Electric Power Systems Research 102 (2013) 20–32

Contents lists available at SciVerse ScienceDirect

Electric Power Systems Research

journal homepage: www.elsevier.com/locate/epsr

A distributed implementation of multi-area power system state estimation on a cluster of computers

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A R T I C L E I N F O

Article history:
Received 8 October 2012
Received in revised form 10 March 2013
Accepted 1 April 2013
Available online 30 April 2013

Keywords:
Multi-area state estimation
Hierarchical architecture
Decentralized architecture
Paraller processing
Distributed processing
Message-passing interface (MPI) protocol

A B S T R A C T

This paper presents an efficient weighted least squares (WLS) distributed algorithm for multi-area power system state estimation including measurements provided by the supervisory control and data acquisition (SCADA) system and the synchronized phasor measurement units (PMUs). Each area performs independently its own state estimation using local measurements and exchanges border information at a coordination level that computes the system-wide state. The basic criterion of partitioning a power system into several control areas is to have areas as equal in size as possible, so that the workload on each area processor is as balanced as possible, and interconnections between distinct areas be limited, as much as possible, to reduce the amount of inter-process communication necessary. A true distributed implementation on a cluster of computers running Linux is developed. The code is written in C and sparse linear algebra routines from the Portable, Extensible Toolkit for Scientific computation (PETSc) library are used. Communication among area processors and the coordinator processor is implemented by using the MPICH2 implementation of the message-passing interface (MPI) protocol. By using extensions MPICH-G2, ES-MPICH2, MVAPICH2 of MPICH2 protocol, a portable Web-based distributed multi-area state estimator can be developed based on geographically distributed and heterogeneous cluster of computers. The proposed distributed approach has the same accuracy and redundancy level as the centralized estimator and provides the same solution only from the strictly mathematical point-of-view, by assuming that the measurement arrival delays and skew errors are identical to those of the centralized state estimator. Numerical simulations with a 1180 bus system, partitioned into equally or unequally sized area networks, demonstrate the efficacy of the proposed implementation in comparison with a centralized WLS state estimation.

1. Introduction

State estimation (SE) has become the very basic and most powerful tool for system operators to use in monitoring and controlling power systems. The goal of state estimation is to provide a reliable and accurate estimate of the state variables, which include bus voltages and phase angles. After the restructuring of the power systems, ISOs/RTOs are faced with the need to monitor and coordinate energy transactions across TSO borders in large interconnected networks. Real-time measurements are used for this purpose and are processed by the state estimators at the ISO control centers (CC). Each CC will have its own local SE which processes measurements received from its regional substations. A system-wide state estimation solution becomes necessary well beyond the extent covered by each CC. Hence, the idea of multi-area state estimation (MASE) methods, which are currently gaining renewed interest.

Two processing techniques are used to solve the MASE problem: parallel and distributed. A widely accepted distinction between them is that the parallel processing employs a number of closely coupled processors while distributed processing employs a number of loosely coupled and geographically distributed computers. In most cases parallel processing would definitely expedite the solution process, but distributed processing may not guarantee a faster solution speed due to the synchronization penalty. However, obtaining a fast solution speed is not the only purpose of distributed processing. For a large power system, distributed processing can bring more flexibility and reliability in monitoring and control and can save on large investment in communication networks. Two computer architectures have been proposed for the MASE problem: the *hierarchical* and the *decentralized*.

In hierarchical MASE, a master processor distributes the work among slave computers performing local area SE and, subsequently, coordinates the local estimates. In [1] the local state vectors are

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http://dx.doi.org/10.1016/j.epsr.2013.04.002

re-estimated through a non-iterative procedure, using as pseudo-measurements the previous local estimates. In [2] the technique of diakoptics is used to exploit the nearly block diagonal structure of the Jacobian matrix. The two-level estimator in [3] is based on non-overlapping areas and is using the state estimates at boundary buses as pseudo-measurements. Method [4] is intended for parallel computation by using power flow measurements at tie lines. Method [5], which is conceptually very similar to [3], is using a heuristic approach with arithmetic means in the coordination level. In [6], six approaches to coordinate the solution of local SE are analytically formulated and reviewed. An extensive review of hierarchical SE methods and an improvement of method [3] are provided in [7]. The two-step solution methodology of [8] is based on an optimization technique with coupling constraints at the centralized level. In [9], each area is individually solved and at the second level a reduced model involving tie lines and boundary measurements is handled. The coordination phase of the above methodologies [1–9] takes place only once at the end of the local SE process. In [10] the central processor broadcasts the current state to each local processor, which computes its portion of all matrices and vectors that are gathered and processed at the central level. The parallel computation algorithms [11,12] significantly speed up the computational process. The work [13] uses rectangular coordinates, along with an extension of a second-order load flow algorithm. A diakoptical static SE algorithm is proposed in [14]. A MASE approach for solving the weighted least absolute value (WLAV) state estimation is presented in [15] and [16] based on the Dantzig-Wolfe decomposition principle. In [17] and [18] the so-called "auxiliary problem principle" is applied to develop a two-step procedure based on border-bus overlapping areas. A distributed constrained SE problem is solved in [19] by a successive quadratic programming and a parallel dual-type method. A central coordinator receives the results of individual area SE as well as PMU and border measurements and computes the system wide solution in [20]. A distributed SE for mega grids is proposed in [21] where a central coordinator receives state estimation solutions from individual areas and coordinates them. In [22] an optimization problem with equality constraints is set up, with the placement of PMUs based on the bordered-block diagonal form. In [23–25], the aggregated state estimation solution is obtained from the local SE solution, using synchronized phasor measurements to increase the accuracy. A diakoptic-based SE algorithm is presented in [26], utilizing PMUs that are used to coordinate the voltage angles of each subsystem SE solution. In [27] substation level measurements are pre-processed by a linear estimator and the information provided is then integrated with a conventional nonlinear SE. A distributed algorithm, that is capable for distributed observability and bad data analysis, is proposed in [28]. A multilevel framework that facilitates seamless integration of existing state estimators that are designed to function at different levels of modeling hierarchy is described in [29]. A general parallel dual-type SE method, using the framework of method [19], is proposed in [30]. In all the above methodologies [1–30] the local SE solutions are repeatedly coordinated after each iteration.

