A Novel Approach for Enhancement of State Estimation in Renewable Power System

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Abstract: The traditional power systems are usually centralized systems, in which the control, operation and monitoring are performed by the centralized control center, e.g., SCADA. However, with the development of renewable energy, power systems are getting more and more distributed. So, it becomes necessary to establish the distributed power system operation methods for these power systems. In this research, the distributed techniques for the renewable power systems are proposed based on the consensus protocol technique from graph theory. These techniques cover the three important problems in power systems, i.e., economic dispatch, state estimation, and optimal power flow. First, the Distributed Economic Dispatch (DED) approach is proposed. In this part, both the PI controller and Neural Network (NN) controller are utilized to design the distributed algorithm to minimize the power system's operational cost in a distributed way. The communication- failure-tolerant DED algorithm is proposed to improve the robustness of the approach during communication failure. Also, the DED algorithm considering line loss model is proposed. On the other hand, an information propagation method is provided to develop the Distributed State Estimation (DSE) algorithm. Then, the bad data detection and measurement accuracy improvement topics in state estimation are discussed.

Keywords:, Renewable Energy, Power grid, Wind turbines, Power Flow.

I. Introduction

In recent decades, renewable energy is getting more and more popular, a lot of PV panels and wind turbines are connected to the power grid, in which power generation becomes distributed in modern power systems. With the distributed energy resources (DER) being connected, it is more complex and less efficient to use the traditional centralized control center to coordinate all of these distributed facilities. Therefore, it is necessary to develop a distributed control, operation, and optimization scheme to achieve higher efficiency and better performance in distributed power systems. Then, based on the proposed DED algorithm and DSE algorithm, the Distributed Optimal Power Flow (DOPF) method is developed. Finally, the AC power flow model is considered to build the distributed AC State Estimation method and distributed AC Optimal Power Flow method.

At the end, the proposed methods are verified in the MATLAB/simulation software. The 4-generator system model, IEEE 10-generator 39-bus system model, WSCC 9-Bus system model, and some specially designed power system models are employed in the tests. The results of the simulation show that the proposed methods reach the desired performance. There are several advantages for distributed methods. Because of the distributed characteristic, the distributed system can be more robust, more economical, and higher efficient. For example, in [1], a distributed algorithm for the electricity market is proposed to protect the privacy of load aggregators and generators and to reduce the computational complexity of the centralized approach. This is because that the connectivity of the distributed structure is usually higher than the centralized structure (i.e. star network), and the calculation can be done by a bunch of cheap devices in parallel in a distributed system instead of the expensive control center. Besides these advantages, the development of distributed control system also benefits the conventional centralized power system, since the distributed control system can be implemented as an auxiliary or backup system for the centralized control system to improve the robustness and efficiency of the power system.

In this research, three important topics for power systems will be covered and the distributed solutions for these topics will be proposed. These topics are: Economic Dispatch (ED), State Estimation (SE), and Optimal Power Flow (OPF).

Economic dispatch is an important problem in power systems. The solution of the economic dispatch ensures the power system to be operated under the most economical condition. State estimation is also an important technique for power system operation. It is usually performed by Energy Management System (EMS) [2-4] in control centers to acquire the states of the power system. The major objective of state estimation is to monitor the states of power systems, estimate the unmeasured data, improve measurement accuracy, and detect bad measurements. Optimal power flow is a technique used in power system control centers to achieve optimal operation under certain constraints. Similar to the economic dispatch problem, the OPF schemes minimize the operating cost of power systems. In addition, more power flow related constraints are considered in OPF rather than the simple cost minimization in the ED problem. In this research, the power flow limits on all power lines in the power system will be considered in the OPF problem. Based on the consensus protocol technique [5], the distributed version of the above techniques is realized in this research. They are Distributed Economic Dispatch (DED), Distributed State Estimation (DSE), and Distributed Optimal Power Flow (DOPF). For the DSE and DOPF methods, both the DC version which is developed on the basis of the DC power flow model and the AC version which considers the AC power flow model are introduced in this work.

