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Methodology for multiarea state estimation solved by a decomposition method

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ABSTRACT

As power systems are large interconnected systems with a high degree of complexity, the control and operation of such systems become a challenging task. Thus, large-scale power systems are mostly operated as interconnected subsystems. In this paper, the state estimation problem is addressed through a decentralized optimization scheme with minimum information exchange among subsystems. This paper focuses on a methodology for solving the multiarea state estimation problem by a decomposition method. This method is derived from the Lagrangian relaxation method and is named optimality condition decomposition (OCD). Results are presented for the IEEE 118-buses test power system, which has been split into two and three subsystems.

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1. Introduction

The analysis and design of complex engineering systems often require decompose the problem into smaller subsystems in order to handle comprehension and computation difficulties. Decomposition is attractive when a possibly intractable problem may be converted into a set of smaller and simpler problems; it also helps to understand better relationships and tradeoffs among subsystems, which determine the overall behavior of the system. A practical drawback is the increased computational cost for coordinating the subproblem's solution and the linking variables values to achieve the overall system consistency and optimality.

Power systems are large scale systems, requiring analyses that become clumsy and complex. Decomposition techniques may be useful tools for helping to alleviate the appropriate studies. Many classical optimization techniques such as linear programming, nonlinear programming, quadratic programming, Newton and interior point methods have been applied for solving optimal active/reactive power dispatch (ORPD) problems [1,2]. Likewise, evolutionary optimization techniques such as simple genetic algorithms [3], differential evolution [4], evolutionary programming [5], particle swarm optimization [6], evolutionary strategies [7,8], and real coded genetic algorithms (RGA) [9] have been applied. Optimal reactive power dispatch (ORPD) is one of the most cost-effective measures to promote both losses reduction and voltage profile without jeopardizing the system operation. It may be developed as a multi-objective problem that involves objectives such as economical operating condition, system security margin, and voltage deviation [10–14].

In a power system the increment of demand is inevitable, this is due to socio-economic aspects, such as population growth, the development of cities and countries, and the incorporation of new technologies, etc. Therefore, the operating conditions of a power system at a given point in time can be determined if the network model and complex phasor voltages at each bus are known. Since the set of complex phasor voltages fully specifies the system, it is referred to as the state of the system [15].

Estimating the state of the power system, it is possible to take control actions in order to reach a desired operating point. Large-scale power systems are mostly operated as interconnected subsystems, where each one is responsible for a part of the power grid, thus forming a distributed structure operated by a central coordinator. It is often desirable to preserve the autonomy of each subsystem. A decentralized operation can be preserved while still attaining overall optimality by applying decomposition techniques [16]. In this paper, a decomposition procedure is described and applied to solve the state estimation problem of a multi-area system.

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Decomposition techniques are optimization methods applied to mathematical problems that become difficult to be solved directly. These techniques solve many power system problems, and may provide potential advantages in computational efficiency and useful information as part of the decomposition process [16].

From an electrical engineering point of view, the efficient solution of large-scale linear and nonlinear optimization problems may require exploiting any special structure. Examples of special structures that may be exploited in the original model are network constraints, integer and continuous variables, dynamic dependencies, etc. To advantageously apply a decomposition technique, the problem under consideration should have the appropriate structure [17]. Two of the common structures become:

1. *Complicating constraints*: These are common constraints that usually depend on most of the variables and complicate the problem because they prevent that the sub-problems associated with the others variables may be solved separately.
2. *Complicating variables*: These are the common parts of the blocks of constraints that are related to integer variables, and the non common parts are related to continuous variables. Treating integer variables becomes more complicated than treat with continuous ones. The integer variables complicate the problem's solution, or prevent a straightforward solution.