In decentralized MASE, the central coordinator computer is missing and each local processor communicates only with processors of neighboring areas, exchanging border information. In [31] a coordinated algorithm is presented for distributed state estimation by considering PMU measurements at both subsystem and coordination levels. In [32] the "spatial quantization" and the "spatial sweep" techniques are used in a system composed of border-bus overlapping areas. In [10] an approach is developed where each processor solves asynchronously the SE problem corresponding to its area by using a relaxation-based approach. In [33] a parallel processing algorithm performs repeat solutions for SE suitable for MIMD (multiple instruction, multiple data) type multiprocessors. A recursive quadratic programming with the dual method are combined in [34], assuming a high speed data communication network. In [35], recognizing the complexity and practical difficulties of [34], each processor is in charge of an entire area, not a single bus, and a much simpler partially asynchronous block-Jacobi method is adopted. In [36], [37] asynchronous processing is used to simulate a parallel and distributed state estimation algorithm with a parallel virtual machine (PVM) software for geographically distributed processors. Work [38] presents a parallel weighted least-square state estimation algorithm on shared-memory parallel computers using an LU-based conjugate gradient solver. A distributed concurrent textured algorithm is proposed in [39] to determine the state of the whole grid. A relaxation-based approach is proposed in [40], based on optimization concepts. An implementable distributed state estimator for geographically separated areas is presented in [41]. A Lagrangian relaxation decomposition technique, capable of identifying bad data in a decentralized manner, is presented in [42]. Two algorithms for distributed state estimation and false data detection are proposed in [43]. The distributed state estimation algorithm [44,45] is based on the more relaxed assumption that not all the control areas must be locally observable and that no central coordinator is needed. A testbed is proposed in [46] for evaluating power system distributed applications, considering data exchange among distributed areas.

A critical review of the state of the art in MASE, that significantly enhances and updates an earlier survey on the topic [47], is provided in [48]. Other applications of parallel and distributed processing to power systems are quoted in [49–58].

This paper proposes a distributed approach to solve the multi-area state estimation problem. The overall system is decomposed into a certain number of predefined non-overlapping areas and each area independently executes its own state estimator based on local measurements. A central coordinator receives the estimated values of boundary measurements and states, and computes the system-wide solution. The paper is organized such that Section 2 describes the multi-area state estimation formulation, Section 3 describes the steps and Section 4 provides the MPI based implementation of the distributed state estimation algorithm. Section 5 provides the test results with a 1180 bus system, and Section 6 offers the conclusions.

2. Formulation of the multi-area state estimation problem

Consider that a measured power system, comprising n buses, is partitioned in r non-overlapping interconnected and observable control areas A_i, i.e. areas that have no bus or branch in common and are connected via tie-lines ending at border buses. Each area is assumed to have n_i buses such that $n=\sum_{i=1}^{r} n_i$. The available measurement set may comprise traditional measurements (branch power flows, bus injections, and bus voltage magnitudes) provided by SCADA, as well as synchronized measurements (bus voltage and branch current phasors) provided by PMUs. It is assumed that a PMU can measure both the voltage phasor of its own bus and the current phasors of some or all its incident branches. The polar formulation (magnitude and phase angle) for the current phasor measurements is used as proposed in [59].

Each area is governed by its own *local* computer, that is responsible for estimating its own state, and is connected by communication links to a *coordination* computer. Let $A(i)$ be the set of all buses in area A_i. A bus $k \in A(i)$ is internal in area A_i if all its neighbors $l \in A(i)$. A bus $k \in A(i)$ is boundary at area A_i if some of its neighbors $l \in A(i)$, $j \neq i$. If $I(i)$ and $B(i)$ are the sets of internal and boundary buses of area A_i, respectively, then $A(i) = I(i) \cup B(i)$. According to the measurement classification of Fig. 1: