

Radial Distribution Power Flow Studies in a Remotely Distributed Environment

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Abstract—With the continued push toward dispersed generation and distributed intelligent devices throughout the distribution system, a proper analysis method for understanding the operation of the evolving overall system is required. This work aims to demonstrate a method for distribution system power flow studies in a remotely distributed environment. The method involves distributing the simulation of a power system across physically remote sites through the creation of a network of stand-alone power system simulations. To gain knowledge of larger system behavior, these simulations share measurement information and locally calculated results via the Internet. A software implementation of the proposed method will be presented along with results from a 97 bus test distribution system.

I. INTRODUCTION

Distribution system monitoring and control is increasingly becoming more distributed in nature. The point of control and data acquisition is no longer located solely at the substation or centralized control center. Increasingly, distributed resources are being outfitted with intelligent devices capable of performing complex monitoring, calculation, and control operations [1]. With the increased level of decentralized control, a new set of analysis tools is required.

A remotely distributed simulation platform will allow for select measurements and locally calculated results from distributed monitoring and control devices to provide information concerning the entire system state. This is in contrast to power transmission system studies which are often performed on internal and external networks of different control areas. Studies of a power distribution system with a large number of decentralized controllers installed cannot be approached in a similar manner as transmission systems due to a higher level of coupling within the system.

The analysis of electric power distribution systems from a distributed standpoint has been investigated in the past. In [2], a parallel radial distribution power flow was implemented in which network feeders were partitioned and processed on transputers to reduce computation time. More recently, work has addressed issues arising from the

increasing distributed nature of monitoring and control. In [3], a dispersed generation communications system is proposed to address the increased amount of information both necessary and available to operate such resources. The application of intelligent control agents for distribution systems with dispersed generation is presented in [4]. This method attempts to make local control decisions determining proper DG on/off status by using local measurements and communication between agents, while acting under a global directive of ensuring system stability.

This paper addresses the topic of radial distribution power flow via a remotely distributed environment. Specifically, this paper will present:

- a network partition model with source and load equivalents
- a distributed power flow procedure utilizing remote processors
- a software architecture for remotely distributed simulations
- simulation results on a 97 bus test distribution system

In contrast to previous methods which distribute calculations to reduce computation time, the proposed method aims to distribute calculations based on the decentralized monitoring and control areas in the network. With the increase of intelligent electronic devices in power distribution systems, a direct application of this work lies in the development of new distributed monitoring and control schemes. These schemes will result from studies on measurement redundancy and control techniques for protection device coordination and network reconfiguration. The proposed simulation environment can be used to determine control actions at both the local level and the system level since it can quantify the impact on the entire network.

The new proposed method will be presented in Section II followed by a description of the software architecture in Section III. Section IV presents simulation results of a 97 bus distribution system followed by conclusions in Section V.

II. DISTRIBUTED DISTRIBUTION SYSTEM ANALYSIS

The approach of solving radial distribution system power flow in a remotely distributed environment is presented below. The concept of network partitions including source and load equivalents will be presented. In addition, the procedure for distributed power flow including initialization and system convergence, as they pertain to this work, will be presented.

A. Network Partitions

The original distribution system under study must first be decomposed into distinct partitions, each of which will be solved at a remote location. Historically, distributed processing led to the partitioning of the network to balance the computational load of the analysis to be performed. In this work, while network partitioning can be done to improve computational requirements, the idea is to partition the original system based on the physical structure of the distribution system and/or physical locations of installed processing elements. Network partitions will therefore have a physical relationship to each other. Specifically, adjacent network partitions are defined to be ones where a direct electrical connection between partitions, such as a branch or a bus, exists. Then, adjacent partitions will communicate with each other to perform system level analysis. For radial distribution systems we can refer to adjacent partitions, in relation to the substation, as upstream or downstream from each other.

