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Exploiting autoencoders for three-phase state estimation in unbalanced distributions grids

P.N. Pereira Barbeiro[a,b], H. Teixeira[a,b], J. Krstulovic[a,b], J. Pereira[a,b], F.J. Soares[a,b,*]

[a] INESC TEC—INESC Technology and Science (formerly INESC Porto), Porto, Portugal
[b] Faculty of Engineering, University of Porto, Porto, Portugal

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ABSTRACT

The three-phase state estimation algorithms developed for distribution systems (DS) are based on traditional approaches, requiring components modeling and the complete knowledge of grid parameters. These algorithms are capable of dealing with the particular characteristics of DS but cannot be used in cases where grid topology and parameters are unknown, which is the most common situation in existing low voltage grids.

This paper presents a novel three-phase state estimator for DS that enables the explicit estimation of voltage magnitudes and phase angles in all phases, neutral, and ground wires even when grid topology and parameters are unknown. The proposed approach is based on the use of auto-associative neural networks, the autoencoders (AE), which only require an historical database and few quasi-real-time measurements to perform an effective state estimation.

Two test cases were used to evaluate the algorithm's performance: a low and a medium voltage grid. Results show that the algorithm provides accurate results even without information about grid topology and parameters. Several tests were performed to evaluate the best AE configuration. It was found that training an AE for each network feeder leads generally to better results than having a single AE for the entire system. The same happened when different AE were trained for each network phase in comparison with a single AE for the three phases.

1. Introduction

The operation and management of distribution systems (DS) is becoming more complex due to the multitude of assets that are starting to be deployed in these networks. New storage devices, flexible loads, microgeneration units, distributed generation and electric vehicles can be very useful to improve DS efficiency, but only if new operational methods and tools are used by distribution system operators (DSO) to efficiently manage and control all these distributed resources. A tool of unquestionable value for this purpose is a state estimation (SE) algorithm suited for DS. Such tool will aid the DSO to monitor and operate the DS in quasi-real-time, similarly to what already happens in transmission networks.

The majority of the SE techniques existing nowadays are based on conventional methods, being the most common the weighted least squares (WLS) [1]. These methods were initially designed for transmission networks and their success relies on the complete knowledge of grid technical parameters and topology and a big amount of quasi-real-time measurements available (high redundancy).

Although conventional methods are very accurate for transmission networks, their application to DS is not straightforward since these networks usually have multi-phase lines (sometimes with an asymmetrical cable infrastructure), loads and microgeneration/dispersed generation unevenly distributed among phases and a reduced number of quasi-real-time measurements available. An even more important issue is the lack of information about network topology and parameters, particularly at the low voltage (LV) level.

Some changes to traditional SE methods have been proposed in the literature, which make them capable of coping with some of the DS characteristics. When the number of quasi-real-time measurements is not enough to guarantee observability of a WLS state estimator, pseudo-measurements can be generated using historical data or load curve assessment, as described in [2–6]. The authors of [7,8] developed WLS based methods to perform single-phase

* Corresponding author at: INESC TEC (formerly INESC Porto), Campus da FEUP, Rua Dr. Roberto Frias, 378, 4200-465 Porto, Portugal. Tel.: +351 22 209 4212; fax: +351 22 209 4050.
E-mail address: fsoares@inescporto.pt (F.J. Soares).

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AE	autoencoders
ANN	artificial neural networks
DMS	distribution management systems
DS	distribution systems
DSO	distribution system operator
DTC	distribution transformer controller
EPSO	evolutionary particle swarm optimization
GPRS	general packet radio service
HLRR	hidden layer reduction rate
LV	low voltage
MSE	mean square error
MV	medium voltage
POCS	projection onto convex sets
SE	state estimation
WLS	weighted least squares

SE assuming a smart grid scenario [7,8]. The contribution of phasor measurements units to enhance distribution SE algorithms has been analyzed in detail in [9–11]. In other works, such as [2,12], authors have applied artificial neural networks (ANN) to estimate system state variables. In all these studies, the unbalanced nature of the DS was never taken into account (balanced load conditions were always assumed). This is a key point since only a three-phase analysis allows getting a complete quasi-real-time snapshot of the system, something indispensable for its correct monitoring and control. As an example, in case of emergency conditions (e.g. over or under voltage profiles), three-phase SE may be used to implement precise load control actions to the costumers that are effectively contributing for the problem instead of affecting all the clients in a given area.

