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# Off-line tracking of series parameters in distribution systems using AMI data☆

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ABSTRACT

In the past, electric distribution systems have lacked measurement points, and equipment is often operated to its failure point, resulting in customer outages. The widespread deployment of sensors improves distribution level observability. This paper presents an off-line parameter tracking procedure that leverages the increased deployment of distribution level measurement devices to estimate changes in impedance parameters over time. Parameter tracking enables the discovery of non-diurnal and non-seasonal changes, which can be flagged for investigation. The presented method uses an unbalanced distribution-system state-estimator and a measurement-residual based parameter-estimation procedure. Measurement residuals from multiple measurement snapshots are combined to increase effective local redundancy and improve robustness to measurement noise. The input data used in the experiments consists of data from devices on the primary distribution system and from customer meters, via an AMI system. Results of simulations on the IEEE 13-Node Test Feeder with 307 measurements and 246 parameters are presented to illustrate the proposed approach applied to changes in series impedance parameters. The proposed approach can detect a 5% change in series resistance elements with 2% measurement error using less than 1 day of measurement snapshots for a single estimate.



## 1. Introduction

Historically, electric distribution systems have lacked observability and equipment has been operated to the point of failure, resulting in temporary loss of load while repairs or replacements are carried out. One example is a cable splice failure, in which joints that are made between cables on the primary of a distribution feeder degrade over time and then either fail to maintain conductance along the line or short to ground after the insulation degrades [1]. Techniques have been developed to anticipate these failures, including field measurements of temperature [2] or waveform monitoring [3], but they require the deployment of additional equipment. Other examples of equipment failure that will result in a change of series impedance values over time include breaker contact degradation and transformer shorting. The degradation of breaker contacts over time due to arcing leads to growing impedance and eventual failure. Transformers that are operated above their power rating can experience pinpoint insulation breakdown, resulting in a short between adjacent windings. All of these equipment failure could be avoided with an algorithm that can track series impedance over time.

In transmission systems, techniques such as state estimation (SE) and parameter estimation (PE) have been used to track the state of the system and to estimate system parameters [4]. Some distribution systems have added a sufficient number of measurement points to adopt those same techniques with the deployment of advanced metering infrastructure (AMI). While the primary purpose of deploying AMI revenue metering automation, the data collected can be used by other applications, including SE and PE.

SE in transmission systems dates to the 1970s [5], and several approaches to a theoretical framework specifically tailored to SE on unbalanced distribution systems were developed in the 1990s [6–8]. The practical application of distribution system (DS) SE has become feasible in recent years with the rapid increase in DS measurement points—including intelligent switches, various automation devices, AMI, and micro-Phasor Measurement Units. Practical details of DS SE techniques have been extensively studied. These studies include robust approaches to radial DS with low redundancy [9–12], and measurement fusion across different systems at different time intervals [13]. This paper extends the previous work on transmission system PE to DS.

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PE requires the same measurement set and system model as SE and builds on SE algorithms [4,14]. Examples of parameters that can be estimated include series impedance of cables, transformer impedance, and regulator tap settings. This paper considers series impedance of cables, but the other two examples can be addressed by the algorithm developed herein. First proposed in 1974 [15], the technique of augmenting the state vector with a set of suspect parameters has been widely studied [16–20]. An alternate approach, which is adopted in this paper, makes use of normalized measurement residuals [21–23], a byproduct of the SE procedure. The authors of [24] proposed a method for identifying incorrect network parameters based on simple equality constraints and normalized Lagrange multipliers.

Measurement redundancy and noise can be limiting factors in PE. There is, however, an approach to mitigate low redundancy and high noise. This is achieved by combining information from multiple measurement snapshots into a single PE update (e.g., consecutive supervisory control and data acquisition (SCADA) samples). The technique has been successfully applied at the transmission level for parameter error identification using a measurement residual-based approach [25] and to off-line multiple-state-and-parameter estimation with an augmented state vector [26].

Previous work in power system PE has been confined to transmission systems, where high measurement redundancy is typical and a reduced-order single-phase model is used [4]. This paper outlines a process that includes full three-phase unbalanced DS SE and tracking of estimated parameters over time in order to identify changes in parameter values. While DS SE has been explored extensively in recent years, PE techniques have so far not been applied to distribution systems.

