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Heuristic monitoring method for sparsely measured distribution grids

Jan-Hendrik Menke [a,*], Jan Hegemann [a], Stefan Gehler [a], Martin Braun [a,b]

[a] Department of Energy Management and Power System Operation, University of Kassel, Wilhelmshöher Allee 71 - 73, 34121 Kassel, Germany
[b] Fraunhofer Institute for Wind Energy and Energy System Technology, Königstor 59, 34119 Kassel, Germany

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ABSTRACT

There is an increasing interest in operating the power system close to its limits in order to avoid grid reinforcements. Distribution management requires the knowledge of grid state parameters, but outfitting grids with a large amount of measurements is costly. Therefore, we developed a new heuristic monitoring method (HMM) for balanced grids that relies only on few mandatory measurements and enables a fast way to monitor the grid for off-limit conditions. Due to a new formulation of the power flow equations, it has a low computational complexity for radial grids. The method analyzes the network topology; network buses are categorized and sorted into branches. Depending on the location of available voltage measurements, the bus powers of the corresponding branches are adjusted iteratively to better fit the measured voltage. To test the performance of our new algorithm, we design an evaluation process to compare our approach with the standard weighted least squares (WLS) state estimation (SE) method. Simulation results on artificial and real unmeshed distribution grids on the medium voltage (MV) level show very promising results, outperforming the WLS estimator even with a high amount of distributed generation (DG).

1. Introduction

For the operation of a power system, crucial parameters like voltage magnitudes and line loadings have to be known at all times. Depending on these values, the operator can choose measures to maintain operational constraints.

Today's distribution grids are mostly unautomated. Measurements usually exist only at the substation if at all. At the same time an evermore increasing number of flexible producers such as wind or photovoltaic generators (PV) make power flows more and more difficult to predict and potentially increase the strain on the power system. Measures to increase the grid's hosting capacity should be as technically and economically efficient as possible [1]. Creating a redundant measurement infrastructure is often not an option for grid operators due to the associated high investment costs [2,3]. Therefore, there is an increasing interest in operating the power system close to its limits. This necessitates some sort of monitoring system. Since maximum likelihood SE cannot be performed due to the lack of measurements, a monitoring system will merely be guessing the complete system state from a small set of measurements. To ensure its effectiveness in providing estimates for relevant parameters in certain boundaries, we suggest a simulation data-driven approach to validate the monitoring method. Thanks to rising processing power, a large number of simulations can be performed with a wide range of grid scenarios. This allows the analysis of the expected margin of errors between simulated, exact parameters, and the parameters which are approximated by the monitoring method. Our iterative monitoring method consists of three parts:

1. A new formulation of the power flow algorithm for radial networks which, compared to the backward-forward sweep, only uses one iteration and has a low computational complexity.
2. A new process to approximate grid variables in defined tolerances if a very low amount of measurements is available (see Fig. 1 for a typical result).
3. A comprehensive simulation and test process to compare different grid monitoring methods extensively.

Afterwards, we present results from one real and two artificial distribution grids generated with the new process to show the quality and robustness of our method in comparison to the standard WLS method.

2. Review of monitoring approaches

Approaches to power system monitoring can be classified in different ways. On the one hand, there are SE methods, in which an optimization problem is solved analytically or by heuristic

* Corresponding author.
E-mail address: jan-hendrik.menke@uni-kassel.de (J.-H. Menke).

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Fig. 1. Typical voltage profile approximation by our monitoring method and the WLS algorithm as a reference. The exact voltage is shown for comparison.

optimizers. On the other hand, if the amount of measurement is too low, monitoring methods try to make accurate guesses as to the system state. In this section, a brief review of existing monitoring methods, tailored specifically to distribution grids with few measurements, will be given.

2.1. State estimation without measurement redundancy

The standard process to estimate the grid state, WLS SE, is widely used in operational control centers of transmission grids [4]. It was first developed by Schweppe et al. in the late 1960s and early 1970s [5]. A high number of (redundant) measurements are processed in such a way that the resulting state minimizes the squared errors between the calculation and the measurements. The minimum amount of measurements needed for observability is $m = 2n - 1$, where m is the number of measurements and n the number of network buses. The estimated state vector consists of complex voltages for all buses, from which all power flows in the grid can be derived.

