An Online Equivalent Method of Large-Scale Wind Power Based on Multi-source Data Fusion

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Abstract With the rapid increase of wind power centralized grid-connection scale, the security and stability of power grid are greatly affected. In order to simulate the dynamic characteristics of wind farm accurately, a large-scale wind power online equivalent method based on multi-source data fusion is proposed. The operating state of the state estimation modeling network is identified by the fusion of multi-source real-time data such as SCADA, PMU and security and stability control system. When the error of branch power flow or node voltage at the boundary is large, the active power regulation range of wind power generators is determined by comprehensively considering the actual measurement collected by the wind farm centralized control system and the prediction information of the wind power prediction system. The active power of each wind farm is determined by quadratic programming model. The wind power generators are grouped according to the topology in the wind farm, then each group is subdivided according to static characteristic and operating state in turn. The dynamic models and static parameters of equivalent wind power generators and equivalent transformers are calculated. The proposed method is proved to be fast and effective through the analysis of a practical power grid example.

Keywords Large-scale wind power · Multi-source data fusion · Quadratic programming · Equivalent wind power generators

1 Introduction

With the further enhancement of power supply and transmission capacity, the network source structure was further optimized, and the installed scale of new energy increased significantly. In 2017, the installed capacity of new energy

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generation nationwide accounted for 53.7% of the total power generation, exceeding 50% for the first time. Northwest China accounted for 32.8% of the new energy units added [1]. The incremental contribution of new energy generation has also grown significantly. In 2017, new energy power generation increased by 36.6% year-on-year, 30.1% higher than the growth rate of total power generation. Nine provinces, including Qinghai and Gansu, account for more than 10% of the province's electricity generation [1].

At present, some farms and networks in the new energy cluster control system are not modeled in the Energy Management System. As a result, it cannot take into account the impact of unmodeled plants and network during the online security and stability analysis and scheduling operation auxiliary decision-making, new energy accommodation capacity calculation and emergency control. The corresponding fault, monitoring elements, sections and adjustment measures cannot be set. The accuracy of online security stability analysis results is affected [2–4].

The operating characteristics of wind farm determine its influence on power system. Power flow calculation and electromechanical transient simulation are important measures to study the influence of wind farm on power system [5–7]. On the one hand, the SCADA system only covers the low-voltage side busbar of the wind farm transformer currently, so it cannot provide a detailed model of the wind farm. On the other hand, the wind farm is composed of multiple wind turbines with small capacity. If detailed models are used in power flow calculation and electromechanical transient simulation, the models are not only complex and huge in scale, but also take a long time to calculate, which is not suitable for engineering applications [2–9].

In the part of state estimation modeling network, aiming at the serious problems such as bus voltage over-limit and equipment overload caused by the fault of new energy farms, the safety and stability control emergency control devices (the third security defense line) are usually used to implement automatic control of the power grid, such as load cutting and system splitting. Due to the asynchrony and accuracy difference between the state estimation data and the measured data of security and stability control system, the reliability and rapidity of the real-time control are affected. This paper identifies the real-time operation state of power grid by integrating multi-source real-time data including SCADA, PMU and security and stability control system. Based on power flow calculation and analysis of power grid, it can provide high-quality basic data for rapid, reliable and accurate control of overloading of power grid bus voltage and equipment.

By using the measured data of the new energy real-time monitoring system, the boundary of the state estimation modeling network is identified automatically through network topology analysis. The new energy power station model is added to the state estimation model. Therefore, new energy operation characteristics and control strategies can be fully considered to improve the accuracy of online security and stability analysis and decision-making. The active power regulation range of the new energy unit is determined by comprehensively considering the actual measurement collected by the wind farm centralized control system and the prediction information of the wind power prediction system. The quadratic programming model is adopted to determine the active power of each wind farm and to reduce the error of new energy fluctuation to the measurement to keep the power flow of boundary node and tie lines unchanged. By using the online equivalent technology of wind power generators, and combining the real-time wind power data, stability parameters, protection configuration and other model information, the units in the wind farm and their corresponding transformers are grouped into equivalent groups to meet the requirements of online calculation.

