A Schedule Power Flow Generating Method Based on State Estimation

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Abstract. Generating schedule power flow rapidly and accurately is an important step in security checking. In consideration of poor convergency property and calculating speed of conventional methods based on power flow calculations, this paper proposes a schedule power flow generating method based on state estimation to calculate schedule power flow. Pattern recognition is used to select similar section by comparing planned data and historical power flow to take the power flow of similar section as redundant measurements of state estimation. In state estimation calculation with transmission power constraints based on maximum correntropy criterion, measurements corresponding to generation schedule, load forecasting and maintenance schedule are assigned large weights. The schedule power flow calculated by the method could satisfy planned data conditions and transmission power constraints. Cases of IEEE 9-bus system and a practical power grid verify the effectiveness and calculating accuracy of the method.

1. Introduction
Schedule power flow is the basis of security checking of generation schedule, maintenance schedule and dispatching operation for planning personnel and dispatchers. The accuracy of schedule power flow is fatal to grasp the weak links in power grid operation in the future accurately and ensures the security and economic efficiency of planning. The generation of schedule power flow is the key of the function realization of security checking.

The schedule power flow should have the following characteristics [1]:

(1) The schedule power flow should satisfy the planned data conditions including maintenance schedule, generation schedule and load forecasting as accurately as possible.

(2) Interface transmission power flow should satisfy the planned value accurately to avoid the calculating error of a region transmitting to other regions, so that the schedule power flow of regions can be calculated independently.

(3) If the planned data are incomplete, the schedule power flow should be calculated according to principles in practical power grid operation, in order to make the schedule power flow close to the real power flow.

The methods of schedule power flow generating are all based on power flow calculation at present:
The method based on data integration and power flow adjustment is the basic method of schedule power flow generating [2, 3]. The method integrates planned data, network models and historical power flow to generate the complete power flow that meets the dispatching schedule. By invoking power flow calculation program, the method adjusts the unbalanced active and reactive power and generates schedule power flow which is convergent and satisfies the operation constraints. However, the convergence property cannot be ensured because it's affected by the initial value of power flow calculation.

The optimization method based on interior point algorithm divides the schedule power flow generation into active power optimization and reactive power optimization [4]. The method balances the unbalanced active power flow among planned data in active power optimization, and solves the distribution of reactive power which satisfies the system power loss minimization condition in reactive power optimization. Optimization problems are both solved by interior point algorithm, and also have convergence difficulty.

The power distribution method based on interfaces controlling improves the conventional power flow equations and controls transmission power by appointed generators [5]. The method approaches planned active power step by step, and proposes several schemes of generation redistribution according to unbalanced power. However, the scheme of generation redistribution which is made artificially may be different from distribution mode of real power flow, so the accuracy of schedule power flow may not be high.

This paper presents a schedule power flow generating method based on state estimation. Similar section flow is searched by pattern recognition as the initial value of state estimation calculation to ensure the convergence of the method. The state estimation based on maximum correntropy criterion considering interface transmission power constraints is used to generate the schedule power flow, which is close to planned data. IEEE-9bus system and a practical power grid are used to validate the applicability of the method.

2. Method Design
The method presented in the paper solves two key issues.

The first issue is how to make the interface transmission power in schedule power flow satisfy planned data constraint accurately by state estimation calculation. Interface transmission power constraint is a quadratic equality constraint. Conventional methods which solve zero injection constraints problems such as modified Newton methods are not applicable [6]. Large weight method cannot make the constraints satisfied accurately. Lagrange multiplier method is weak in computational complexity and numerical stability [7]. This paper presents state estimation calculation considering interface transmission power constraints to make the constraints satisfied accurately and efficiently.

The second issue is how to make the schedule power flow close to the power flow in practical system. Current method to adjust unbalanced power is to make a scheme of generation redistribution artificially, but different regional power grids should have different and more precise power flow redistributions [1]. This paper presents a search method based on pattern recognition to search similar section flow in planned data from flows of historical sections, which is used to be the initial value of state estimation calculation. The method helps to make a scheme of power redistribution, which embodies the regional power flow distribution characteristics and makes the calculation results close to the power flow of practical system.