As in previous papers, a combination of SCADA and AMI measurements is used as the data set. A measurement-residual based approach for the calculation of parameter values is adopted. The technique of combining multiple measurement snapshots, used in order to increase effective local redundancy and improve the robustness of estimated parameters to noise, is applied for the first time to the measurement-residual based method of PE. Finally, a standard statistical test, the two-sample *t*-test [27], is applied to determine whether a parameter has had any statistically significant changes over time.

The paper is organized as follows: Section 2 gives an overview of the SE and PE algorithms that form the foundation of the approach developed in this paper. Section 3 presents the measurement dataset and Section 4 an experimental simulation of DS series parameter estimation. Section 5 concludes the paper and sets out future work.

## 2. State estimation and parameter estimation fundamentals

In this section, a brief overview is given of the state and parameter estimation techniques that form the basis of the proposed parameter tracking algorithm. The weighted least squares (WLS) approach to SE is used, and parameter values are estimated using residual sensitivity analysis.

### 2.1. Weighted least squares state estimation

The authors of [10] apply several SE approaches to a DS and conclude that WLS is preferred for DS. The inputs to the SE process are a redundant set of measurements and a mathematical model that relates those measurements to the state variables. The parameters of the system, including series and shunt impedances, regulator tap positions, and shunt capacitor states, are used to formulate the mathematical model. The state variables are the nodal voltage magnitudes and phase angles. The three-phase formulation of WLS necessary for DS SE was described in [8].

The relationship between the measurement vector $z$ and the state vector $x$ is given by a vector of nonlinear equations, $h$, with measurement error vector $e$.

$$z = h(x) + e. \tag{1}$$

The state of the system is estimated by minimizing the objective function $J(x) = [z - h(x)]^T R^{-1} [z - h(x)]$, where $R$ is the covariance matrix of measurement errors. Due to the nonlinearity of the system, a direct solution is not possible and an iterative, gradient descent, approach is taken. A first-order Taylor-series approximation is used. Updates to the state vector are iteratively applied until smaller than a threshold, at which point the SE has converged to an estimate. A necessary condition for SE is that the system must be observable (i.e., the Jacobian matrix $\partial h(x)/\partial x$ must be full rank at every iteration) [4].

### 2.2. Residual sensitivity approach

The parameter tracking approach adopted here uses the measurement residuals that are calculated when SE completes [4]. The sensitivity matrix gives the relationship between residuals and measurement errors,

$$r = Se \tag{2}$$

where: $r$: measurement residuals, $S$: sensitivity matrix

A linear relationship can be found between measurement residuals and parameter errors [21].

$$r_s = \left( S_{ss} \frac{\partial h_s}{\partial p} \right) \varepsilon + \overline{r_s} \tag{3}$$

where: $_{ss}$: the subset of measurements that are impacted by $p$, $S_{ss}$: sub-matrix of $S$ corresponding to measurements related to $p$, $h_s$: nonlinear functions relating measurements to states, $\overline{r_s}$: residual from true parameter value, $p$: parameter, $\varepsilon$: error in parameter value

The relationship given in (3) can be interpreted as a local estimation problem and the optimal value of $\varepsilon$ in the least squares sense can be computed. A detailed mathematical development for (4) from (3) can be found in [21]:

$$\varepsilon = \left[ \frac{\partial h_s^T}{\partial p} R_s^{-1} S_{ss} \frac{\partial h_s}{\partial p} \right]^{-1} \frac{\partial h_s^T}{\partial p} R_s^{-1} r_s \tag{4}$$

where: $R_s$: sub-matrix of the covariance matrix $R$ of measurement errors.

The measurement residuals are a byproduct of the SE process, but the calculation of $S$ requires an additional post-SE step to calculate and involves inverting the Gain matrix [4]. Because the size of the Gain matrix scales with the size of the system and the size of measurements, the computation becomes more computationally taxing as system size increases. Note that only the subsets of the matrices corresponding to the measurements that are affected by the selected parameter value are used. For the estimate of a series resistance of a section of cable, only the power injection and voltage magnitude measurements at the nodes on each end of the section and the power flow measurements on the section are used. Since each calculation requires only local information, the computational burden of calculating $S$ could be reduced by adopting the methods described in [11]. The SE problem is factorized into a hierarchical set of SE problems, which interact through a few boundary points. This approach is well-suited to SE on distribution systems with radial topologies, where there are clear subsections and well-defined interface points. Once the factorized SE has been solved, $S$