Implementation of Frequency Aware Distributed Power Flow Simulation and Analysis System for Interconnected Power System based on Multi-Agent System

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Abstract. With the diversified development of power source, power grid and electric load, power system is characterized by integrated transmission & distribution system, hybrid AC/DC transmission and bidirectional power flow, which could be a big challenge for operation and control of interconnected power system. According to the design ideas of Java Agent Development Framework (JADE), a frequency aware distributed power flow simulation and analysis system is implemented based on multi-agent system. The techniques of reactive power-voltage sensitivity analysis and dynamic power flow asynchronous iteration are applied for the proposed system to reflect the voltage support incidence relation of interconnected power system. Frequency regulation characteristics of generations and loads are considered to characterize the frequency change caused by fluctuation of renewable generations and disturbance of loads. Timing simulation of interconnected system is achieved to illustrate the spatial and temporal distribution of energy flow, which can provide an important support for power system operation and control. The validity and effectiveness of the proposed techniques for power flow calculation are tested in the modified IEEE 118-bus system and Shandong provincial power grid of China. The test results verify the applicability and the effectiveness of the proposed system.

1. Introduction
With the increasing temporal and spatial distribution of generations and loads, the power grid is wide-area interconnected. Distributed solution algorithm based on decomposition and coordination mechanism could be an effective analysis and calculation method to adapt to this kind of interconnected power grid. At present, the distributed algorithm of power system based on decomposition and coordination mechanism has made some progress in theoretical research. A message-passing distributed-memory parallel power flow algorithm is proposed in [1]. Reference [2] proposes a distributed power flow method based on ward equivalent. An adaptive preconditioner is constructed for Jacobian-free Newton-GMRES methods for the distributed simulations of power systems [3-4]. A distributed dynamic power flow algorithm based on asynchronous iteration model is proposed in [5]. In [6], a distributed state estimation method for multi-area power systems is proposed in which each area performs its own state estimation using local measurements, and exchanges border
information at a coordination state estimator. In [7], active and reactive power flow is proposed for multi-area systems on automatic generation control in the presence of rapidly changing loads. Reference [8] discusses on using reduced networks for distributed DC power flow. In [9], the computation framework of iterative decomposition-coordination algorithm for real-time available transfer capability (ATC) assessment is proposed for multi-area power systems. The aforementioned work are mainly focused on the theoretical research on the distributed algorithm, and do not involve the implementation technology of practical algorithms, and even some literature proposes practical evaluation indexes of distributed simulation algorithm, but only for the synchronous iteration and under the basis of rated system frequency, and do not consider the system frequency deviation due to changes in nodal load disturbance or power fluctuation caused by renewable generations, which is not realistic.

In addition, with the increasing integration of renewable generations, such as wind generation and photovoltaic power generation, diversified development of power source, power grid and electric load, power system is characterized by integrated transmission & distribution system, hybrid AC/DC transmission and bidirectional power flow, which could be a big challenge for operation and control of interconnected power system. The fluctuation of renewable generations and load disturbance call for the frequency aware simulation and analysis method taking into account the frequency regulation characteristics of all kinds of generations and loads for interconnected power systems [10].

JADE (Java Agent Development Framework) is an open-source software Framework, which supports the implementation of multi-agent systems and complies with the FIPA specifications [11]. According to the design ideas of JADE, a frequency aware distributed power flow simulation and analysis system is implemented based on multi-agent system. The techniques of reactive power-voltage sensitivity analysis and dynamic power flow asynchronous iteration are applied for the proposed system to reflect the voltage support incidence relation of interconnected power system. Timing simulation of interconnected system is achieved to illustrate the spatial and temporal distribution of energy flow, which can provide an important support for power system operation and control. The validity and effectiveness of the proposed techniques for power flow calculation are tested in the IEEE 118-bus system and Shandong provincial power grid of China.

The organization of this paper is as follows. Section 2 describes the general framework of frequency aware distributed power flow simulation and analysis system. Section 3 gives the key techniques used by the proposed system. In Section 4, numerical system test are presented to demonstrate validity and efficiency of the proposed system, followed by conclusion in Section 5.