The flow diagram of the method is shown in Figure 1:

1. Search for similar section flow: Search similar section flow in planned data from flows of historical sections.
2. State estimation calculation: Planned data and part of similar section flow are used to be measurements of state estimation calculation to calculate a balance schedule power flow, in which transmission power flow constraints are satisfied accurately and nodes’ injection and outflow power are close to generation schedule and load forecasting.
3. Search for Similar Section Flow

Current methods to generate schedule power flow are weak in convergence of calculation applying in large-scale power system, because the differences between initial value of power flow calculation and actual value affect the convergence property seriously. This paper uses state estimation calculation to generate schedule power flow. Due to redundant measurements, state estimation calculation is easier to converge. However, the errors of initial value of state estimation calculation can also affect the convergence property and accuracy.

The target of searching for similar section flow is to find the most similar section flow in planned data and network topology, and to take the similar section flow as measurements of state estimation calculation.

3.1. Method of Calculating Similarity Index

The similarity among sections is divided into network topology similarity and planned power flow similarity. Network topology similarity shows the similarity in line maintenance schedule between the planned section and historical sections. Planned power flow similarity shows the similarity between generation schedule, load forecasting of planned section and corresponding power flow of similar sections.

In order to calculate network topology similarity, practical power grids are abstracted into undirected graphs. Buses in network are abstracted into nodes, and branches in network are abstracted into sides. Adjacency matrixes of planned section and historical sections can be calculated based on line connectivity and line maintenance schedule. Calculating formula for network topology similarity is shown in Formula 1, the smaller \( \text{sim}(A, B) \) is, the more similar the planned and similar sections are.

\[
\text{sim}(A, B) = |A - B| = \text{tr}[(A - B) \cdot (A - B)^T]
\]  

In Formula 1, \( A \) means the adjacency matrix of similar section, \( B \) means the adjacency matrix of planned section.
Planned power flow similarity shows the degree of similarity between planned data of planned section and corresponding power flow of similar sections. Calculating formula for planned power flow similarity is shown in Formula 2, the smaller \( \text{sim}(p_{sc}, p_{si}) \) is, the more similar the planned and similar sections are.

\[
\text{sim}(p_{sc}, p_{si}) = \sum_{i \in S} (p_{sc}(i) - p_{si}(i))^2
\]  

(2)

In Formula 2, set \( S \) means the set of buses given planned data, \( p_{si} \) means planned power, \( p_{sc} \) means actual power of corresponding buses in historical sections.

Calculating formula for similarity index is shown in Formula 3.

\[
\text{sim} = k \cdot \text{sim}(A, B) + \text{sim}(p_{sc}, p_{si})
\]  

(3)

In Formula 3, \( k \) means the weight of network topology similarity. Convergence property and accuracy of calculation are more affected by network topology similarity than planned power flow similarity. Accordingly, the weight is used to choose the more similar section in topology first.

3.2. Selection Methods of Similar Section

Selection methods include single-time section selection and similar day selection.

In single-time section selection method, the similar section is chosen by comparing the similarity indexes of planned section and historical single-time sections. Operation mode of power grid varies periodically in a day. Different generations and loads also vary differently in a day. Thus, the search scope of single-time section selection method is too large, and the computing efficiency is low.

In similar day selection method, similarity indexes of time sections in a day are summed up to show the similarity of days. After comparing the similarity indexes of planned day and historical days, the corresponding time section of the most similar day is chosen to be similar section. Similar day selection method conforms to the periodic change regulations of power grid operation. The computing efficiency of the method is higher, which could apply to the calculation of day-ahead schedule power flow.

4. State Estimation Calculation

The target of state estimation calculation is to generate schedule power flow which satisfies interface transmission power constraints and is close to planned data based on generation schedule, load forecasting, maintenance schedule and power flow of similar section.

The state estimation is based on robust estimation with interface transmission power constraints. Large weights are assigned to measurements which correspond to generation schedule and load forecasting, in order to make schedule power flow close to planned data.

Part of power flows of similar section and active and reactive power of buses given planned data are regarded as measurements. Measurement equations are set up to make robust estimation generate balanced schedule power flow which satisfies planned data conditions.

