A Chain-table Storage Structure Based Forward/Backward Sweep Method for the Power Flow Calculation in a Distribution Network with DFIG Wind Generators and Battery Energy Storage Systems

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Abstract. In this paper, a chain-table storage structure based forward/backward sweep (FBS) method is proposed to calculate the power flow distribution of a distribution network (DN) with DFIG wind generators and battery energy storage systems (BESSs). It is one of the key techniques for solving the problem of optimal charging/discharging scheduling of BESSs. With the consideration of DFIG wind generators and BESSs, the general node model is presented and the chain-table based storage structure is used to storage radial DNs with less memories. Further, the reactive power compensation strategy of PV wind generators is proposed and integrated into the primary FBS method. Finally, the modified PG&E 69 node distribution system is used to conduct the simulation experiments. Experimental results prove that the proposed method owns excellent performances.

Introduction

Nowadays, a number of DFIG wind generators are connected into distribution systems. As a result, the penetration level of renewable energy sources is very high [1]. Meanwhile, a number of expensive battery energy storage systems (BESSs) are installed to mitigate the fluctuations of wind powers [2-3]. In order to fully exploit the potentials of BESSs, the optimal charging/discharging scheduling needs to be calculated out in advance [4-5]. Solving this problem needs a number of key techniques one of which is the power flow calculation method for a DN with DFIG wind generators and BESSs.

In the past twenty years, a number of power flow methods are presented to calculate the power flow in DNs. Among them, Forward/backward Sweep method is regarded as the most promising method for its special virtues [6]. However, the traditional FBS method mainly focuses on radial DNs. In order to use this method to various distribution networks, many improvements are proposed [7-8], including memory structure, compensation strategy, and so on. However, for the integration of wind generators, BESSs and other distributed generators, further improvements are still necessary.

This paper focuses on the chain-table storage structure based BFS method for the power flow calculation in a DN with wind generators and BESSs. The main contributions include the chain-table based memory structure, the reactive power compensation strategy of PV wind generators and the improved two-loop BFW method. The reminder of this paper is arranged as follows. First, the chain-table based memory structure is designed. Further, the strategy of compensating the reactive powers of DFIG wind generators is proposed and integrated into the final improved power flow calculation method. Finally, numerical experiments are conducted and the main contributions of this paper are summarized.

Memory Structure Design for the Storage of a DN with Wind Generators and BESSs

With the integration consideration of wind generators and BESSs, each node in a distribution network is summarized as a general node as shown in Fig. 1. In Fig. 1, ‘CurrentNode’ denotes the current node, which owns a number of property elements, such as ‘ParentNode’, ‘ChildNode 1’, ‘ChildNode 2’, ⋯, ‘ChildNode NH’, ‘LOAD’, ‘DG’, and ‘BESS’. Here, DG denotes various distributed generators, such as wind generators, photovoltaic batteries, and so on. The technology of structure is exploited to model the general node. By property elements ‘ParentNode’, ‘ChildNode 1’, ‘ChildNode 2’, ⋯, and ‘ChildNode NH’, the parent node of ‘CurrentNode’ and all of its children nodes are
searched, respectively. Meanwhile, the chain-table technology is used to design the memory structure for the storage of the whole DN. With the address mapping relationship among all nodes, the tree-shape storage area, which structure is referred to [7], is set up.

**The Improved BFS Power Flow Method**

Here, the BFS method is chosen to calculate the power flow during a transition time interval. During a time interval, the current of a BESS is constant and it is dominated by two different statuses of capacity (SOC), namely, starting status and ending status. The SOC status is chosen as the control variable for the optimal charging/discharging scheduling of a BESS. Here, the wind generators are assumed to run in PV node mode.