II. Related Work

Different methods have been proposed to realize the distributed algorithms for different topics in power systems. In this section, the existing methods for distributed economic dispatch, distributed state estimation, and distributed optimal power flow are introduced. The conventional economic dispatch approaches are designed mainly for centralized power systems, in which a centralized control center is needed to calculate the power output reference for each generator. Many different methods have been developed to solve the ED problem in the conventional centralized power system. These methods include Lambda-iteration, gradient methods, Newton's method, and dynamic programming [6]. Since the ED is an optimization problem, the heuristic optimization methods, such as genetic algorithm [7], particle swarm optimization [8], and Neural Network Approach [9], are also applicable for the ED problem. Also, an advanced method like oblivious network design has been employed in [10] to develop the new oblivious routing economic dispatch (ORED) algorithm, in which the economic dispatch can be achieved while managing congestion and mitigating power losses. There are some existing papers for distributed OPF problem. In [29], a distributed OPF algorithm is developed, in which the alternating direction multiplier method (ADMM) is used to decompose the optimization problem into several sub problems. However, in this method, the power system is required to be divided into several areas, and the centralized method is still used within each area. So, the algorithm is not completely distributed. On the other hand, only the local power constraint and voltage limit constraint are considered in [29], but the constraints related to multiple buses, such as line flow constraint, are not discussed. It makes the proposed method in [29] less useful in practice since many important problems in OPF are multi-bus problems, e.g., the line flow constraint and the N-1 contingency problem. Similarly, three Distributed DC Optimal Power Flow (DDCOPF) methods based on ADMM are proposed in [30], in which the power system is also divided into small areas, and the centralized method is also needed within each area. Similarly, the ADMM-based methods are discussed in [31-33]. Since ADMM-based methods require the power system to be partitioned into sub-areas, these methods are not totally distributed methods. According to the existing research discussed in the challenge for the consensus-based distributed economic dispatch is to obtain the power mismatch information in a distributed system and thus satisfy the power balance constraint in the DED problem. However, this problem can be easily solved by control methods. For example, the frequency controller in the peer-to-peer control method [40] is designed to balance the active power in the power system. Based on this concept, the PI controller and Neural Network (NN) controller are employed to develop the DED method. According to the literature review, the existing distributed state estimation methods are not fully distributed. Most of them require area partitioning on the power system. To overcome this drawback, a fully distributed state estimation method without any centralized structure or facility (e.g. SCADA, local control center, or GPS) is proposed in this section so that the state estimation can be realized with only the distributed smart meters. Also, a novel information propagation algorithm is proposed as the basis of the proposed DSE method. The information propagation algorithm can help the smart meters to broadcast their local data to the entire system with a distributed communication network. The proof of the convergence of the proposed information propagation algorithm is provided. In addition, the distributed WLS method for the normal sensor network [5] and the DC power flow model [6] are adopted to develop the DSE method.

III. Preliminary Knowledge

3.1 Some Basic Knowledge from Graph Theory

In a distributed power system, the communication network can be modeled by an undirected graph $G = (V, E)$, where $V = \{v1, v2, \dots, vn\}a$ is the set of vertices in the graph which denotes the n buses in the power system. $E = \{el = \{vi, vj\} \mid vi, vj \in V\}$ is a special subset of $V \times V$ which represents the set of m edges between any two linked vertices in G. The two linked vertices are called "neighbors" to each other.

There are four important matrices from graph theory that will be useful in this research. They are A (adjacency matrix), D (degree matrix), I (incidence matrix), and L (Laplacian). The adjacency matrix $A = [aij]$ for an undirected graph is a $n \times n$ symmetric matrix which describes the adjacency relationships of the vertices in the graph. The element aij at the ith row and jth column of the matrix A is 1 if there is an edge that connects the vertex vi to $(i \neq j)$, i.e. vj is a neighbor of v . Otherwise, aij is zero. Note that the diagonal elements of the adjacency matrix are all zeros since there is no edge to connect a vertex with itself. In a graph, the set of neighbor vertices of a certain vertex vi is defined as the neighborhood set Ni of vertex vi, and the cardinality of the neighborhood set Ni is called the degree $d(vi)$ of vertex vi, which represents the number of vertices connected to vertex vi. Matrix $D = [(vi)]$ is called the degree matrix, in which the elements of the matrix are the degrees of the vertices in the graph. Contrary to the adjacency matrix, the degree matrix only has non-zero elements on its diagonal.