4.1. State Estimation Based on Maximum Correntropy Criterion

State estimation based on maximum correntropy criterion uses the definition of correntropy in the field of information science. Correntropy describes the mutual information of measurements and estimates, and is taken as the objective function of state estimation. State estimation based on maximum correntropy criterion is able to reject gross error [8].

Definition formula of correntropy is shown in Formula 4.

\[
I = \frac{1}{m} \sum_{j=1}^{m} K(z_j - h_l(x))
\]  

(4)
In Formula 4, $I$ means correntropy, $m$ means the number of measurements, $z_i$ means measurements, $h_i$ means estimates, $K$ means kernel function.

Expression of correntropy is shown in Formula 5, if the Gauss Kernel Function is used as the kernel function.

$$I = \frac{1}{\sqrt{2\pi m\sigma^2}} \sum_{i=1}^{m} \exp\left(-\frac{(z_i - h_i(x))^2}{2\sigma^2}\right)$$ (5)

In Formula 5, $\sigma$ means kernel width.

Calculating formula for optimal kernel width value based on Silverman principle is shown in Formula 6, if the measurements follow normal distribution.

$$\sigma_{opt} = \left(\frac{4}{2n+1}\right)^{1/(n+4)} \times m^{-1/(n+4)} \times \delta$$ (6)

In Formula 6, $n$ means the number of states, $\delta$ means the standard deviation of measurements. When $n$ is large,

$$\sigma_{opt} \approx \delta$$ (7)

Objective function of state estimation based on maximum correntropy criterion is shown in Formula 8.

$$\min_x f(x) = \left[1 - \sum_{i=1}^{m} \exp\left(-\frac{(z_i - h_i(x))^2}{2\sigma^2}\right)\right]$$ (8)

State estimation based on maximum correntropy criterion can reject gross error, because measurements can affect the value of objective function significantly only if the residual error is in certain range, which is decided by kernel width and the properties of Gauss Kernel Function.

Robust estimation is used to assure the accuracy of calculation when the similar section and planned section are not similar enough, and to avoid that calculated schedule power flow is closer to the power flow of similar section than planned section.

4.2. Special Processing Method for Planned Data Constraints

Large weights are assigned to measurements which correspond to generation schedule and load forecasting, including active and reactive power of buses. When a measurement is assigned large weight, the estimation residual error will be small, and the calculated schedule power flow will be closer to generation schedule and load forecasting.

Calculating formula for line transmission power is shown in Formula 9.

$$P_{ij} = v_i^2 g - v_i v_j g \cos \theta_{ij} - v_i v_j b \sin \theta_{ij}$$ (9)

In Formula 9, $g$ means line conductance, $b$ means line susceptance.
To make the interface transmission constraints satisfied accurately with numerical stability, this paper uses special processing method for calculating state of buses with line transmission constraint on one side.

In the process of iterating state values in state estimation, the value of state \( v_j \) is calculated by \( P_{ij}, v_i, \theta_i \) and \( \theta_j \) based on Formula 9, instead of adding \( \Delta x \) solved by normal equations. This is an effective method to make the interface transmission constraints satisfied accurately.

The special processing method can affect the convergence property of state estimation calculation. Thus, the value of state \( v_j \) should be excluded from the termination conditions of iteration, so that the equations can converge to a solution efficiently.

5. Cases and Analysis of Results

5.1. IEEE 9-Bus System Case

This paper uses IEEE 9-bus system case to confirm the effectiveness of state estimation based on maximum correntropy criterion. BUS2 and BUS3 are buses given generation schedule. BUS5, BUS6 and BUS8 are buses given load forecasting. The line between BUS7 and BUS8 is transmission interface 1. Maintenance schedule is not considered.

Other 20 measurements of state estimation are bidirectional active and reactive power between BUS2 and BUS7, bidirectional active and reactive power between BUS5 and BUS7, bidirectional active and reactive power between BUS4 and BUS6, active and reactive power from BUS8 and BUS7, active and reactive power from BUS9 and BUS3, active and reactive power from BUS4 and BUS1.