2 Multi-source Data Fusion

Multi-source real-time data of SCADA, PMU and security and stability control system are integrating to identified the real-time operation state of power grid by considering the different characteristics of real-time data reliability, precision and sampling period.

2.1 Multi-source Data Acquisition and Self-checking

According to measuring time of security and stability control system data, the minimum time deviation of the measured data from PMU is extracted. According to the feasible areas of active power, reactive power and bus voltage measured data of the equipment, the real-time data of PMU, security and stability control system and latest RTU are respectively checked for error data. Then the error data can be removed.

2.2 Multi-source Remote Measurement Data Fusion

For the same station with multiple sets of safety control devices, the average value of the real-time data of each device is taken as the real-time data of the station in the security and stability control system. For the remote measurement x of RTU data, if the remote measurement x has corresponding real-time data x_1 of security and stability control system and measured data x_2 of PMU, formula (1) is used to calculate the remote measurement x. The weighted coefficient is λ.

$$x = \lambda x_1 + (1 - \lambda)x_2 \tag{1}$$

2.3 Multi-source Remote Sign Data Fusion

According to the principle that the reliability of the remote measurement data is greater than the remote sign data, the remote sign data of the real-time data of security and stability control system and the measured data of PMU are checked and corrected respectively. For the remote sign data of the real-time data of the security and stability control system, the remote measurement data of the real-time data of the security and stability control system should be used to check and correct the remote sign data of circuit breakers and disconnectors in the real-time data of the security control system. Similarly, for the remote sign data of PMU measured data, according to the measured data of PMU in the same station, the remote measurement data of PMU measured data should be taken as the standard to check and correct the remote sign data of circuit breakers and disconnectors in the measured data of PMU.

The values of the remote sign data of circuit breakers and disconnectors in the real-time data of the security and stability control system were used to update the corresponding values in the RTU data. Then, the values of the remote sign data of circuit breakers and disconnectors in the PMU measured data were used to update the values of other corresponding in the RTU data. If the real-time data doesn't exist corresponding measurement data security and stability control system data or PMU, according to the RTU data in the same station, check and correct the remote sign data of circuit breakers and disconnectors in RTU data according to the remote measurement in RTU data. Now, the remote sign data of circuit breakers and disconnectors in the whole network fused with multi-source data can be generated.

2.4 Network Topology Update and Node Power Balance Check

According to the checked and modified RTU data, the grid topology analysis can obtain the information of the computing nodes and the topology islands of the grid. The power balance of the calculated nodes is checked. For the calculated nodes whose power unbalance is greater than the set threshold value, the power unbalance can be reduced and eliminated by equipment turnover in the station and modifying the injection power of equivalent branches.

3 Wind Farm Flow Adjustment

New energy power station is excluded in state estimation generally. In order to accurately simulate the dynamic characteristics of wind farm, the new energy power station model by artificial modeling mode is automatically integrated. The measured value acquired by the centralized control system of wind farm is taken as the initial active value of new energy generator.

Because data source of the unmolded network (hereinafter referred to as low voltage network) is inconsistent with the state estimation model part (hereinafter referred to as main network), and the actual measurement collection cycle is inconsistent, boundary power flow may have errors. When boundary branch flow or node voltage has a larger deviation, it is necessary to regulate the wind farm flow to ensure the flow rationality of all network.

Wind farm generator and load of the low voltage network are selected as the adjustable node. The active adjustment range of new energy generator is confirmed by the forecast information of wind power forecast system in order to adjust the active power of tie line in low voltage network. According to the active power sensitivity of adjustable nodes to tie lines and the target value of the AC line active power transmission (measured value), the minimum sum of weighted adjustment active quantity is taken as the target, and the active adjustment quantity of adjustable node is worked out by quadratic programming algorithm. The constraints will be relaxed when the quadratic programming algorithm has no solution. When the solution is given out, the AC line and deviation value not accorded with the constraints are given out at the same time.

