Network Modeling for Distributed Simulations of Unbalanced Power Systems

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Abstract

With the increasing presence of distributed intelligence throughout power systems, the possibilities for distributed control and operation schemes are becoming progressively more attractive and feasible. Multi-phase distribution power flow is a tool which calculates the operating state of an electric power distribution system and is used to support all other planning and operation applications. This paper will derive models for the distributed analysis and simulation of distribution systems and will present their use in calculating the power flow solution using physically remote distributed processors.

To perform the power flow, distributed analysis models for multi-phase distribution systems have been developed and are embedded in a distributed algorithm. These include network partition models and equivalent source and load models which are used to represent each of the subsystems in the distributed analysis. A distributed processor test bed has been designed to test the performance of the models in distributed simulations. Results will be presented which validate the accuracy of the proposed models and algorithm.

1. INTRODUCTION

Multi-phase distribution power flow is a method for determining the operating state of a distribution system given the network parameters, topology, generation and load. The power flow problem forms the basis of all distribution system planning, operation, and optimization schemes. Traditionally, distribution power flow calculations and system operations are performed at a centralized distribution control center. In modern distribution systems however, intelligent devices are distributed throughout the network which are capable of performing monitoring, computation, communication, and control operations. By utilizing the computation and communication capabilities of these devices, the burden of solving the computationally intensive distribution power flow problem may be ceded to the devices involved in actually controlling the network.

This work presents mathematical models necessary to analyze, design, and operate the electric power system in the presence of these distributed intelligent devices. These models then specify what data requirements are needed to subsequently perform the distributed simulation. The processing and control of system operation can then be decentralized.

In the past, detailed component models have been developed for use in distribution system analysis [1, 2]. These models are used to represent specific distribution system components for use in the power flow calculation. To perform a distributed power flow however, new models are required to represent each subsystem and, in addition, the interaction between each of these subsystems. Therefore, this paper will present distributed analysis models which are then used to perform distributed multi-phase distribution power flow.

The distributed analysis of power distribution systems has been investigated in the past. In [3], a distributed state estimator was presented which aimed to increase computational efficiency and improve estimation reliability. The converter coupling points in the DC zonal system seen in avionic and naval power systems were used as natural boundaries to create sub-grids by which to distribute the network. The idea of using network device locations to create natural boundaries is employed in this paper as well. The focus of this work will however be on multi-phase distribution systems and distribution power flow analysis.

The paper will expand on the distributed analysis models first presented in [4]. The use of these models in a distributed power flow algorithm will then be presented. An implementation of the algorithm will be presented along with simulation results on a 5 bus test system.

2. DISTRIBUTED ANALYIS MODELS

For a distributed analysis of the system, the network is first partitioned into subsystems. Each subsystem is modeled in detail at a local processor to which it is assigned while the remaining network will be represented at each location by equivalents. This section will first discuss network partitioning and then present network equivalent models. The details and assumptions of the partition process will be presented along with figures illustrating the concepts. An overview of the equivalent models will also be presented.

Distribution systems are operated primarily in a radial structure which is used for its simplicity of design and protection schemes. As such, the focus of the derivations of the following equivalent models will be presented with respect to systems of a radial topology.

2.1. Network Partitions

The distribution system will be divided into network partitions which are constructed based on the measurement capability, control capability, or control area of each distributed device in the network. Partitions are formed such that adjacent partitions share a bus of the original, un-partitioned system. For radial systems, partitions may also be referred to as upstream or downstream from one another with respect to a specified source in the network.

When partitioning the original system, each partition represents one or more systems each with the following characteristics:

- One bus will serve as the equivalent source bus of its respective partition, selected as the bus closest to the substation. This bus will model the upstream partitions as an equivalent voltage.
- End buses of each partition will serve as equivalent load buses. These buses will model downstream partitions as an equivalent load

2.2. Partition Modeling Details

The partitioning process occurs at a specific set of buses of the original system. These buses are then shared between two or more partitions in the partitioned system. Partitions are represented to each other through measurements or calculated data relayed through the communication network.

Figure 1 illustrates how a bus is shared between two partitions for the distributed analysis. A voltage sensor is used to measure and communicate the bus voltage to the adjacent downstream partition while current sensors are used to communicate the equivalent current injection to the adjacent upstream partition. In the distributed power flow calculation this process is mimicked through the iterative calculation and post-processing of these values. Mimicking the measurement process through iterative calculations allows for distributed simulations to be conducted on a variety of test systems.