3.2 .Consensus Protocol

Base on the above knowledge, a consensus protocol can be designed for a network system. The consensus protocol can be used for several important applications of power systems. For example, suppose the generators (vertices) in a power system (an undirected graph G) need to calculate (or estimate) a quantity such as the desired incremental cost of the generators. The consensus protocol can help the generators to reach a consensus about the quantity.where "the graph is connected" means that, for every two vertices in the graph, there is at least one path between them. In other words, there are no isolated parts in the graph. (0) is the initial value of xi. $\mathbf{1}$ is a $n \times 1$ vector which all elements are 1, i.e. $\mathbf{1} = [1,1, \ldots ,1]T$. (Lw) is the maximum eigenvalue (in absolute value) of Lw.Therefore, the stability of the consensus protocol (4) in a connected graph can be guaranteed by tuning the weight coefficient wk on each vertex to force the weighted Laplacian Lw to satisfy the Lemma 1.

3.3. Centralized Economic Dispatch

The objective of the ED problem is to calculate the power generation for each generator so that the entire power system works in the most efficient condition. By neglecting the transmission losses, the ED problem is an optimization problem which to minimize the following objective function, in the centralized control center by collecting the generation data from all generators.

3.4. Centralized State Estimation

The Weighted Least-Squares (WLS) is a commonly used method in power system state estimation [6]. Assuming that there is a measurement device to detect a state θ in the system .WLS state estimation is employed to estimate the voltage magnitudes and phase angles on different buses by the noisy measurements of the real power, reactive power, current, transformer tap position, and voltage magnitude [6]. In this research, the work is focused on state estimation using DC power flow analysis. So, the measurements are the real power on each transmission line and the states are the phase angles on different buses. In addition, the estimation can be used to improve the accuracy of the measurements.

3.5. Distributed State Estimation over Sensor Networks

In a distributed network, numerous meters (or sensors) are installed to measure the same quantity in the system. By connecting the meters together to form a sensor network, the redundant measurement can be used to improve the accuracy of state estimation and measurement results.

3.6. Optimal Power Flow Problem

The OPF (optimal power flow) problem is an advanced version of economic dispatch in which it also aims to minimize the cost of the power system meanwhile it does not only consider the power balance between the total load and total generation in the power system but also take the power flow model in consideration to ensure the power is balanced on each bus. In addition, the OPF problem usually has more constraints such as the line flow constraints.

IV. Proposed Methodology

The Based on the preliminary knowledge above, the proposed distributed algorithms for economic dispatch, state estimation, and optimal power flow will be introduced. In the first two sections, the distributed economic dispatch and distributed state estimation based on the DC power flow model will be developed. Then, the distributed optimal power flow method will be established on the basis of the first two distributed methods. In the last two sections, the distributed AC state estimation and distributed ACOPF methods will be presented.

4.1. Distributed Economic Dispatch

According to the existing research discussed in Chapter 2, the challenge for the consensus-based distributed economic dispatch is to obtain the power mismatch information in a distributed system and thus satisfy the power balance constraint in the DED problem. However, this problem can be easily solved by control methods. For example, the frequency controller in the peer-to-peer control method [40] is designed to balance the active power in the power system. Based on this concept, the PI controller and Neural Network (NN) controller are employed to develop the DED method.

The proposed DED control algorithm is summarized in Algorithm 1.

