A Review on Distribution System State Estimation

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Abstract— This paper presents a survey of methods for distribution system state estimation (DSSE) for electric power distribution systems. State assessment has many roots in the monitoring and control of power transmission systems for many decades, which have not yet been widely implemented in distribution grids. However, with low carbon technology, the introduction of distributed generators, more actively managed, intelligent power distribution networks, and improvements in monitoring and communication infrastructure, DSSE is gaining considerable research interest. DESSE presents many unique challenges due to the properties of distribution grids, and many well-established methods used in transmission systems are not directly applicable. This paper presents a detailed survey of the methods available for DSSE, reviewing approximately 60 papers from major journals.

Keywords: Distribution System Status Assessment; Distribution Networks; Distribution Generators

I. Introduction

Since the early development of the concept in the early 1970s [1], the energy system has state estimation (SE)
A crucial part of the operation and maintenance of broadcasting systems worldwide. Until recently, the application of SE at the distribution level, i.e. the Distribution System State Estimation (DSSE), has not been of major interest. This is because distribution networks have traditionally been designed and operated as passive systems, where power flows are unidirectional and easy to predict and manage. However, distribution networks are seeing the penetration of distributed energy sources such as small to medium-sized distributed generation (DG), demand-responsive loads, electric vehicles and storage capacity equipment.

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This has led to a need for better scrutiny of distribution systems and the need for distributed system operators (DSOs) to play a more active role in monitoring and controlling the operation of networks. The DSSE is of crucial importance in this context. Since distribution networks have different characteristics for transmission networks (eg radial structure, high R / X ratios, phase mismatch and very low volume and quality of available measurement data), many of the techniques and approaches developed for "conventional" broadcast-level SE are for DSSE Not directly applicable. Therefore, several SEs specifically designed for application at the distribution level have been proposed in the literature in recent years. However, despite the increasing importance of DSSE, the authors could not find a relevant survey paper in the literature, summarizing the current state of the art and discussing research trends and future directions in the DSSE area. Although there are many survey papers and books with literature reviews in the general field of SE [2] - [11], they deal mainly with methods and techniques applicable to broadcast systems and are not specifically focused on developments and applications of DSSE. This paper aims to fill this gap by providing a survey of the most important methods and algorithms currently available for DSSE. In addition, the use of novel computational intelligence techniques and machine learning approaches and their potential benefits in this context of DSSE will be explored. The paper is structured as follows: Section II describes the main methods and applications of DSSE. Section III describes the current state of the art and highlights some of the more advanced techniques currently available. Section IV discusses the use of computational intelligence methods in DSSE. Finally, conclusions are drawn in Section V.

II. DSSE Techniques and Applications

A. Assessing the state of a traditional power system

SE is used to improve system monitoring, to check for and detect errors in both system dimensions and network parameters, and to minimize measurement and communication against system noise. Detailed summaries of the main methods and applications of SE of conventional electrical systems can be found in [3] - [5].

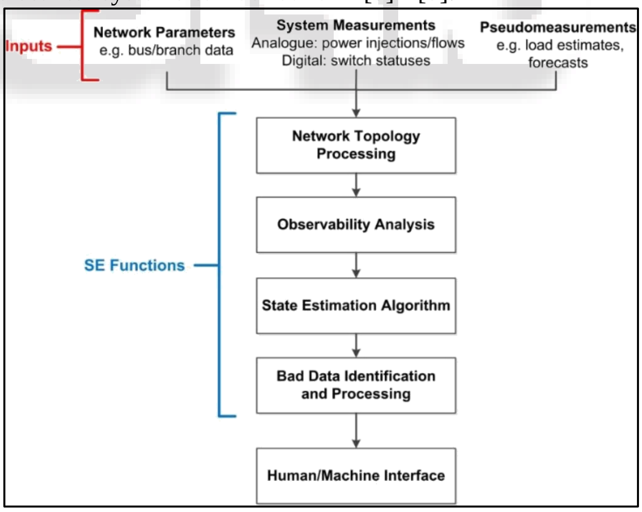

Fig. 1: Graphical overview of major processes and information flows

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Fig. 1 shows a graphical overview of the main processes and information flows. First, the topology processor verifies that the network parameters (eg line and switch conditions) provided to the estimator are correct, which ensures that the network model is accurate and up to date [12] - [15]. Subsequently, observational analysis confirms that adequate measurement data are available for SE. Observability can be quickly determined by examining the null space of the

Jacobian matrix [16]. If the network or its components cannot be observed, it is necessary to provide the estimated values of the network inputs (often referred to as duplicate dimensions). SE uses available measurement data to find a solution specific to the system state. Finally, bad data processing is used to identify and delete data affected by gross errors and noise, e.g. Due to measurement or communication system failures [17] - [21].