The decomposition of a problem can be evaluated using mathematical techniques of decomposition, allowing to model and apply different solution techniques for each subproblem. The decomposition techniques often used for decomposable mathematical structures are:

- *Dantzig-Wolfe* [18]: applied to linear and nonlinear problems, continuous and noncontinuous, with *complicating constraints*.
- *Lagrangian relaxation* (LR) [19]: applied to linear problems, noncontinuous, with *complicating variables*. Likewise, applied to nonlinear problems, continuous and noncontinuous, with *complicating constraints*.
- *Augmented Lagrangian* (AL) [20,21]: applied to linear problems, continuous, with *complicating constraints*. Applied to linear problems, noncontinuous, with *complicating variables*; and applied to nonlinear problems, continuous and noncontinuous, with *complicating constraints*.
- *Optimality condition decomposition* (OCD) [22]: applied to nonlinear problems, continuous and noncontinuous, with *complicating constraints*.
- *Benders decomposition* (BD) [23]: applied to linear and nonlinear problems, continuous and noncontinuous, with *complicating variables*.

Several decomposition techniques, such as Lagrangian relaxation (LR) [24–26], the relaxation techniques based on augmented Lagrangian (AL) functions [27–29], and the optimality condition decomposition (OCD), are used for dealing with nonlinear problems with decomposable structure, specifically with complicating constraints.

These techniques have been applied in many study cases, among them: multiarea optimal power flow control [16,17,30,31], multiarea decentralized state-estimation [32–35], decentralized power flow optimization [36], distributed control of energy hubs [37–40], economic power dispatch [41–43], voltage control [44–46], and optimal reactive power flow [1]. The OCD exhibits the most efficient computational behavior in many cases [17,47].

In this paper, the proposed methodology for solving the multiarea state estimation problem is the decomposition method OCD, which is employed for analyzing nonlinear problems with complicating constraints with decomposable structure.

The paper is organized as follows. Section 2 describes a brief review of the multiarea state estimation. Section 3 describes the OCD decomposition method. Section 4 proposes the methodology and implementation details. Section 5 illustrates the proposed method; results are presented on the IEEE 118-bus test power system. Section 6 draws the conclusions.

2. Review of multiarea state estimation (MASE)

Multiarea state estimation (MASE) may be classified according to the following criteria [48]: (i) area overlapping level; (ii) computing architecture; (iii) coordination scheme; (iv) process synchronization; (v) solution methodology. According to the criteria, the proposed methodology deals with:

(a) *Non-overlapping areas*: subsystems that do not have common buses nor branches. They are connected by tie-lines ending at border buses, those tie-lines define the interconnecting areas.
(b) *A decentralized architecture*: where each local agent communicates only with those agents in charge of neighboring areas, exchanging border information. There is not a central agent.
(c) *Coordination at the iteration level*: results are submitted for coordination among neighboring areas after each iteration of the local state estimation (SE).
(d) *Process synchronization*: in the decentralized architecture, the process is asynchronous, each local agent performs iterations at its own pace, using the best information available from its neighbors.

In the paper the followed solution strategy relies on a decentralized scheme, with coordination at the iteration level.

Many state estimation problems rely on the conventional weigthed least squares (WLS) formulation. Most hierarchical schemes, at both local and central levels, rely on an iterative scheme to solve the normal equations of concern. In decentralized schemes, with possible coordination at the iterating level, the Lagrangian relaxation-based algorithms are usually adopted.

A category of the MASE approaches formulates the WLS equations as an optimization problem, usually involving a Lagrangian function explicitly handling constraints imposed by network equations and/or boundary conditions.

2.1. Formulation

The problem's formulation consists on an objective function and the constraints. The overall system is decomposed into a certain number of non-overlapping areas or subsystems on a geographical basis [49,50], Fig. 1.

Each area carries out its own state estimation, using local measurements, and exchanges border information (estimated boundary states and measurements) at a coordination state estimator, which computes the system-wide state. It is assumed that all areas S_i are observable. Observability and bad data analysis are accomplished in a distributed manner [49].

The multiarea state estimation problem can be formulated as a constrained WLS minimization problem [49]:

$$\text{minimize} \quad J(x) = r_c^T R_c^{-1} r_c + \sum_{i=1}^{r} r_i(x_i)^T R_i^{-1} r_i(x_i) \tag{1}$$

$$\text{subject to} \quad r_c = z_c - h_c(x) \tag{2}$$

where $J(x)$ is the scalar error function of the estimation; r is the number of non-overlapping areas (or subsystems); z_i is the vector of internal measurements in area S_i; r_i is the residual vector of the estimated internal measurements; r_c is the residual vector of the

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