2. General Framework of Frequency Aware Distributed Power Flow Simulation and Analysis System

The frequency aware distributed power flow simulation and analysis system adopts multi-tier decomposition-coordination architecture, i.e. the coordination unit layer and the subsystem unit layer. Each layer is clearly separated and called by using the defined interface specification. The integration mode of loose coupling is adopted in each application of the system. The application modules of the system are loose-coupled integrated to ensure the ability to effectively respond to multi-access.

2.1. Multi-agent system based system technical structure
Figure 1 Schematic diagram of multi-agent system based system technical structure

A multi-agent system is a computerized system composed of multiple interacting intelligent agents within an environment. Multi-agent systems can be used to solve problems that are difficult or impossible for an individual agent or a monolithic system to solve. JADE provides a powerful task execution and composition model, peer to peer agent communication based on the asynchronous message passing paradigm. JADE simplifies the implementation of multi-agent systems through a middle-ware that complies with the FIPA specifications. According to the design ideas of JADE, a frequency aware distributed power flow simulation and analysis system is implemented based on multi-agent system. The schematic diagram of multi-agent system based system frequency aware distributed power flow calculation system structure is shown in Figure 1.

The implemented system is composed of coordination unit and a number of subsystem calculation units. The decomposition-coordination mechanism can avoid the complicated process of exchanging data directly between subsystem units, and separate management part and computing part organically, which can achieve the maximization of utilization of resources.

Each subsystem calculation unit realizes the power flow calculation by using the equivalent network model of local energy management system, and undertakes data interaction with the coordination unit. The designed subsystem calculation unit includes two parts: the management agent and the calculation agent. The management agent is responsible for receiving a user instruction, and interacting with the coordination unit. The calculation agent is responsible for distributed power flow calculation coordinated by the coordination calculation agent of the coordination unit.

The coordination unit can be located in the control center at the relatively higher level, and manage the data from the various subsystem units, which avoids the complex data exchange between subsystems. The coordination unit is composed of the coordination management agent and the coordination calculation agent. Coordination management agent is responsible for managing the receiving and processing of various commands and calls from subsystem units. The coordination calculation agent is responsible for initializing and triggering the coordination calculation process, and it is managed by the coordination management agent.

2.2. System deployment structure
The hardware configuration for the implementation of the distributed power flow system includes the calculation server, monitoring workstation, maintenance workstation, intranet and interface with existing energy management system (EMS)/supervisory control and data acquisition (SCADA) system. The computation parameters of power flow are from EMS/SCADA, and the corresponding operation data is acquired by remote terminal units (RTU). A simple two-layer system deployment structure is illustrated in Figure 2.

The coordination unit and the subsystem units are deployed with the calculation server, monitoring workstation, maintenance workstation, intranet and interface with EMS/SCADA system. And the calculation results and convergence status can also be checked by Web browser, which is physically isolated from the intranet.

In addition, new child calculation units can be derived from the subsystem units, and all these make up a tree system deployment structure.

3. Key techniques

3.1. Frequency regulation characteristics analysis

Arbitrary power balance between generations and loads is expected on the premise of rated frequency at all times. However, with the increasing integration of renewable generations, such as wind generation and photovoltaic power generation, and the diversified development of electric loads, the frequency change caused by the fluctuation of renewable generations and loads disturbance cannot be ignored. In each period, the system frequency change and power flow solution can be calculated based on the given base-point generations and loads, as well as the frequency regulation characteristics of generators and loads. The frequency regulation characteristics of generations or loads can be represented approximately in linear form. That is:

\[ P = P' + \beta \Delta f \]  

where, \( P \) denotes the actual power of the generation or load, \( P' \) represents constant power component which is independent of frequency, \( \Delta f \) represents the frequency deviation \((f - f_0)\), \( f \) is the actual frequency, \( f_0 \) is the nominal frequency, \( \beta \) is the frequency characteristic factor, and it is
negative for generations and for loads.