The above problem model can be described as formula (2):

$$
\begin{aligned}
\min f &= \sum_{i=1}^{N} \alpha_i \Delta P_i^2 \\
s.t. \sum_{i=1}^{N} K_{ji} \cdot \Delta P_i &= \Delta P_{lj} \quad j = 1,\ldots,M
\end{aligned}
\tag{2}
$$

The active (reactive) adjustment quantity of adjustable node i is ΔP_i. ΔP_{lj} is the differential value of target AC line j between the low voltage network and main network. α_i is the weighted value of adjustable node i. K_{ji} is the active (reactive) sensitivity of the adjustable node i to the target AC line j. N is the scale of adjustable nodes. M is the scale of target AC lines.

This problem has the solution under the condition of the partial derivative of equation $L = \sum_{i=1}^{N} \alpha_i \cdot \Delta P_i^2 + \sum_{j=1}^{M} \lambda_j \cdot \left(\sum_{i=1}^{N} K_{ji} \cdot \Delta P_i - \Delta P_{li}\right)$ are zero on ΔP_i and λ_j, namely:

$$\begin{cases} \frac{\partial L}{\partial \Delta P_i} = 2\alpha_i \Delta P_i + \sum_{j=1}^{M} \lambda_j \cdot K_{ji} = 0 & i = 1, \ldots, N \\ \frac{\partial L}{\partial \lambda} = \sum_{i}^{N} K_{ji} \cdot \Delta P_i - \Delta P_{ij} = 0 & j = 1, \ldots, M \end{cases} \tag{3}$$

For the node voltage, first to select the adjustable node according to the sensitivity relationships between the voltage of main network node and the reactive of low voltage network node. Then, according to the length of the steps, the reactive load of low voltage network load node is adjusted by quadratic programming algorithm. Finally, the active flow is verified after successfully matched the voltage.

4 Wind Farm Equivalent

According to the measured data of wind farm, static model parameters, protective parameters of wind power generator, terminal transformer parameters and other relevant data information are used to group wind turbines. Then, wind turbines will be grouped according to on-off state, type of wind power generator, rated active, dynamic model parameters, protective setting value, active power and pitch angle. All wind power generators and their corresponding terminal transformers will be divided into several teams. Each team contains several groups, and every group contains several wind power generators. The rated active, upper limit and lower limit of active power, active power, reactive power and other parameters of equivalent wind power generator and equivalent transformer are calculated to meet the requirements of online security and stability analysis.

4.1 Wind Farm Parameters

The real-time information of wind power generator in all wind farms, static model parameters, protective parameters, terminal transformer parameters and other information are obtained by external system.

According to the reasonable range of the equipment parameters, the rationality check for the obtained data is carried out combined with the Expert System judgement based on the above information. The error existed in the data and the suspicious data are corrected.

4.2 Wind Power Generator Grouping

According to the topological connection relationships between wind power generator and feeder, the wind power generators and terminal transformers in wind farm are divided into several teams. The wind power generators in each team are grouped according to on-off state, type of wind power generator, rated active, stable parameters, protective setting value, active power and pitch angle in turn. The achievement steps are shown as below:

1. The wind power generators in wind farm are grouped by the topological connection relationships between wind power generator and feeder. The wind power generators connected to the same feeder are divided into the same team.
2. The terminal transformers in wind farm are grouped by the topological connection relationships with the feeder. The terminal transformers connected to the same feeder are divided into the same team.
3. The wind power generators in all teams are grouped by the on-off situation, the power-on wind power generators are divided to the same group. The power-off wind power generators are divided to another group.
4. The wind power generators in all groups are grouped by the types of wind power generators (including constant speed, double feeder and direct drive). The same type wind power generators are divided to the same group.
5. According to the rated active of all wind power generators, the wind power generators with the same or similar rated active (rated active is within $\pm$ 5% is regarded as similar) are furtherly divided to the same group.
6. According to the stable parameters of wind power generators, the ones with the same stable parameters are furtherly divided into the same group.
7. According to the protective setting value of wind power generator. The ones with the same protective setting values are furtherly divided into the same group.
8. For the groups with double feeder or direct drive type, according to the active power of wind power generator, the wind power generators in groups are furtherly divided into 3 groups within three ranges (active power is between 0 and P_{set}, active power is between P_{set} and 1.0 pu, active power is equal 1.0 pu). P_{set}(using per unit) is the presetting active power threshold, which is set by the engineering's practical requirements.
9. Aim at the groups with double feeder or direct drive type, and active power is 1 pu, the wind power generators in groups are furtherly divided into 3 groups within three ranges (pitch angle is lower than the rated minimum $\beta_{\min}$, pitch angle is larger than the rated maximum $\beta_{\max}$, pitch angle is between rated minimum $\beta_{\min}$ and rated maximum $\beta_{\max}$).

