}}$ and $Q_{SVC,i}^{\text{min}}$ represent the upper/lower limits of the adjustable reactive production of the static var compensator.

Capacitor Banks

$$H_{i,t}\Delta Q_{i,t}^c = Q_{i,t}^c \tag{16}$$

$$0 \le H_{i,t} \le H_{\max} \tag{17}$$

where $H_{i,t}$ is an integer variable that represents the switched times of the capacitor banks, $\Delta Q_{i,t}^c$ indicates the reactive power output for each single capacitor, and H_{max} is the total number of capacitor banks.

2.2.5. Energy Storage.

$$E_{i,t}^{SOC} + P_{i,t}^{ch} \eta_{ch} \Delta T - \frac{P_{i,t}^{dis}}{\eta_{dis}} \Delta T = E_{i,t+\Delta T}^{SOC}$$
(18)

$$E_{SOC,i}^{\max} \times 20\% \le E_{i,t}^{SOC} \le E_{SOC,i}^{\max} \times 80\%$$
(19)

$$0 \le P_{i,t}^{ch} \le P_{i,t}^{ch,\max} D_{i,t}^{ch}$$
(20)

$$0 \le P_{i,t}^{dis} \le P_{i,t}^{dis,\max} D_{i,t}^{dis} \tag{21}$$

$$D_{i,t}^{ch} + D_{i,t}^{dis} \le 1$$
 (22)

where $E_{i,t}^{SOC}$ is the stored energy, η_{ch} and η_{dis} are the charging/discharging efficiency respectively, $E_{SOC,i}^{max}$ is the maximum stored electric energy of ES, both $D_{i,t}^{ch}$ and $D_{i,t}^{dis}$ are 0-1 variable, representing the charging and discharging state, respectively.

3. Case study

The established model is verified on a revised IEEE 33-bus distribution network which is given in Figure.1. The parameters are derived from [6]. The forecast data of WP, photovoltaic(PV) and load are shown in figure 2. The numerical simulation is carried out in MATLAB 2018b, modelled in Yalmip package and solved by commercial solver Gurobi on a PC with Intel(R) Core(TM) i7-5300 2.56Ghz, 16G RAM.

2113 (2021) 012056 doi:10.1088/1742-6596/2113/1/012056



Figure 1. The modified IEEE 33-bus distribution network system



Figure 2. Load and renewable energy curve.



Figure 3. System net load between two methods.

For the ease of presentation, the single open-loop method is called Method 1, while the single active dispatch method is called Method 2 and the conventional single reactive power scheduling approach is called Method 3. The objective of Method 2 is the minimization of the operation cost of ADN by optimizing active power regulating resources (i.e., the control variables), which mainly includes ES and DGs, not includes CBs and OLTC. Minimzing the losses of the ADN by optimizing the reactive output of CBs ,DGs and OLTC taps is the objective function of Method 3.

3.1. System Netload Analysis

Figure 3 dsiplays the overall user demand curve of the ADN predicted by the presented method and Method 1. Comparing with the actual overall user demand of the ADN, we can easily infer that the presented method can better track the flux of renewable energy sources.

The prediction result of Method 1 is quite differed from the actual total user demand of the system at some time slot. However, the prediction result of the proposed method can be consistent with the actual total load curve of the ADN. Therefore, the presented approach in the paper is much better than Method 1 in tracking system fluctuations. The main reason is that the single open-loop optimization only predicts the total load of the system in the day-ahead, while the proposed method, based on MPC, repeatedly revises the forecast results within the day, reducing the prediction error. We can further conclude that the receding horizon control strategy can reduce the prediction error.

3.2. Distribution Network Losses Analysis

To verify the superiority of the presented method in diminishing system network losses, the proposed method is compared with Method 2 and Method 3. The network loss using these dispatch methods is obtained through numerical simulation, as shown in figure 4. Table 1 exposes the total operational system cost of these three methods.

	Table 1. System Cost for Three Method		Table 2. Solution time for two case study systems.			
_	Dispatch Method	System Cost (\$)	Numerical example	Indicators	Original Model	Second-order Cone Relaxed Model
	Method 2	3.8477e+04	IEEE 22 hours	~		Model
	Method 3	4.3954e+04	system	Single optimization duration	18.24 s	0.61 s
	The proposed method	3.4853e+04	IEEE 118- bus system	Single optimization	173 s	1.42 s



Figure 4. Network loss between three methods.

It can be watched from figure 4 and table 1 that the prosented method in this paper is much better than Method 2 and Method 3 in reducing network losses. The reason for this phenomenon is that, different from the transmission network, the branch resistance is close to the reactance in the DN, and there exists a strong coupling between active power and reactive power. Therefore, the effect of joint active and reactive power optimization approach in the ADN is much better. Real-time system operation results of the proposed method are given in figure 5 and figure 6.

2113 (2021) 012056 doi:10.1088/1742-6596/2113/1/012056



Taking 15:00 to 18:00 as an example for analysis, during this period, photovoltaic output decreases and load demand increases. To alleviate the shortage of active power of the system, the ES system discharges. Meanwhile, to preventing the increase of network loss brought by the long-distance reactive power transmission, the OLTC ratio drops and the reactive compensation output of CB increases.

3.3. Solution time analysis

Numerical simulations are varified on the IEEE 33-bus and IEEE 118-bus network system to further verify the effect of the second-order cone relaxation on algorithm solution time, as given in table 2.

It can be observed from table 2 that, the second-order cone relaxation technique can reduce the algorithm solution time significantly, which is more obvious in large-scale systems. Thus, the proposed MPC-based multi-timescale joint active and reactive optimal scheduling approach is effective and superior.

4. Conclusion

To effectively deal with the fluctuation and uncertainty of the renewable energy sources output and load, this paper presents a multi-timescale dispatching method coordinating active and reactive power in the ADN. In the proposed model, a variety of regulating resources are formulated and coordinated to guarantee the economic performance and security of the system. The main conclusions are summarized as follows:

1) The multi-time scale dispatching framework based on MPC technique is presented to deplete the influence of the fluctuation of RESs in the ADN, which is conducive to the stability of system operation.

2) Unlike the conventional single active or reactive power optimal dispatching, the joint optimization method of active and reactive power may further diminish the network operating losses, which improves the economic performance of the active distribution network.

3) The second-order cone relaxation technique is adopted to recast the dispatch problem, which improves the convergence speed of the algorithm markedly.

With the liberalization of electricity market, distributed energy sources within the demand side will take a vital part in the energy collaborative management of ADN and generally displace the conventional generation plants. The new operating paradigm of ADN integrating various and dispersed DERs is the focus of the authors' future work.

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