Frequency aware timing simulation of interconnected system is achieved in the proposed system. The frequency regulation characteristics of conventional generators, wind farms, photovoltaic power systems and variety of loads are considered [10]. In addition, the secondary regulation mechanism of synchronous generators and the management mechanism for tie-line power are taken into account. Thus the control mechanism of interconnected power system operation can be realized to accurately characterize the frequency change under the nodal injection fluctuation circumstance.

3.2. Reactive power-voltage sensitivity analysis

Analysis about the iterative power flow calculation interpenetration characteristics between transmission and distribution network containing distributed generations and variety of loads is realized. The characteristics show that the distribution network has the characteristics of receiving end or the power source part in the active power aspect, and has certain voltage support initiative under the voltage support of transmission network in the reactive power aspect. During the coordination process of transmission and distribution network operation, the active power and the reactive power may be in strongly coupled state, which demonstrates the necessity of the implementation of a unified analysis of the transmission and distribution network. On this basis, under the active and reactive power balance constraints, taking the transmission grid as the main coordination unit and some distribution network as the subsystem unit, power flow calculation model which displays the correlation between distribution network and transmission network is built. And at the same time, the decomposition and coordination power flow algorithm with cut-off point voltage as covariant is realized in the proposed system for the interconnected transmission and distribution network. In practice, it shows that the algorithm is simple and effective. Besides, under feasible conditions, the algorithm is with great convergence, which could satisfy the requirements of the distributed computation of interconnected transmission and distribution network.

3.3. Dynamic power flow asynchronous iteration technique

Figure 3 Diagram of coordination computation for two subsystems.

A new asynchronous iterative algorithm is proposed for decomposition and coordination dynamic power flow of interconnected power system. In the algorithm, buses can be selected freely in each subsystem. Interior and exterior iterations are designed in the algorithm. The former is used to achieve an isolated dynamic power flow solution for a subsystem and the latter is designed to achieve coordination between the two layers. By modifying the equivalent injection power on the boundary buses during the exterior iteration, a consistent power flow result with that for whole system can be obtained. The diagram of coordination computation for two subsystems is shown in Figure 2.

As shown in Figure 2, Area A power system and Area B power system are interconnected by tie
lines $l_m$ and $l_n$. Figure 2(b) shows the local equivalent model of Area A power system, which contains the electric network of Area A, tie lines $l_m$ and $l_n$, and the equivalent injection power $\hat{S}_{eq}$ and $\hat{S}_{eq}^n$ of Area B power system by Ward equivalent method[2]. Similarly, Figure 2(b) shows the local equivalent model of Area A power system, which contains the electric network of Area B, tie lines $l_m$ and $l_n$, and the equivalent injection power $\hat{S}_{eq}^i$ and $\hat{S}_{eq}^j$ of Area A power system. Based on the aforementioned coordination mechanism, independent dynamic power flow is conducted by the inner layer computation, boundary status variables are coordinated by the outer layer computation.

In addition, sparse technology such as dynamic node numbering method, parallel computing and dynamic RAM deployment technology are used in the implemented system to promote the computing efficiency.

3.4. Distributed power flow calculation framework

![Figure 4 Distributed power flow calculation flow diagram.](image)

Integrating the above key technologies, the flow diagram of the distributed collaborative power flow calculation method applied to the system is shown in Figure 4. The whole calculation framework is mainly divided into two layers of loop structure. The outer loop structure uses dynamic power flow asynchronous iteration technique to realize the coordination between areas of the interconnected power system. The inner loop structure uses reactive power-voltage sensitivity analysis technique to achieve the coordination of power flow results between transmission and distribution network in each area. And through the two-layer calculation, the frequency adjustment function can be achieved.
4. Numerical system test
Based on the JADE framework of multi-agent systems, the frequency aware distributed power flow calculation program of interconnected power systems is coding by using Java language on Eclipse platform. A distributed computing environment is built for the network parallel assembly of the proposed distributed power flow idea. In the laboratory, a distributed computing network based on local area network (LAN) is constructed by using the data communication mechanism of JADE. The computing environment consists of five servers with a 3.10-GHz processor and 32 G bytes of RAM, one server for the coordination unit; another four servers for subsystem units. The coordination unit can exchange data with each subsystem individually or simultaneously.