Similar day selection method is used in the case. Historical power flows of 60 days per hour are generated by creating two kinds of generation curve for BUS2 and BUS3 and three kinds of load curve for BUS5, BUS6 and BUS8. Random deviations are added on the curves to generate historical generation power, load power and power flow. Generation schedule and load forecasting of planned day are set in the same way to select similar day. Transmission power constraint can be calculated by power flow calculation.

Results of state estimation using power flow of the similar section in similar day are shown in Table 1.

| Measurement                  | Similar Section Power Flow/MW | Planned Data/MW | Result of State Estimation/MW | Absolute Error/MW |
|------------------------------|-------------------------------|-----------------|------------------------------|------------------|
| Active generation of BUS2    | 159.00                        | 157.06          | 157.17                       | 0.11             |
| Active generation of BUS3    | 137.32                        | 146.14          | 145.79                       | 0.35             |
| Active load of BUS5          | 155.21                        | 166.89          | 165.60                       | 1.29             |
| Active load of BUS6          | 153.67                        | 159.74          | 159.68                       | 0.06             |
| Active load of BUS8          | 63.60                         | 63.00           | 62.39                        | 0.61             |
| Active power of Transmission interface 1 | 40.10                      | 34.99           | 34.99                        | <0.01            |

The results in Table 1 show that the error of active power of transmission interface 1 is less than 0.01MW, and the errors of active power of buses with generation schedule or load forecasting are all less than 1.29MW. Absolute errors and error rates of other measurements in state estimation are slightly higher than power of buses with generation schedule or load forecasting. Absolute errors of other measurements are all less than 3MW (/Mvar), and average of error rates of other measurements is 5.61%.

The results confirm that the schedule power flow generated by the method can satisfy interface transmission power constraints accurately and is close to other planned data.
5.2. A Practical Power Grid Case
This paper uses a practical power grid case to confirm the effectiveness of the method proposed in the paper. Planned section is 15:00 on 29 October 2018. Injection and outflow power of buses in the results of state estimation of planned section are taken as generation schedule and load forecasting. Computing elements include 106 500kV buses, 239 AC lines, 233 transformers, 76 generators and 88 reactive compensators.

183 hourly sections a week before planned section (0:00 on 22 October 2018 to 14:00 on 29 October 2018) are taken as historical sections. Corresponding results of state estimation calculation are taken as historical power flow. Single-time section selection method and similar day selection method are both used to select similar section. Similar section selected by single-time section selection method is 11:00 on 26 October 2018. Similar section selected by similar day selection method is 15:00 on 28 October 2018.

State estimation calculation program is run to generate schedule power flow based on power flow of similar section and planned data. Results of qualified rates of voltages and power flow of buses and branches are shown in Table 2. If absolute error is less than 10MW (/Mvar) or error rate is less than 5%, the injection or outflow power of the bus is qualified. If absolute error is less than 15MW (/Mvar) or error rate is less than 10%, the power flow of the branch is qualified. If error of voltage amplitude is less than 0.05p.u., the voltage is qualified.

| Selection Method            | Qualified Rate of Buses | Qualified Rate of Branches | Qualified Rate of Voltages |
|-----------------------------|-------------------------|---------------------------|---------------------------|
| Single-time section selection | 87.13                   | 70.86                     | 87.73                     |
| Similar day selection       | 95.28                   | 84.21                     | 99.05                     |

Qualified rates of buses are higher than qualified rates of branches evidently because of large weights. Qualified rates in similar day selection method are higher than qualified rates in single-time section selection method. Comparing with basic methods based on several times of power flow calculation, the method proposed in the paper has higher computing speed, in which state estimation is performed for only one time. The qualified rates confirm that the schedule power flow generated by the method satisfies planned data conditions with high accuracy.

6. Conclusion
Generating schedule power flow rapidly and accurately is important basis of security checking. This paper proposes a schedule power flow generating method based on pattern recognition and state estimation. Similar section is selected by pattern recognition to obtain redundant measurements. State estimation is performed to calculate the states and power flows of planned section by assigning large weights to measurements corresponding to generation schedule and load forecasting. The method has advantages on convergence property and computing speed. The cases of IEEE 9-bus system and a practical power grid verify the accuracy and effectiveness of the method.

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