**BESS Charging/Discharging Power Calculation during a Certain Transition Time Interval.**

With the consideration of capacity constraint of a BESS, the SOC variable is chosen to constitute the control vector. The charging/discharging power of a BESS is denoted as the function of two SOC variables, namely, the end status $SOC_{t+1}$ and the starting status $SOC_t$ of this transition stage. Hence, the BESS charging/ discharging power $P_{BESS,t}$ is represented as follow.

\[
\Delta SOC_t = SOC_{t+1} - SOC_t
\]

(1)

\[
P_{BESS,t} = \frac{\Delta SOC_t}{\Delta t}
\]

(2)

Here, $\Delta SOC_t$ denotes the difference of the two SOC statuses corresponding to two moments, namely, the time moment $t$ and the time moment $t + 1$. $\Delta t$ is the length of the transition time interval. Here, the transition stage is regarded as a constant power charging/discharging procedure.

**Reactive Power Compensation Strategy of PV Wind Generators.** For a wind generator running in PV node mode, the difference between the potential set value of this wind generator and the real voltage of the node, where this generator is installed, doesn’t always equal to zero at the end of each sweep step in a primary BFS method. In order to remove this difference, the reactive power outputs of DFIG wind generators need to be compensated. Here, the number of wind generators is assumed to be $N$. Based on superposition theorem and KCL law, the following equations are set up [8].

\[
\begin{bmatrix}
\Delta \vec{E}_1 \\
\Delta \vec{E}_2 \\
\vdots \\
\Delta \vec{E}_N
\end{bmatrix} =
\begin{bmatrix}
Z_{11} & Z_{12} & \cdots & Z_{1N} \\
Z_{21} & Z_{22} & \cdots & Z_{2N} \\
\vdots & \vdots & \vdots & \vdots \\
Z_{N1} & Z_{N2} & \cdots & Z_{NN}
\end{bmatrix}
\begin{bmatrix}
\Delta \vec{i}_1 \\
\Delta \vec{i}_2 \\
\vdots \\
\Delta \vec{i}_N
\end{bmatrix}
\]

(3)

Here, $\Delta \vec{E}$ is a $N \times 1$ vector and it includes $N$ voltage mismatches of PV wind generators. $\Delta \vec{i}$ is also a $N \times 1$ vector and it includes $N$ current deltas of PV wind generators. $Z$ is a $N \times N$ impedance matrix and its diagonal element $Z_{ii}$ is the impedance sum of the circuit from wind generator $i$ to the root node, and its non-diagonal element $Z_{ik}$ is the sum of common impedances between the circuit from wind generator $i$ to the root node and the circuit from wind generator $j$ to the root node.

For simplification, (3) is represented as follow.

\[
\Delta \vec{E} = Z \Delta \vec{i}
\]

(4)

Further, (4) is transformed into the following equation.

\[
\Delta \vec{i} = Z^{-1} \Delta \vec{E} = Y \Delta \vec{E}
\]

(5)

Here, $Y$ is represented in detail as

\[23\]
In matrix $Y$, each element can is represented as

$$Y_{ik} = G_{ik} + jB_{ik}$$

As a result, $\Delta I_i$ is described as

$$\Delta I_i = \sum_{k=1}^{N} Y_{ik} \Delta E_k$$

At the same time, by the automatic voltage controller installed for each PV wind generator, the potential phase of each PV wind generator naturally equals to the voltage phase at the node connected with the wind generator denoted by $\theta_k$. Hence, $\Delta E_k$ is represented as follow.

$$\Delta E_k = (E_k - U_k) \angle \theta_k$$

From (8) and (9), the current delta of wind generator $i$ is represented as

$$\Delta I_i = \sum_{k=1}^{N} (G_{ik} + jB_{ik})(E_k - U_k) \angle \theta_k$$

In order to calculate the reactive power delta of wind generator $i$, $\Delta E_k^* \Delta I_i$ is multiplied to two sides of formula (10). As a result, the following equation is gained.

$$\Delta P_i - j\Delta Q_i = (E_i) \angle (-\theta) \sum_{k=1}^{N} [(E_k - U_k)(G_{ik} \cdot \cos \theta_i - B_{ik} \sin \theta_i) + j(E_k - U_k)(G_{ik} \cdot \sin \theta_i + B_{ik} \cdot \cos \theta_i)]$$