To compensate for the missing measurements in distribution grids, it is possible to introduce new types of measurements until the $m \geqslant 2n - 1$ criterion is met and WLS SE can be applied. Virtual measurements are measurements that can be inferred from the surroundings, for example network buses without power injections (muffles). Pseudo measurements are power injection measurements which are created by prognoses rather than direct measurements [6]. Information about the consumers and producers at a specific bus is combined with load profiles, weather conditions and further information to form a pseudo measurement for that bus (see [7]). The combination of real measurements, virtual measurements and pseudo measurements can be sufficient for WLS SE [8]. The drawback is the lower accuracy of the estimated state due to inherently inaccurate nature of the pseudo measurements. Another drawback is the need for additional information about customers at the unmeasured buses and further complexity due to weather prediction (used for PV, wind generation).

In [9], the WLS estimator is extended by a second optimization problem which adjusts the WLS-estimated bus power injections to match measurements more closely. There is a small positive effect on the accuracy which depends strongly on accurate measurements.

2.2. Alternative approaches

Different methods have been developed to approximate grid variables with few measurements. In [3], a method to calculate the state of low voltage (LV) grids with few measurements is presented. Instead of using a state estimator, a load-flow approach is taken. A network is split into areas; the boundaries are where incoming and outgoing power flows are measured. The measured power going into an area is divided onto the unmeasured buses inside, either linearly or to create a worst-case result. A power flow calculation (PFC) generates the resulting grid state.

A mixture of a genetic algorithm and a particle swarm optimizer to minimize the difference between calculated and measured values is used in [10]. The amount of measurements is very low compared to the amount of buses. Unmeasured buses get assigned contracted load values with lower and upper limits, which can change over multiple iterations. Power generated by DG is either added as a fixed value or an optimization variable. The algorithm is able to find very accurate solutions to match the measurements, however it is unknown if the unmeasured state variables are matched well by the estimation.

In [11], the problem of missing measurements is solved by rearranging power flow equations for the existing measurements through Hamiltonian cycle theory. Arranged in this manner, all state variables for a power system can be calculated by a backward-forward sweep power flow calculation for the test cases. Voltage magnitudes are approximated with artificial neural networks in [12]. After a training phase, the measurements are fed into an artificial neural network which outputs the voltage magnitudes of a test feeder. It is discussed in [13] that a simulation-based load estimation can be performed in the software openDSS if its load allocation methods are used to adjust load estimates when combined with a new random search algorithm. In [14], a load scaling procedure is combined with a power flow to iteratively match bus power injections with measurements.

Our approach differs in that we try to minimize the voltage differences while adjusting bus powers of a complete branch. The aim is not to get an accurate load allocation, but an overall voltage profile and line current magnitude estimate to determine off-limit conditions.

3. Grid monitoring by heuristic power adjustment

Contrary to transmission grids, where the knowledge of all power flows is required for safe grid operation, distribution grid operators fear off-limit conditions of voltage and line currents due to high amount of DG [1]. These can be checked for by monitoring both the voltage magnitudes and the line loadings of a grid. Therefore, our method does not aim at estimating the grid state and focuses on both aforementioned variables.

The approach is load-flow based and suitable for grids with a very low amount of measurements. Critically, voltage magnitude, active and reactive power flow through the transformer have to be measured at the substation. At least another voltage magnitude measurement has to exist in the grid. The power of DG is ideally measured as well (often a priority in grids with high distributed energy resource (DER) penetration, e.g. Germany's BMWi rollout strategy [15, p. 5f.]). Measurements of different types (bus power injections, line power flows, line currents) can be added, but are not mandatory to the method's functionality. The method is described using different exemplified grids. In this paper, we concentrate on radial grids, which is a common grid structure on the distribution level [16]. Nevertheless, a simulation with a meshed network shows the general feasibility of the method. For now, we only use balanced grids.

3.1. Proposed heuristic monitoring method

A flow chart of the algorithm is displayed in Fig. 2: Nonrecurring tasks, e.g., setting substitute load values for unmeasured buses, are performed before the measurements are processed iteratively.