In 5–9 grouping process, if the number of groups is larger than $N_{\max}$ after grouping, grouping will be stopped in this step. $N_{\max}$ is the presetting maximum grouping number, which is set by the engineering's practical requirements.

4.3 Wind Power Generator Equivalent

According to the grouping result, the wind power generator in each group is equivalent to an equivalent wind farm generator. Then the parameters of all equivalent generators and equivalent terminal transformers are worked out.

The rated active, active maximum, active power, reactive power, wind generator number of equivalent generators, as well as the rated capacity of equivalent transformer all can be obtained by Formula (4) polymeric single generator or transformer. The rated capacity of a single wind power generator is solved by formula (5). $P_{eq,nom}$, N_{eq} are respectively the rated active of equivalent generator and the quantity of wind power generator. The active lower limit, reactive upper and lower limit of equivalent generator are all solved by formula (6). $k_{p\min}$, $k_{q\max}$, $k_{q\min}$ are respectively the active lower limit coefficient, reactive upper limit coefficient, reactive lower limit coefficient. The resistance, reactance of equivalent transformer are equal to the parallel resistance, reactance of the operating transformers in the team. The conductance, susceptance of equivalent transformer are equal to the parallel conductance, susceptance of the operating transformers in the team.

$$x_{eq} = \sum x_i \tag{4}$$

$$P_{nom} = P_{eq,nom}/N_{eq} \tag{5}$$

$$\begin{cases} P_{\min} = k_{p\min} \cdot P_{eq,nom} \\ Q_{\max} = k_{q\max} \cdot P_{eq,nom} \\ Q_{\min} = k_{q\min} \cdot P_{eq,nom} \end{cases} \tag{6}$$

After finished the above equivalent processes, the measured result of the original output wind farm is replaced by the equivalent wind farm model parameters, which are used for online security and stability.

5 Case Verification

A certain wind farm in the state estimation data is equivalent to a 35 kV load, the power is 1.1383 + j0 MVA. With 12 wind farm generators in total in wind farm, the topological relationship is shown in Fig. 1.

Parameters (known value) of every transformer are R = 0.23, X = 4.6. No. 1–7 wind power generators are stopped, and the measured value of others are shown in Table 1.

According to the wind farm equivalent methods as stated in Sect. 4 of this paper, all the wind power generators in this wind farm can be divided into 3 groups. The generators within the dotted circle in Fig. 1 are the same group. The equivalent topological diagram is shown in Fig. 2, and the power of all equivalent machines

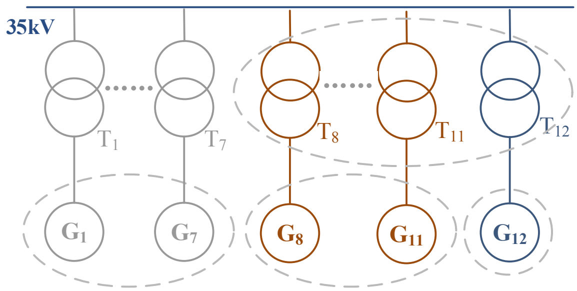

Fig. 1 Grouping for the generators in a certain wind farm

Table 1 Measured value of all wind power generators

Generator number	Measured value (MVA)
8	0.16 + j0.03
9	0.33 + j0.07
10	0.248 + j0.05
11	0.315 + j0.06
12	1.478 + j0.3

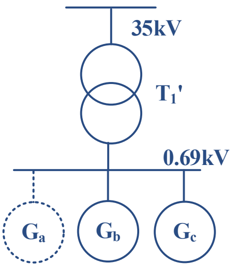

Fig. 2 Equivalent topological diagram

are shown in Table 2. The parameters (known value) of equivalent transformer are $R = 0.046$, $X = 0.92$.