This issue is tackled in several publications available in the literature that specifically address the three-phase state estimation topic [13–19]. Two common points can be found in these works: neutral voltage is never explicitly estimated since Kron's reduction is usually applied; and the algorithms are based on complex three-phase mathematical equations that require the total knowledge of grid technical parameters and topology. As in the majority of these works phase-to-neutral voltage is disregarded, the voltage imbalance is often miscalculated. This inaccuracy is particularly important in 4-wire LV grids, where connection of single-phase loads provokes imbalances in the system and the appearance of a return current divided by the neutral and ground circuits. This results in a reduction of phase-to-neutral voltage for single-phase customers. The importance of knowing voltage and neutral currents becomes evident when observing the more common neutral designs in DS, which are normally favorable to the appearance of neutral and ground currents (due to the unbalanced nature of the loads). Knowing neutral voltages has also a great importance when its use is related with power quality, safety or energy losses. Taking into account the size and complexity of some DS, it is reasonable to admit that a three-phase state estimation tool based on the conventional approaches will increase the computational burden in a considerable manner. This would probably make these techniques unfeasible for quasi-real-time applications.

An effective distribution SE algorithm should therefore be capable of dealing with all the particular characteristics of DS, take advantage of the telemetry measurements that may be available (both in quasi-real-time or historical records stored in distribution management systems—DMS) and, at the same time, be fast enough to run in quasi-real-time.

This paper proposes an innovative method for complete three-phase state estimation (voltage magnitudes and phase angles in all phases, neutral and ground wire), which is based on the use of a particular kind of ANN—the autoencoders (AE). The method takes advantage of the data gathered from the smart metering infrastructure, both in quasi-real-time and historical, and then uses artificial intelligence capabilities to learn the behavior of the grid and accurately estimate the state of the system at any moment. This avoids two vital steps of the traditional state estimation algorithms: (1) modeling the complex three-phase equations, which may lead to heavy iterative algebraic calculations and numerical/convergence problems and (2) characterizing all the grid parameters, which are often unknown in LV grids. Another important feature is that the proposed method is very flexible regarding the type of electrical variables that can be passed to the SE algorithm, meaning that a full exploitation of all the available telemetry information is always performed. In other words, measurements such as active/reactive powers consumed or generated, active/reactive power flows, current magnitudes, voltage magnitudes/phase angles, power factors, and even energy measurements can be used whenever they are available in quasi-real-time. For all these reasons, the proposed method can be used for any grid, independently of the neutral and earthing system adopted type of loads/generators present in the system and quasi-real-time measurements available.

The algorithm performance was tested in two typical Portuguese distribution grids: a 4-wire LV grid with several single and three-phase loads, microgeneration units and smart meters and a 3-wire medium voltage (MV) grid with distributed generation, residential and industrial clients and different telemetry technologies. Accuracy and running times were analyzed under different conditions. The tests performed included: varying the number of neurons in the AE hidden layer, different AE types (global vs. local) and different scenarios regarding number and type of technologies capable of transmitting measurements in quasi-real-time. For the purpose of this work, the term "quasi-real-time" is used in the sense of measuring the variables in a short period of time, around 15 min (or even less, depending on the communication infrastructure).

2. Autoencoders applied to the three-phase state estimation problem

AE are frequently applied in areas related with pattern recognition and reconstruction of missing sensor signals [20,21]. Their application in the power systems area is confined to a few works. In two interesting papers, [22] and [23], the authors used AE to reconstruct missing measurements in the SCADA of the DMS, to identify errors in breaker status and to find the power system topology. Nevertheless, the use of AE as "the core" of a three-phase state estimation algorithm was never implemented nor tested. AE, or auto-associative neural networks, are feedforward neural networks where the size of the output layer (number of neurons) is always equal to the input layer. The typical architecture of an AE is a neural network with only one middle layer (Fig. 1). This simple architecture is frequently adopted since in the generality of the applications, networks with more hidden layers does not bring any benefit and have proved to be more difficult to train [24].

With adequate training, an AE learns the data set pattern and stores in its weights manifold information about the training data. The training process of an AE is conducted to display the output equal to its input. The first half of the AE approximates the function f that encode the input space to the space compressed S'. For an input space composed by an n-dimensional input vector x_k (k = 1, 2, . . ., n), the output values of the hidden neurons form a m-vector given by:

$$h_p = f_a\left(W_{a_{(m,n)}} x_k + B_{a_m}\right), \quad k = 1, 2, \ldots, n \text{ and } p = 1, \ldots, m, \qquad (1)$$