To partition the system in this fashion, using measurements to perform the distributed analysis it is then necessary to assume:

- voltage sensors are present at each boundary bus
- current sensors are present on the outgoing branches of each boundary bus

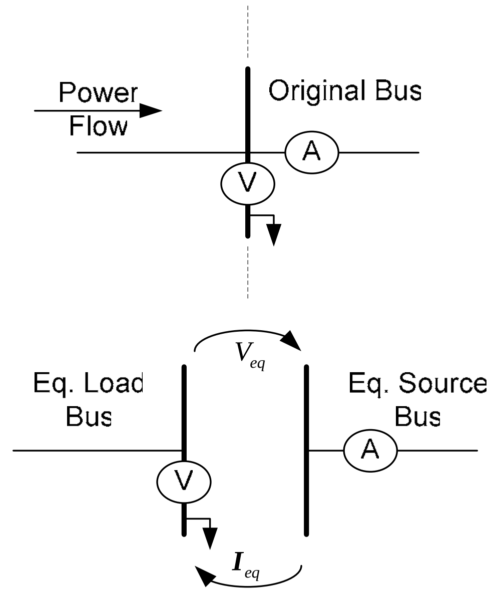

Figure 1: Illustration of bus sharing for distributed analysis

- all existing bus injections are known and are represented on the upstream side of the shared bus

For illustration, this partitioning concept has been applied to the radial 5 bus system shown in Figure 2. As can be seen, due to the sharing of each boundary bus, the number of buses has increased to 8 in the distributed system. In addition, existing injections can be seen to be represented on upstream equivalent load buses.

For systems which contain branching buses, changes to this partitioning scheme will occur only if the system is partitioned at one of the branching buses. In such a case, the number shared buses will increase by the incidence rate on the bus. A current measurement is then required for each of the buses incident to the branching bus and the upstream voltage measurement must be communicated to each of the shared equivalent source buses. The convergence criterion of the solution algorithm, discussed later in this paper, is defined based on these voltage measurements. Partitioning at branching buses will then increase the number of values to be checked to determine if the algorithm has converged.

2.3. Equivalent Models

The voltage and current measurements for the distributed simulations are represented by post-processing power flow results from each partition. The parameters of each equivalent source bus are updated using information communicated from its respective adjacent upstream partition. Specifically, the equivalent source bus model of partition *i*, with adjacent upstream partition *i*-1, is:

$$\boldsymbol{V}_{i,0}^{(k)} = \boldsymbol{V}_{i-1,eq.load}^{(k)} \tag{1}$$

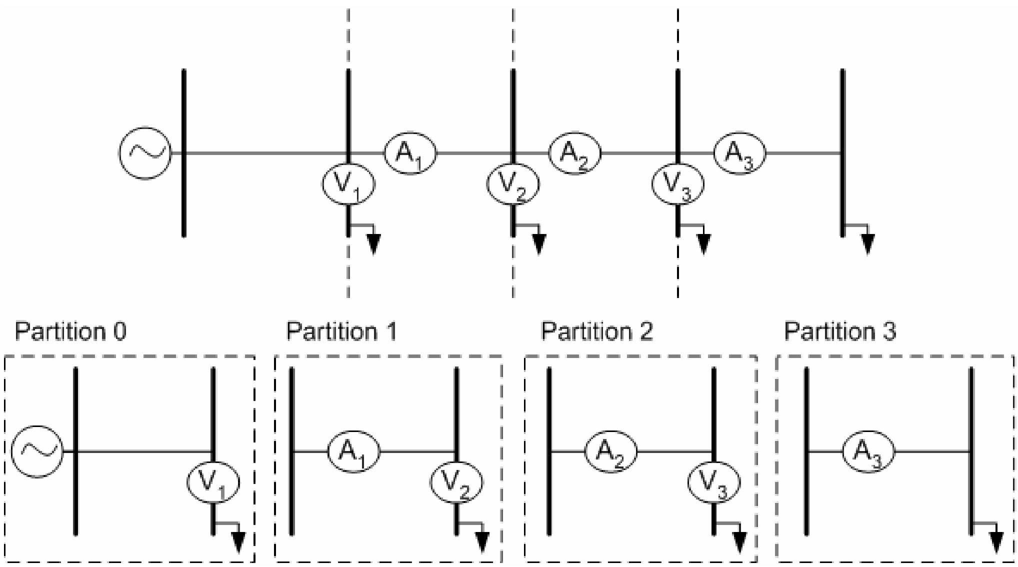

Figure 2: Diagram of a 5 bus partitioned distribution system

where:

$\boldsymbol{V}_{i,0}^{(k)}$: complex (n_{ph} x 1), multi-phase equivalent source bus voltage vector update of partition i, iteration k

$\boldsymbol{V}_{i-1,eq.load}^{(k)}$: complex (n_{ph} x 1), multi-phase equivalent load bus voltage vector of the corresponding upstream partition i-1, iteration k

n_{ph} : number of phases present on the respective bus or branch

The equivalent current injection is calculated as the total current output from the equivalent source bus of the respective partition. The equivalent current injection of partition i is then:

$$\boldsymbol{I}_{eq,\,i}^{(k)} = \sum_{\forall\ br \in B_i} \boldsymbol{I}_{i,\,br}^{(k)} \qquad (2)$$

where:

$\boldsymbol{I}_{eq,\,i}^{(k)}$: complex (n_{ph} x 1) multi-phase equivalent current injection vector, partition i, iteration k

$\boldsymbol{I}_{i,\,br}^{(k)}$: complex (n_{ph} x 1) multi-phase current on branch, partition i, iteration k

B_i : Set of all branches connected directly to the equivalent source bus, partition i

3. ALGORITHM

Using the derived distributed analysis models, a solution algorithm for calculating the system states is proposed. The algorithm calculates the state of the whole system by iteratively running a traditional power flow on each partition using distributed processors which communicate results. The solution process is iterative; therefore, the equivalent source bus voltages are initialized for the first iteration. This section will present the solution algorithm for solving the distributed power flow as well as an implementation of the proposed algorithm using commercial software packages.