Algorithm 1 The Algorithm on the ith Generator

1: Initialize (0) with an arbitrary value.2:
Set parameters w_{ij}, Kp_i and Ki_i.
3: **for** $k > 0$ **do**
4: Measure the frequency $f_i(k)$ in the grid
5: Receive the Lagrange multipliers $\{(k-1) \mid j \in \mathrm{N}\}$ from neighbor nodes6:
Send the local Lagrange multiplier $\lambda(k-1)$ to the neighbor nodes.
7: Calculate the new Lagrange multiplier (k) by (30)-(32).
8: Calculate the generator reference (k) by (12).
9: Set the output reference of the generator by $P_i^*(k)$.
10: Let $k = k + 1$.
11: end for

Now, let's discuss the convergence of the proposed method. By the control objective, the Lagrange multipliers of all generators should be identical to achieve the economic dispatch. So, in the following paragraphs of this section, the convergence of the Lagrange multipliers under the proposed algorithm will be discussed, i.e., $\lambda 1(k) = \lambda 2(k) = \cdots = \lambda nb(k)$.

4.2. Distributed State Estimation

According to the literature review, the existing distributed state estimation methods are not fully distributed. Most of them require area partitioning on the power system. To overcome this drawback, a fully distributed state estimation method without any centralized structure or facility (e.g. SCADA, local control center, or GPS) is proposed in this section so that the state estimation can be realized with only the distributed smart meters. Also, a novel information propagation algorithm is proposed as the basis of the proposed DSE method. The information propagation algorithm can help the smart meters to broadcast their local data to the entire system with a distributed communication network. The proof of the convergence of the proposed information propagation algorithm is provided. In addition, the distributed WLS method for the normal sensor network [5] and the DC power flow model [6] are adopted to develop the DSE method.

4.3. Distributed Optimal Power Flow

In the proposed distributed OPF method, the power system has two networks: the power network and the communication network. The power network connects the loads and generators with the transmission lines. The communication network links all the generator controllers together and also connects all the smart meters. In addition, each generator controller connects to a smart meter (or, a smart meter can be installed as a part of the controller) to obtain the power flow information. In the proposed scheme, the DSE algorithm runs on the smart meters, and the proposed DDCOPF algorithm is executed on the generator controllers

4.4 .Numerical Simulations

In this section, the proposed DED control scheme is simulated in several different power systems, which are a four-generator power system, an IEEE 39-bus system, and other four power systems with different sizes. The simulations are conducted in Matlab Simulink software. In the first two cases, the normal economic dispatch and frequency control problems are studied. Then, the communication-failure-tolerant consensus protocol is tested in a power system with communication failure. After that, the consensus protocol considering the line loss model is simulated. Finally, a sensitivity analysis for the system size is provided to show the applicability of the proposed method in different power systems.

4.5. Simulation for Distributed AC State Estimation

In this section, the proposed Distributed AC state estimation is tested in MATLAB on IEEE 14-bus system, IEEE 39-bus system, IEEE 118-bus system, and IEEE 300-bus system. In addition, a case study over IEEE 118-bus system with different communication network topology is provided to show the impact of the network structure on the performance of the AC DSE.

Case study on IEEE 14 Bus System

The structure of the IEEE 14 bus system is shown in Figure 4.1. In this system, 17 DSE units are installed on the power lines. The dash lines in the figure are the communication lines that connect the DSE units.