Obviously, $\Delta P_i$ is equal to 0 and the imagine parts of two sides are equal. After the necessary rearrangement, $\Delta Q_i$ is represented as

$$\Delta Q_i = E_i \cdot \sin \theta \sum_{k=1}^{N} (E_k - U_k)(G_{ik} \cdot \cos \theta_i - B_{ik} \sin \theta_i) - E_i \cdot \cos \theta \sum_{k=1}^{N} (E_k - U_k)(G_{ik} \cdot \sin \theta_i + B_{ik} \cdot \cos \theta_i)$$

The total reactive power of PV wind generator $i$ for the $(h+1)$-th outer loop is represented as

$$Q_{i}^{(h+1)} = Q_{i}^{(h)} - \Delta Q_i^{(h)}$$

**Flowchart of the Proposed forward/backward Sweep Method**

When the chain-table based memory structure and the compensation strategy of reactive powers of PV wind generators are integrated into the primary BFS method, the final flowchart for the power flow calculation of a DN with PV wind generators and BESSs is shown in Fig. 2. In Fig. 2, the flowchart includes two-loops, namely, inner loop and outer loop. The primary BFS method is conducted at the inner loop where the reactive power outputs of PV wind generators are fixed. The reactive power compensation of PV wind generators is conducted at the outer loop after an inner loop ends. Rearranging all nodes into the chain-table based memory area is based on the technology of topology identification. Here, the principle of depth priority is adopted. When a distribution network is placed into the chain-table based memory area, the technology of recursive functions is adopted to conduct the forward current sweep calculation, the backward voltage sweep calculation, the result output and so on [8].
Numerical Experiments

Description of Case Distribution System. Here, the modified version of the PG&E 69-node distribution network as shown in Fig. 3 is used to test the performance of the improved FSW method. Four PV wind generators and four BESSs are installed at eight new nodes, namely, 69, 70, 71, 72, 73, 74, 75, and 76, respectively. The eight new nodes are connected into the primary network by eight new lines. The active power outputs of four wind generators are 50kW, 100kW, 100kW, and 400kW, respectively. The charging/discharging powers of four BESSs are 600kW, 100kW, 350kW, and -750kW, respectively. Here, the positive powers mean charging actions while the negative powers correspond to discharging actions. Each BESS or wind generator is equipped with a switch for the linking status control.

Experimental Results. Here, nine scenarios are selected to test the performance of the improved BFS method and the corresponding test results are shown in Table 1. From Table 1, it is seen that the operation of distribution networks has been improved with the integration of BESSs. Usually, the active power outputs of wind generators raise the voltage levels of a distribution network. This causes overvoltage. However, BESSs can both raise and decrease the voltage levels of the relative nodes in a distribution network. By optimal active power outputs of BESSs, the voltage profiles of distribution networks are recovered back into the stipulated ranges. For example, with the discharging power of BESS 3, the lowest voltage is raised to 9573.09 V in Scenario 2 from 9148.67 V in Scenario 1. At the same time, with the charging power of BESS0, the lowest voltage is decreased to 9730.49 V in Scenario 7 from 9730.56 V in Scenario 6.
In order to further show the performance of the proposed method, the voltage profiles of four typical scenarios, namely, S0, S1, S3, S8, are shown in Fig. 4. The red profile is caused by optimal BESS combinations. BESS0, BESS1 and BESS2 are in charging statuses while BESS3 in discharging status. The voltage convergence process at node 53 in Scenario 8 is shown in Fig. 5. Each red rectangle denotes an inner forward/ backward sweep loop corresponding to the same set of given reactive powers of wind generators while each small grid on the lateral axis is a forward/backward sweep step within an inner loop. It is seen that the convergence process is fast and robust. The voltage of node 53 becomes stable after just 1 compensation step of reactive powers of wind generators.

**Conclusions**

In this paper, an improved FBS method is proposed to calculate the power flow of a DN with PV wind generators and BESSs. The main contributions include the chain-table based memory structure for the storage of a DN with wind generators and BESSs, the strategy of compensating the reactive powers of wind generators and the power flow calculation method with two loops. By these three contributions, the size of memory becomes smaller, the number of iteration sweeps is reduced and the convergence of the forward/backward sweep calculation is enhanced.

**References**