At last, according to the methods stated in Sect. 3 of this paper, adjust the boundary branch flow and node voltage to the target values. The adjusted result is shown in Table 2. Therefore, the online equivalent of this wind farm is achieved.

Based on the practical power grid, the large-scale wind power online equivalent method is verified by the following cases:

Case 1: Disregard wind farm model, wind farm is equivalent in high voltage side bus;
Case 2: Regard wind farm model, large-scale wind farm is equivalent online according to the methods as stated in this paper.

When the area near a certain wind farm has the fault, the comparative curve of 330 kV bus voltage is shown in Fig. 3, and the active and reactive power curves of outgoing AC line are shown in Fig. 4 and in Fig. 5 respectively.

Table 2 Power flow of equivalent generator

Generator number	After equivalent (MVA)	After adjustment (MVA)
A	0 + j0	0 + j0
B	1.054 + j0.214	0.508 − j0.168
C	1.478 + j0.3	0.631 + j0.168

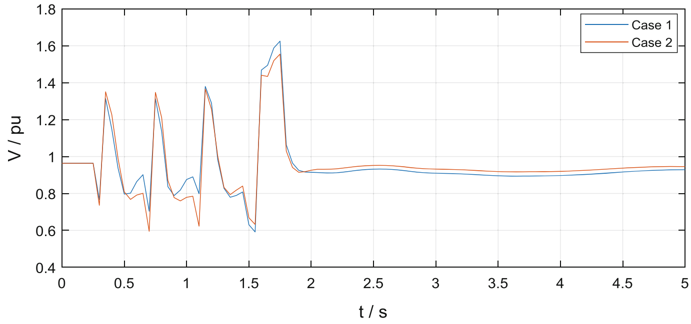

Fig. 3 Bus voltage curve after the fault

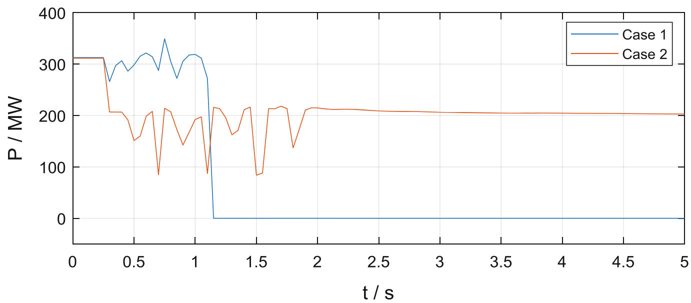

Fig. 4 AC line active curve after the fault

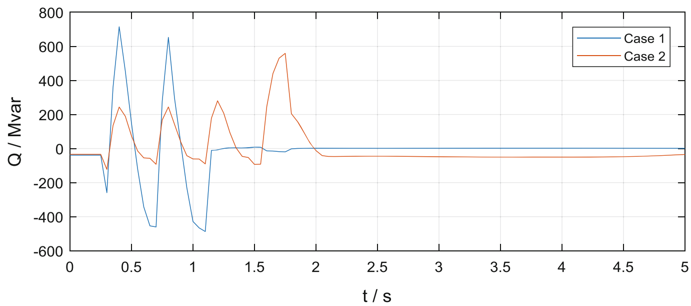

Fig. 5 AC line reactive curve after the fault

In case 2, after the area near the wind farm has the serious fault, the related new energy generators are offline due to the control measures. Due to case 1 hasn't the detailed wind farm model, the capacity is more different from the practical result when it simulated the new energy generator to be offline. The simulation comparison result shows that the equivalent model after online considered the large-scale wind farm can reflect the operation state of the practical power grid more accurately.

6 Conclusion

This paper put forward an online equivalent method of large-scale wind power based on multi-source data fusion. For the state estimation modeling network, multisource data from security and stability control system, PMU, SCADA are integrated to improve the accuracy of the data. According to the real measurement acquired by the centralized control system of wind farm and the forecast information of wind power forecast system, the active power of all wind farms is adjusted by quadratic programming model. The network scale is greatly reduced for simulation calculation by the wind farm equivalent to meet the requirements of online security and stability. The operation result of the practical power grid verified the accuracy and feasibility of this method.

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