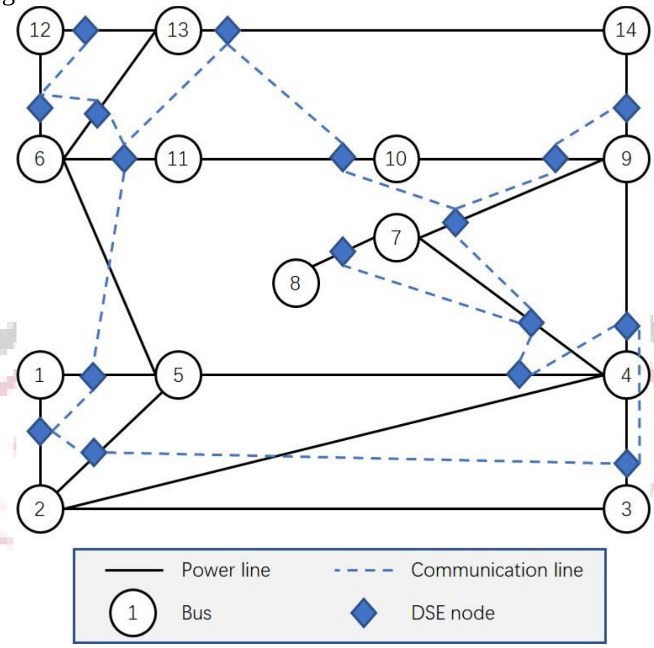

Figure 4.1 The IEEE 14 bus system

4.5. Simulation for Distributed AC State Estimation

The trajectory of the estimated states (the phase angles and voltage magnitudes of the 14 buses) by the proposed AC DSE method is shown in Figure 4.2. The figure shows that the estimated states reach the actual values in about 200 iterations. For the simulation on a PC with Intel Core i7 2.8Ghz CPU and 24GB memory, each iteration takes about 0.001s, so the 200 iterations take about 0.2s which is acceptable compare with the 15 minutes interval between two state estimation in a centralized state estimation method. The proposed AC DSE method is also compared with the traditional centralized state estimation method [6]. The estimated phase angles and voltage magnitudes from node 1 by the proposed AC DSE are compared with the results from the centralized method as shown in Figure 4.3. In the results, the phase angle is in radian and the voltage magnitude is in p.u.. The MSE (Mean squared error) and MAE (Mean absolute error) of each method are listed in Table 4.1