The partitioning scheme used will depend solely on the system and type of analysis desired. For example, a distribution system with controllable dispersed generation may be partitioned according to regions defining generator domains in the system, as presented in [5, 6]. For the simplicity of discussion here, the only limitation enforced for partitioning the original system is that each partition must not contain isolated systems. Each partition of the original system will then result in one radial system with the following characteristics:

- One bus will serve as the equivalent source bus of its respective network partition (in these discussions, selected as the bus closest to the substation)
- One or more end buses of the network partition, which will serve as equivalent load buses representing downstream networks partitions in addition to any load present on the respective bus

It must be noted that a bus of the original system may appear as an equivalent load bus in one partition and as an equivalent source bus in another. In addition, exceptions exist for both of the above cases. A source bus equivalent is not needed for the partition that includes the substation. Similarly, the actual end bus of a line or lateral in the original system will not require an equivalent load in a network partition. All other network parameters of the original system including: loads, sources, and branch parameters will remain the same in their new respective partition.

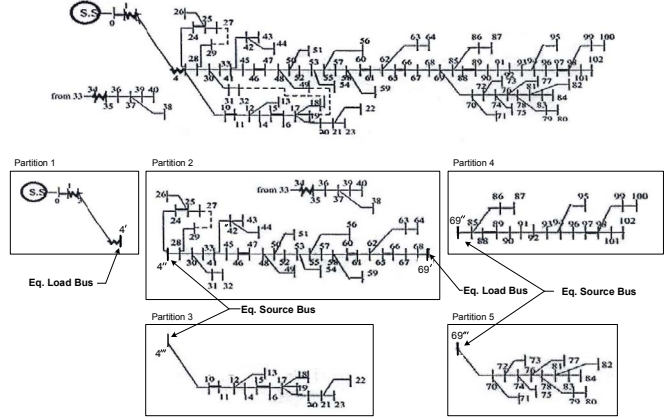


Figure 1. One-Line Diagram of a 97 Bus Partitioned Distribution System

An illustration of network partitioning is displayed in Figure 1. It shows a 97 bus radial distribution system decomposed into 5 partitions containing both source and load equivalents. Please note, adjacent network partitions can be seen from the diagram; for example, Partition 2 and 3 are adjacent to Partition 1. An equivalent source can be seen at Bus 4'' in Partition 2. In addition, Partition 2 has an equivalent load bus represented at Bus 69'. The models and calculation procedures for source and load equivalents are discussed in the following two sections.

1) Source Equivalent

An equivalent source bus is required for each network partition except that which contains the substation. The value of each equivalent source bus voltage will be determined by the voltage of the equivalent load bus of the adjacent upstream network partition. This end bus voltage however is dependent on its equivalent load which is calculated from the downstream networks. This dependence leads to an iterative backward/forward process between partitions; therefore, each of the equivalent source values must be initialized for the first iteration.

To update the source bus voltage for a partition, the partition must wait for a new equivalent source voltage to be passed down from the upstream partition.

$$V_{src,n}^{(k+1)} = V_{end,n-1}^{(k)} \quad (1)$$

Where: $V_{src,n}^{(k+1)}$: (3x1) complex, three-phase equivalent source bus voltage vector update of partition n

$V_{end,n-1}^{(k)}$: (3x1) complex, three-phase end bus voltage of the upstream partition $n-1$

k : The current iteration

2) Load Equivalent

An upstream partition requires an equivalent load to represent downstream network partitions. At each iteration, each network partition will perform a power flow based on

the prevailing equivalent source and load parameters. The solution is then post-processed to calculate an equivalent load value which will be sent to the upstream partition.