One of the problems posed in general SE is the computational complexity of solving the objective function of the SE, which is linear and continuous. To reduce the computational load, some authors have proposed a fast-decomposed SE [22], or direct-current (DC)-only SE by ignoring all branch resistance and shunt elements [5]. However, the methods and assumptions used in the broadcast-level SE described above are often invalid when considering distribution systems

The well-established methods used in "traditional" SE are not directly applicable [23]. This prompted research on the DSSE, that is, a state assessment designed specifically for use in distributed networks.

C. *State of Distribution System Assessment*

Initial research on DSSE began in the 1990s [24] - [27]. DSSE presents many new challenges because the characteristics of distributed networks differ from broadcast networks in the following ways:

Structure: Most distribution networks have a radial structure (though broadcast systems are more mesh), often with higher R / X ratios.

Repeat: For technical and economic reasons, the number of measurement points in distributed networks is much lower than in broadcast networks. Systems tend to be over-determined, not over-determined.

Types of measurement: Most input data available at the distribution level are measurements (or duplicate measurements) of power or current injections. Direct measurements of voltages and energy flows are rare.

Scale and complexity: Distribution systems are diverse (eg, rural networks are very different from urban areas) and have a large number of components. This means that the methods developed for the DSSE must be scalable, have relatively low computational burden, and apply across a variety of network types.

Phase Imbalance: Traditional SE methods assume a network balanced system. However, distribution systems have a significant phase mismatch, which requires the use of complete three-phase system models. Some of the techniques developed to overcome these problems are discussed below.

1) *Converting traditional WLS techniques to DSSE:*

Previous research papers on DSSE have focused on adapting most traditional WLS methods to distributed networks [24], [26] - [28]. However, there are significant limitations in adopting procedures from broadcast-level SE to DSSE, particularly in dealing with noisy input data and "visibility", that is, the ability of the estimator to reach a specific solution in the presence of gross input errors [29]. In addition, due to the structure of distribution systems (radial feeders and high R / X ratios), fast decoupled methods and DC estimators that are often applied in traditional SE do not work when applied to DSSE [30].

2) *Load estimation for DSSE:*

In DSSE, the number of telemeter devices that can provide system measurements is very limited, and is insufficient to allow for the overall network's verifiability or bad data detection. In many cases, the DSSE relies on duplicate measurements of demands at each load point on the network, based on historical data or load instructions.

Less accurate than actual measurements. Load estimation methods and their application to DSSE are discussed in [31] - [33].

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3) *DSSE on Unbalanced Networks:*

In [25], a branch current-based SE methodology is developed, in which network branch currents, rather than node voltages, are used to represent the system state x. The Jacobian matrix H can be decomposed on a per-stage basis, allowing traditional SE methods to be applied to distribution systems that contain unbalanced or single-phase or two-phase lateral feeders. Several papers have developed this approach to develop robust and accurate three-stage DSSE methods [34], [35].

III. State of the Art

This section briefly describes some advanced techniques and applications of DSSE in the literature.

A. *Reference-assisted state assessment*

The SE methods discussed in Section II are consistent, in which the estimation of the system state depends only on the current "snapshot" of the input measurements and not on the previous input data values. There are also SE techniques designed to repeatedly update the state estimate to detect changes during normal operation. This approach is called "dynamic" SE [36], but many authors prefer the term "forecast-aided state estimation" (FASE) to avoid confusion because the term "dynamics" in power systems is associated with transient stability studies. An excellent summary of the key concepts in FASE is given in [9]. Most FASE systems model the system using the state-space form introduced in [37] and the Extended Kalman Filter (EKF) [38]. A short-term indication of state variables (eg several seconds / minutes ahead) is made, and each time new measurements become available, "innovation analysis" can be used to determine whether the new measurements are significantly different. values are values of [39] - [41]. This analysis filters out new input data using EKF equations, allowing for the detection of bad input data and anomalies such as network configuration or parameter errors [37]. Although most FASE methods and applications proposed to date have been streamlined, FASE approaches are also interesting to DSSE, especially if high-resolution data such as phaser measurement units (PMUs) [42] are available from synchronized metering devices. , [43].