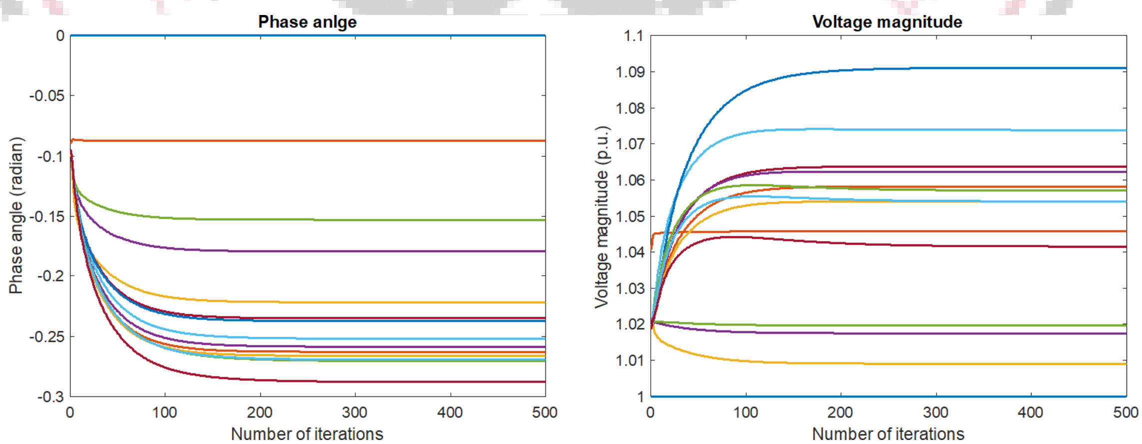

Figure 4.2 The convergence of the AC DSE on IEEE 14 bus system

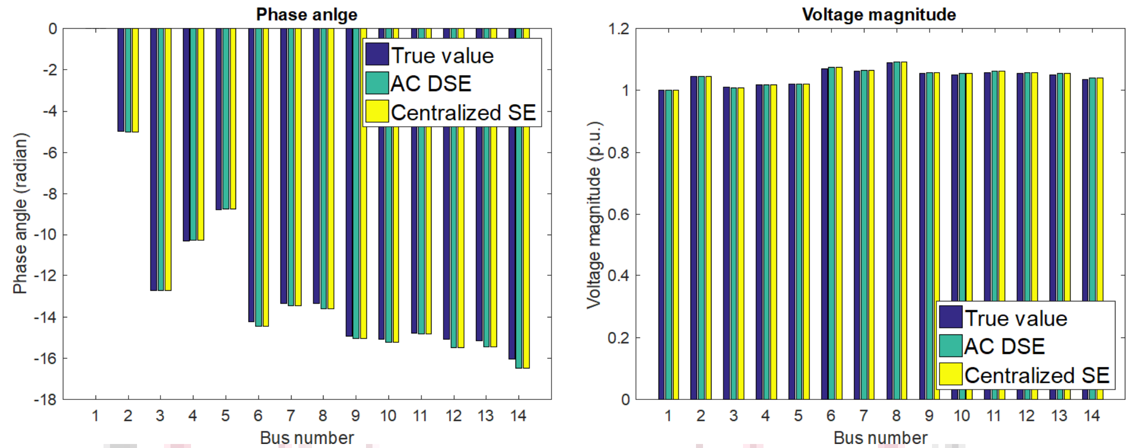

Figure 4.3 Comparison of centralized SE and AC DSE on IEEE 14 bus system

Table 4.1 The Errors of State Estimation Methods on IEEE 14 Bus System

Methods	Centralized SE	Proposed AC DSE	Difference
Phase angle MAE (rad)	0.0016514	0.0016535	0.12716%
Voltage MAE (p.u.)	0.0007402	0.00074041	0.028371%
Phase angle MSE (rad)	4.6457×10^{-6}	4.6579×10^{-6}	0.26261%
Voltage MSE (p.u.)	1.065×10^{-5}	1.0618×10^{-5}	−0.30047%

According to the above results, the accuracy of the proposed AC DSE method is similar to the centralized state estimation method in the IEEE 14-bus system.

4.6. Case Study on IEEE 39 Bus System

The IEEE 39-bus system as shown in Figure 4.4 is adopted in the simulation. There are 46 DSE nodes in the system and the communication network is represented as the dash lines in the figure. The results of this simulation case are listed in Table 4.2.

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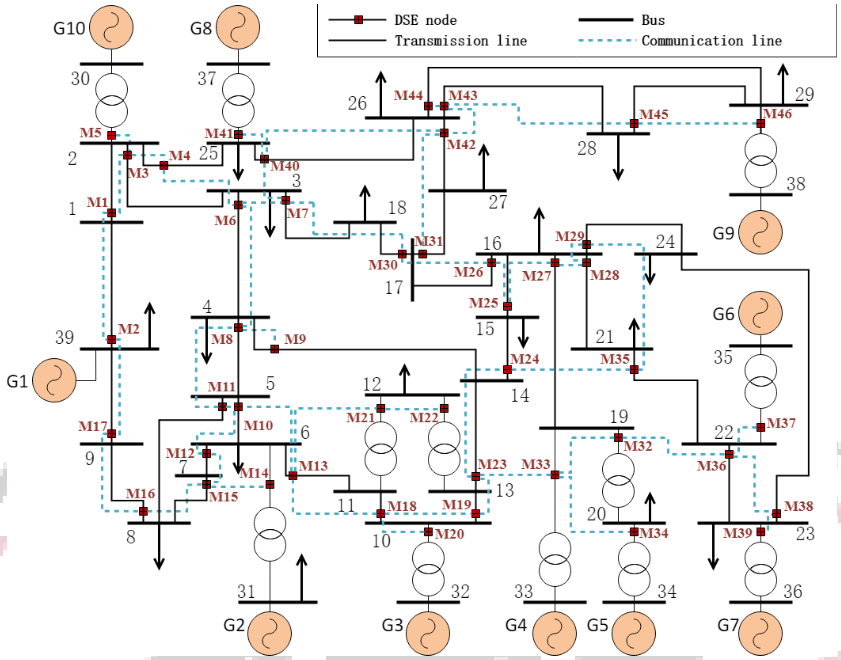