An equivalent power injection is then calculated from the total current injection and the equivalent source voltage of the current iteration:

$$S_{eq,n}^{(k)} = V_{src,n}^{(k)} * I_n^{(k)*} \quad (2)$$

Where: $S_{eq,n}^{(k)}$: (3x1) complex, three phase total power injection vector of partition n

$I_n^{(k)}$: (3x1) complex, three phase total partition current injection vector of partition n

If more than one adjacent downstream partition from the equivalent load bus exists, the equivalent loads from each are aggregated. In addition, the equivalent load must account for load present on the bus in the original system.

$$S_{load,n}^{(k)} = \sum_{i=1}^d S_{eq,i}^{(k)} + S_{orig,n}^{(k)} \quad (3)$$

Where: $S_{load,n}^{(k)}$: (3x1) complex, three phase load vector, placed on equivalent load bus of partition n

d : Number of adjacent downstream partitions from partition n

$S_{orig,n}^{(k)}$: (3x1) complex, three phase load vector of the original system bus

B. Distributed Power Flow Procedure

The following steps outline the proposed procedure using the equivalent source and equivalent load values as discussed above:

Step 1. Set $k = 0$

Step 2. Perform a power flow for each partition which has no further downstream partitions, e.g. Partitions 3, 4, and 5 in Fig. 1.

Step 3. Post-process the solution of each power flow to calculate an equivalent load $S_{eq,n}^{(k)}$

Step 4. Pass equivalent loads through the communication network to upstream partitions/remote processors

Step 5. For each upstream partition, aggregate equivalent loads, if necessary. Perform power flow for these partitions

Step 6. If no further upstream partitions exist, let $k = k + 1$, communicate the end bus voltages to downstream partitions/remote processors and go to Step 7. Else, go to Step 3.

Step 7. Check for system convergence. If convergence has occurred, stop. Else, update voltages and go to Step 2.

In Step 7 of the proposed method, the system is said to converge when the complex bus voltages at each equivalent source bus are within a specified tolerance for two consecutive iterations. In [7], radial power flow solvers have been shown to converge. The process adopted here is a distributed radial backward/forward sweep with convergence criterion as seen below.

$$\left| |V_{src,n}^{(k+1)}| - |V_{src,n}^{(k)}| \right| \leq \epsilon_1 \quad \& \quad \left| \angle V_{src,n}^{(k+1)} - \angle V_{src,n}^{(k)} \right| \leq \epsilon_2 \quad (4)$$

Where: $|V_{src,n}^{(k)}|$: Equivalent source bus voltage magnitude

$\angle V_{src,n}^{(k)}$: Equivalent source bus voltage phase

$\epsilon_{1,2}$: Convergence tolerance for voltage magnitude and phase, respectively

Proof of convergence in the presence of round-off error and inaccuracy introduced due to the communication system is currently under investigation.

III. IMPLEMENTATION

To implement the above method, a custom software architecture has been created integrating a Matlab [8] based distribution power flow solver [9], with National Instrument's LabView [10], to exploit the computation power and function of Matlab with the communication functions of LabView. Each remote session of LabView contains a power flow solver and the case file for a distinct network partition. Each session will establish a communication port with each of its adjacent sessions through which equivalent load and source values will be passed. The TCP communication protocol is used for all communication between each location in a server/client system architecture.

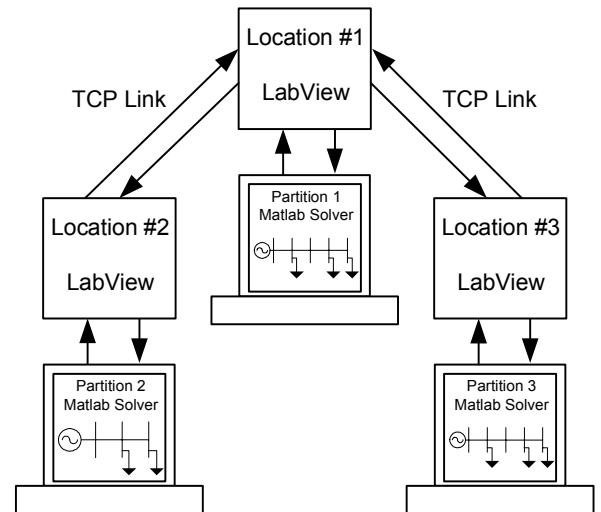


Figure 2. Example software architecture between three partitions

A. Software Architecture

To integrate the Matlab distribution power flow solver with LabView, a LabView function, Matlab Script Node, is implemented in each remote LabView session. Through this function, LabView calls Matlab via an Active X interface, allowing data to be passed to and from Matlab.