B. *Multi-Area and Hierarchical DSSE Techniques*

Since distributed systems are usually very large and dense (eg having several thousand individual nodes), one of the most challenging aspects of implementing a DSSE is computational complexity. In traditional SE methods, all measurements are typically processed in one centralized SE. However, a better solution for large distribution systems Networks can be divided into several smaller sub-networks or "measurement areas" in which the SE is resolved locally [44] - [46]. The multi-region SE system is modeled as introduced in [47].

In the multi-region approach, the SE is resolved locally in each measurement area and only the data are exchanged between the regions where they are bounded by each other. In [46], a multi-region method for DSSE has been developed that meets the performance requirements of real-time applications on most large networks. Traditionally, broadcast-level and distribution-level SE have been developed separately. However, with increased requirements for communication and interaction between transmission and distribution network management systems, and many authors investigating the development of multi-level or hierarchical SEs designed to integrate Transmission SE and DSSE [48], [49].

IV. Computational Intelligence Methods in DSSE

RESs, as well as var compensators, VRs, need to use ULTC transformer global minimaxing algorithms with discrete operation and shorter convergence time. Conventional algorithms, by contrast, require continuous and distinct objective functions and constraints, employing evolutionary algorithms and expert systems such as neural networks and genetic algorithms. Computational Intelligence Methods
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Proposed for applications of energy systems and smart grids. Machine learning techniques are particularly attractive to DSSE. Artificial neural networks have already been widely used in energy systems research literature for load estimation and estimation [50]. In [51], a neural network approach is used to create pseudo-measurements of load point power injections for use in the DSSE algorithm. In [52], the machine learning approach is used to develop load estimates for the DSSE. The advantage of this approach is that load models are designed to re-train themselves when more measurement data become available, which improves the performance of the DSSE over time. Further research on the implementation of “closed-loop” DSSE methods is needed. While almost all SE methods proposed in the literature have open-loop data flow, the data used to estimate closed-loop DSSE loads (and DG outputs) allows the attendee database to be constantly updated and improved based on feedback from SE [53], [54]. The "autonomy" approach to DSSE is demonstrated in [55], in which the DSSE is designed to automatically identify new connections to the distribution network (eg from DG units) and update the system model accordingly. Further application of machine learning techniques is critical in allowing DSSE to be implemented on a large scale. Without the automation of majority control and network model management functions, the implementation of the DSSE in all distributed networks within a DSO area leads to an unreasonable increase in the operator's workload. Future DSSEs are likely to make extensive use of event-inspired approaches, especially to perform sophisticated DSSE functions that require considerable computational effort such as model identification [56], [57]. Karyakramanlo triggered approach, the relevant DSSE is function carried out locally (i.e. in the network Area of interest), only when the dimensions received indicate a potential problem, e.g. Suspected network topology error. This approach is particularly important in the context of DSSE model identification, where the goal is to identify the optimal network model from a range of possibilities. Model identification is particularly relevant in distributed systems where switching conditions across the network are generally not monitored. The authors of [58] have proposed the development of a model bank, in which network configurations that are crucial to DSSE are stored. Based on the DSSE results applicable to each network model, the model with the highest likelihood is chosen as a real network configuration using a redundant Bayesian approach. A three-step state estimation method was developed to increase the accuracy of the load data [31]. The authors presented a method based on Honey Bee Mating Optimization (HBMO) for DSSE, including DGs [58] and used Particle Swarm Optimization (PSO) in [59]60] performed an artificial bee colony (ABC) algorithm based DSSE for distribution networks with DGs. The authors of [61] have developed the Nelder-Mead Simplex Search and PSO (PSO-NM) -based DSSE, which can predict the output and load of the digitalis.

V. Conclusion

This paper presents a detailed survey of methods and applications of state estimation in electric power distribution networks. It discusses the DSSE of novel computational intelligence methods. Despite the high level of research interest over the past two decades, DSSE has not been widely implemented in distributed networks. This is mainly due to the lack of investment in information and information technology infrastructure at the distribution level. However, it is becoming increasingly clear that DSSE plays an important role in the management of future distribution networks, as these systems become more active and complex due to the penetration of variable, highly-dispersed resources, e.g. Small-scale renewable energy, demand-responsive loads, electric vehicles, power storage and micro grids.

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