Figure 4.4 The IEEE 39 bus system

Table 4.2 The Errors of State Estimation Methods on IEEE 39 Bus System

Methods	Centralized SE	Proposed AC DSE	Difference
Phase angle MAE (rad)	0.00018428	0.00018409	−0.1031%
Voltage MAE (p.u.)	0.00019664	0.00019667	0.015256%
Phase angle MSE (rad)	5.5541×10^{-8}	5.5518×10^{-8}	−0.041411%
Voltage MSE (p.u.)	5.0927×10^{-8}	5.0954×10^{-8}	0.053017%

4.7. Case Study on IEEE 118 Bus System

To verify the performance of the proposed method in a big power system, the proposed method is also simulated in the IEEE 118-bus power system model. There are 179 DSE nodes in the system. The results are shown in Table 4.3

Table 4.3 The Errors of State Estimation Methods on IEEE 118 Bus System

Methods	Centralized SE	Proposed AC DSE	Difference
Phase angle MAE (rad)	0.0010439	0.0010585	1.3986%
Voltage MAE (p.u.)	0.0007395	0.00073666	−0.38404%
Phase angle MSE (rad)	1.6417×10^{-6}	1.6991×10^{-6}	3.4964%
Voltage MSE (p.u.)	8.2586×10^{-7}	8.2088×10^{-7}	−0.60301%

VI. Result Analysis

According to the results from the different cases above, the errors of the centralized state estimation and the proposed AC DSE are very close. This result confirms that the proposed AC DSE method has similar accuracy as the centralized method. The performance of the DSE method is usually related to the topology of the communication network. In this case study, the IEEE 118-bus system is used to demonstrate the impact of the communication network structure on the convergence of the estimation. Two different communication network structures are investigated in this study:One is chain connection and another is fully connected. The chain connection is that each node connects to its previous node if it is not the first node and connects to the next node if it is not the last node. For example, for the 179 DSE nodes in the IEEE 118-bus system,node 1 connects with node 2, node 2 connects to node 1 and node 3, node 3 connects to node 2 and node 4, and goes on until node 179 only connects to the node 178. On the otherhand, the full connection means that each node connects to all other nodes in the system. The chain connection structure has the fewest communication lines and the full connectionstructure has the most communication lines.

The simulation results of the two communication network structures in the IEEE 118-bus system are shown in Figure 5.1 and Figure 5.2. The figures show the trajectory of the estimated states and the errors of the results. According to the results, the state estimation in the fully connected communication structure is much fast than in the chain- connected system. The chain-connected system spends about 40000 iterations to reach an accurate result, but the fully connected system only takes 30 iterations. Since the chain- connected structure and the fully connected structure are the extreme cases, other communication structures will have the speed between these two results. In addition, although the chain-connected system takes 40000 iterations to reach the acceptable result, the speed of the algorithm can be improved in the real world by properly setting the initial values of the estimated states with the previously estimated results.