Initial conditions for each equivalent source bus voltages to be passed into Matlab are set via a LabView front panel interface at each remote session. Power flow and post processing operations are performed using the Matlab computation engine on the processor at the respective location. Results are then passed out to LabView as double precision floating decimal values. There the data is converted to a string, written to the TCP connection, and sent to an adjacent network partition in addition to being displayed on the front panel. Figure 2 illustrates an example of the software architecture between three partitions.

B. Communication System Issues

A unique aspect of remotely distributing the distribution power flow of a system is that a real-world experimental platform is created which can integrate the stochastic nature of measurement time delays into the power systems analysis [11]. Power flow results and calculations are sent as time-stamped measurements to adjacent partitions which may then take into account the delay of the incoming measurements in their calculations and control actions. Further time delay analysis may be preformed as well to analyze the effect of varying data traffic, corrupted measurements, and lost connections in the communication system.

IV. SIMULATIONS

The above proposed method has been tested on the 97 bus distribution system displayed in Figure 1. Here, the load model selected for the power flow analysis in Step 5 was a constant impedance load model computed from the equivalent load power $S_{load,n}^{(k)}$. System convergence tolerances for Step 7 were set as $\epsilon_1 = \epsilon_2 = 10^{-6}$.

Results have shown that all phase voltage magnitudes of the distributed power flow are within 0.2% of the results from a non-distributed power flow on the entire original system. Voltage angles were within 0.2°. Table 1, displays the three phase per unit voltage magnitude and voltage angle as sample data for the two equivalent source buses, Bus 4 and Bus 69. The results from both a power flow on the original system and the distributed power flow on the partitioned system are displayed. In addition, a comparison between both results is presented displaying the percent error

TABLE I. 97 BUS TEST SYSTEM EQUIVALENT SOURCE VOLTAGES

Bus	ϕ	Original V		Partitioned V		Error	
		$ V , pu$	$\angle V^\circ$	$ V , pu$	$\angle V^\circ$	$\% V $	$\Delta\angle V$
4	a	0.9768	-3.4998	0.9767	-3.4948	0.0042	0.0050
	b	0.9690	-123.90	0.9698	-123.81	0.0797	0.0927
	c	0.9720	116.37	0.9722	116.41	0.0252	0.0372
69	a	0.9545	-5.1258	0.9535	-5.2280	0.1039	0.1022
	b	0.9404	-126.06	0.9408	-125.99	0.0449	0.0612
	c	0.9544	114.54	0.9533	114.50	0.1179	0.0375

difference of voltage magnitudes and absolute difference between voltage angles.

While results obtained from the distributed process are near the solution of the original system, conditions that result in the distributed procedure converging to the same solution as a non-distributed power flow are currently under investigation. Sources of inaccuracies are suspected to exist in round-off error and data type conversions in the communication between Matlab and LabView.

In addition to the case above, a 3 zone study was shown to successfully converge with minimal error to the solution of a non-distributed power flow on the entire original system. Formal analysis of convergence in relation to partition size and quantity is currently under investigation.

V. CONCLUSIONS

The paper has presented a new method for solving large distribution systems in a remotely distributed environment. The proposed network partition models and distributed power flow procedure has been presented. The method has been implemented using a Matlab based unbalanced distribution power flow solver embedded in remote LabView sessions. The proposed method is intended as a new means to analyze the effects of the increasing presence of distributed system architectures in today's power distribution systems.

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