3.1. Procedure

The solution algorithm of the distributed power flow can be expressed in the following 9 steps:

Step 1. Set k = 0; initialize all equivalent source bus voltages

Step 2. Perform a power flow for each partition which has no further downstream partitions

Step 3. Post-process the solution of each power flow to calculate an equivalent current injection

Step 4. Communicate equivalent injection through the communication network to the adjacent upstream partitions/remote processors

Step 5. For each upstream partition, aggregate equivalent loads, if necessary, and perform a power flow

Step 6. If no further upstream partitions exist, let k = k+1, and go to Step 7; else, go to Step 3.

Step 7. Communicate the end bus voltages to adjacent downstream partitions/remote processors

Step 8. If no further downstream partitions exist, go to Step 9; else, perform power flow on these partitions and go to Step 7

Step 9. Check for system convergence. If convergence has occurred, Stop. Else, go to Step 2

3.2. Convergence Criterion

The convergence criterion of the algorithm is set such that the voltage at each boundary bus is within a specified tolerance for consecutive iterations. This requires that each equivalent source and load bus in the network satisfies this condition. The convergence criterion in terms of equivalent sources buses is then:

$$\left\| V_{i,0}^{(k+1)} \right| - \left| V_{i,0}^{(k)} \right\| \le \varepsilon_1 \quad \& \quad \left| \angle V_{i,0}^{(k+1)} - \angle V_{i,0}^{(k)} \right| \le \varepsilon_2 \qquad \forall \;\; i = 1,\; 2,\; \ldots,\; n_p \quad (5)$$

where:

n_p : number of partitions in the distributed system

3.3. Implementation

When performing a distributed analysis, each partition model and power flow solver must be located on a remote processor. In this implementation, remote personal computers (PC) were used to act as the remote processor at each location. Each PC contained Matlab and LabView software, a case file describing the network partition to be solved, and a multi-phase distribution power flow solver. Communication ports are established between each adjacent partition's processor.

4. DISTRIBUTED SIMULATIONS

To demonstrate the effectiveness of the proposed method distributed simulations were carried out on a test platform. The test platform was constructed using a set of computers with identical specifications connected together via a local area network. The results of the distributed power flow will be compared to those of a traditional power flow on the original system.

The test system used for the distributed simulations is the 5 bus radial distribution system seen in Figure 2. The total nominal load of the system is 6000 kW and 4,500 kVar. The loads are modeled using constant current load models. The nominal voltage of the system is 12.47 kV. The power flow on the un-partitioned original system used the implicit Z-bus Gauss method. For the distributed power flow, the implicit Z-bus Gauss method is used as the power flow algorithm at each partition, with a convergence tolerance in (5) of $\varepsilon_1 = \varepsilon_2 = 10^{-10}$.

4.1. Simulation Results

The test system was partitioned using 4 partitions as shown in Figure 2. Performing a distributed power flow on this system required 8 iterations of the distributed power flow algorithm to converge. The voltage and current characteristics of the distributed system could then be compared to the results of a traditional centralized power flow on the original system.

The comparison showed that the results of the distributed power flow converged to the same solution as the traditional power flow, within the specified convergence tolerances. Table 1 below summarizes the results for the voltage and current measurements shown in Figure 2.

4.2. Observations

The results show that the distributed power flow will converge to same solution as that of a traditional power flow. These results verify the proposed distributed analysis models and algorithm for use in calculating multi-phase distribution power flow.

Table 1: Measurement results summary

Measurement	Original System (p.u.)	Distributed System (p.u.)	Absolute Error
V_1	0.99513	0.99513	2.2E-12
A_1	0.07354	0.07354	2.4E-11
V_2	0.99027	0.99027	7.5E-12
A_2	0.07354	0.07354	2.6E-11
V_3	0.98542	0.98542	8.2E-12
A_3	0.07354	0.07354	4.3E-11

5. CONCLUSIONS

The paper has presented distributed analysis models for distributed multi-phase distribution power flow. Specifically, network partition models and equivalent load and source models were presented. A solution algorithm using the proposed models to perform distributed power flow was also presented. The method is designed to utilize the distributed intelligent devices located throughout the distribution system to calculate distribution power flow.

Simulation results from a 5 bus radial distribution system were used to compare the solution of the distributed algorithm versus the solution of a traditional power flow on the given test system. The results showed that the distributed method converged to the same solution as a traditional power flow for different numbers of partitions.

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Biography

Michael Kleinberg received the B.S. and M.S. degrees in electrical engineering from Drexel University, Philadelphia, PA. He is a currently a research assistant at the Center for Electrical Power Engineering at Drexel University. His research interests include distributed distribution system analysis and simulation.

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