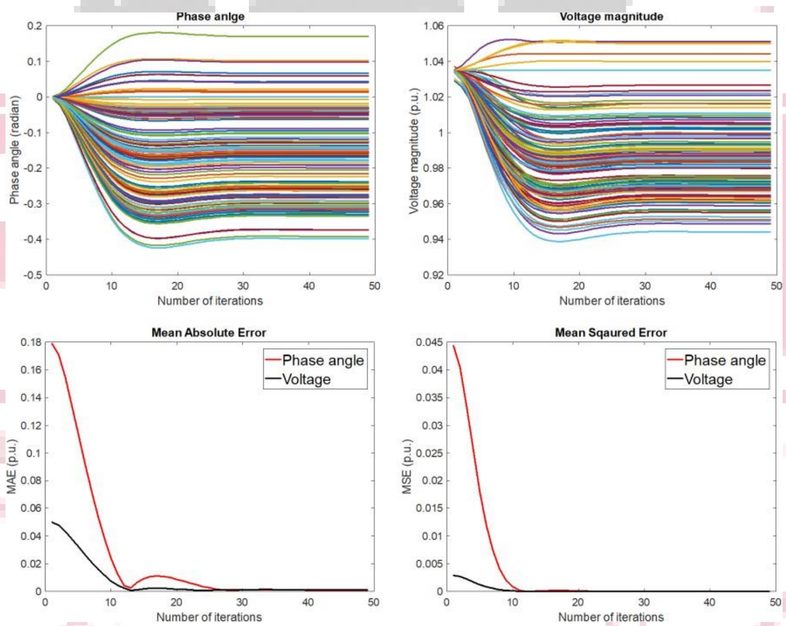

Figure 5.1 The results of fully connected communication network

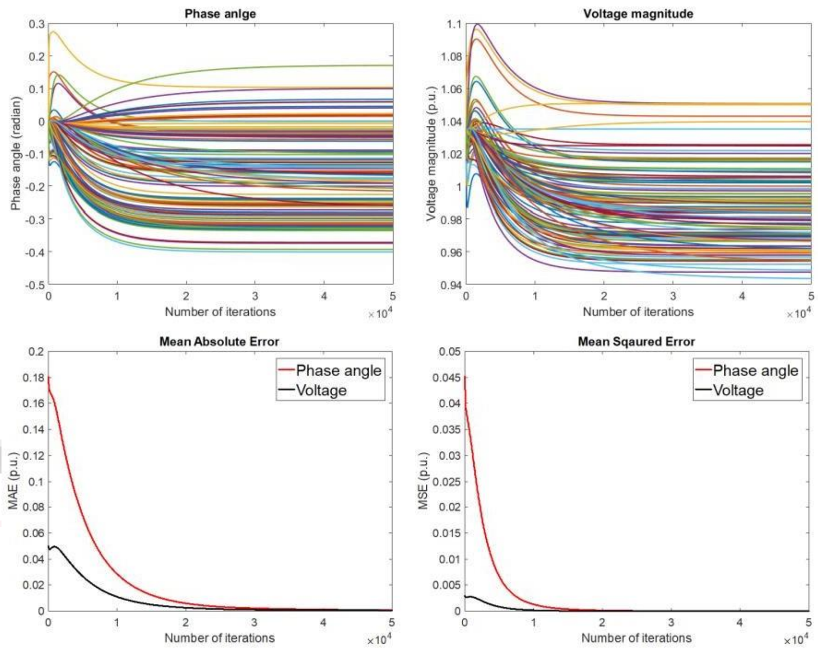

Figure 5.2 The results of chain connected communication network

5.1. Simulation for Distributed Ac Optimal Power Flow

The first case is the ACOPF over the IEEE 9-bus system. There are 9 DSE units and 3 ACOPF units in the system. The 9 DSE units are installed on the transmission lines between buses .Case Study on IEEE 9 Bus System.

5.2. Case Study on IEEE 9 Bus System

The first case is the ACOPF over the IEEE 9-bus system. There are 9 DSE units and 3 ACOPF units in the system. The 9 DSE units are installed on the transmission lines between buses.

VI. Conclusion

Over This research focuses on the three important topics in power systems, i.e., economic dispatch, state estimation, and optimal power flow. In order to handle the distributed characteristics of renewable power systems, the distributed economic dispatch, distributed state estimation and distributed optimal power flow methods are developed on the basis of consensus protocol technique.For the distributed economic dispatch, the distributed algorithm is developed to minimize the power system's operational cost without the centralized control center. To prove the versatility of the proposed approach, both the PI controller and NN controller are utilized to design the distributed algorithm. In addition, a communication-failure-tolerant distributed economic dispatch is provided to ensure the optimal dispatch during serious communication failure. Also, the line loss in the power system is considered to achieve a more detailed optimization. In the simulation, the proposed methods are tested in a 4- generator system and the IEEE 10-generator 39-bus system. Also, a sensitivity analysis is provided to show that the proposed method works well in power systems with different configurations. For the state estimation problem, an information propagation algorithm is developed to share the measured data in the distributed system. With the information propagation algorithm, the distributed state estimation is established. . The proposed method is also tested in a WSCC 9-Bus system and the IEEE 39-bus system in simulation. The bad data detection and the measurement accuracy improvement features of state estimation are also verified in the simulations.

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