4.1. Test on the modified IEEE 118-bus system
The modified IEEE 118-bus system is divided into 3 area grids, the tie-lines and the corresponding endpoint buses are shown in Figure 4. The numbers of buses in each area are 35, 35, and 48 in turn. The parameters of transmission lines, characteristics of conventional units, loads wind and solar time series data can be found from[12].

To illustrate the calculation efficiency of the implemented system, the methods proposed in reference [1] and [7] are taken as comparison. And the network delay time of the calculation system can be estimated by comparison with the serial centralized calculation method for power flow analysis. The test results for comparison analysis are shown in Table 1.

Seen from Table 1 by contrast, the implemented algorithm has obvious advantages in the overall convergence efficiency. In theory, when each subsystem is generally balanced, higher computational efficiency can be achieved by the distributed calculation method, because when the system size is bigger, the power flow calculation time will account for the greater proportion of the whole computation time.

| Methods                  | Iteration times | Computation time (ms) | Total time |
|--------------------------|-----------------|-----------------------|------------|
| The implemented method   | 3               | 329                   | 981        |
| Method in [1]            | 4               | 347                   | 1273       |
| Method in [7]            | 4               | 331                   | 1089       |

4.2. Test on the Shandong provincial power grid of China
A real regional power grid of Shandong province of China is selected as a test system for the
frequency aware distributed power flow simulation and analysis system.

Considering the actual operation of the power grid, the regional dispatching center manages the operation of the transmission network of 220kV and above, including thirty-five 220kV substations and ninety-three 220kV lines. Supply districts are responsible for the operation of the distribution network, and each supply district approximately contains twenty-three 110kV substations, thirty 35kV substations and corresponding distribution lines. In the past transmission and distribution dispatching centers perform their duties separately, and a separate calculation and analysis model can meet the power grid operation needs. However with the increasing proportion of renewable energy, the coupling relationship between the transmission and distribution network will gradually appear. At present, the proportion of distributed renewable energy generation in the region has been 6% ~ 8%. According to the development planning, the proportion of distributed generation in this region will continue to increase until 30%. So a unified and coordinating analysis model of transmission and distribution network is necessary.

In the test system, the 220kV and above voltage level power grid managed by regional dispatching center is set as a coordination system representing the transmission network model. And eleven subsystems are built according to the actual scope of supply districts, representing the distribution network models. The coordination system contains one hundred and ninety-four calculation buses and every subsystem contains about forty calculation buses. The total number of calculation buses in the test system is about six hundred. If the analysis scope is extended to the entire power grid of Shandong Province and 10kV power distribution networks are considered, the calculation will be more difficult for centralized computation. However the simulation and analysis system proposed in this paper can solve the problem effectively.

The field test application shows that the proposed frequency aware distributed power flow calculation system can solve the conflict problem of multi system, multi-access computing and friendly interface with EMS is achieved. And power flow calculation results are accurate and reliable, which is able to meet the requirements of practical application for power system with renewable generations’ integration.

5. Conclusions
In this paper, a frequency aware distributed power flow simulation and analysis system is implemented based on multi-agent system according to the design ideas of JADE. The techniques of reactive power-voltage sensitivity analysis and dynamic power flow asynchronous iteration are applied for the proposed system to reflect the voltage support incidence relation of interconnected power system. Frequency regulation characteristics of generations and loads are considered to character the frequency change caused by fluctuation of nodal injection power. Timing simulation of interconnected system is achieved to illustrate the spatial and temporal distribution of energy flow, which can provide an important support for power system operation and control. The test results in the modified IEEE 118-bus system and Shandong provincial power grid of China illustrate the applicability and the effectiveness of the implemented system.

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