Best-practice guide for quasi-dynamic state estimation   
with the nodal load observer (NLO)

# Introduction to quasi-dynamic state estimation

Static state estimation is a standard procedure in power network analysis to obtain information at all system buses at a given time point. That is, a single set of measurements is used to estimate the system state at one snapshot in time, traditionally by using the weighted least-squares method. However, with such an approach the information contained in the evolution of the system state over consecutive time instants is not taken into account. To this end following the changes of the system by means of quasi-dynamic state estimation is usually proposed. Typically, such methods utilize forecasting of future values, and are thus also known as forecasting aided state estimation (FASE). A typical assumption in this setting is that the system has slowly changing states and that measurement errors can be modelled by Gaussian noise with zero mean and known covariance.

Many state estimation methods developed for the transmission level cannot be implemented at the distribution level without essential changes mainly due to the sparsely instrumented middle- (MV) and low-voltage (LV) grids. Consequently, to ensure observability of the system, so called pseudo-measurements are required. These pseudo-measurements are usually based on historical data or knowledge about controller set points in the grid, and can therefore differ from the real values signiﬁcantly. Hence, large uncertainties are associated with their values, which affects the overall state estimation quality. To this end, the so-called nodal load observer (NLO) has been proposed recently. This method is a disturbance observer based on an extended Kalman ﬁlter as a dynamic state estimation technique. The NLO aims to correct possibly incorrect pseudo-measurements of bus power and then determines the grid state based on reconstructed and corrected values of nodal power and voltage. That is, the NLO proposes not to use directly the possibly incorrect pseudo-measurements, but rather to make use of all available measurement information.

The nodal load observer uses topology information, such as the network model and line impedances, to set up the mathematical model for the relation between nodal voltages and powers. Uncertainties about the measured nodal voltages are considered explicitly in the measurement equation of the state-space model as the measurement noise process

(1.1a)

(1.1b)

where in the standard nodal load observer denotes the vector of measured nodal voltages. As the essential feature of the nodal load observer is the estimation of the errors in the pseudo-measurements, the states (1.1a) are given as

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The nodal load observer utilizes a dynamic model for the evolution of the errors in the pseudo-measurements. A very simple model is given, for instance, by assuming that these errors can be described as a random walk

(1.2)

with

The resulting general model for the nodal load observer is thus given as

(1.3a)

(1.3b)

with matrix denoting the dynamic model employed. The covariances and , associated with the model noise process and the measurement noise , respectively, are assumed to be known.

The equations of the Kalman filter are then given as

In the Kalman filter, uncertainties associated with the measurements are taken into account as noise processes as long as the corresponding state-of-knowledge distribution is Gaussian.

The Kalman filter provides an estimate of the state error covariance for which it was shown in the GridSens project that it represents an uncertainty associated with the state estimate in line with the *Guide to the Expression of Uncertainty in Measurement* (GUM). Consequently, the uncertainties associated with the estimated pseudo-measurement errors can be used to propagate uncertainties from the measured network states to the estimated state values, for instance by evaluation of the corresponding physical equations which map nodal voltage to the respective network state.

# General preconditions for applying the NLO

The nodal load observer as implemented for this tutorial uses measured nodal voltages, measured bus powers and measured power flow between buses (from bus *i* to bus *j*). As pseudo-measurements bus powers are considered. In principle, the concept of the NLO can be applied to a much broader set of scenarios. In the GridSens project, for instance, a three-phase implementation of the NLO was developed. For the sake of simplicity, though we here only consider a simple single-phase network.

In the here considered implementation of the NLO, all data (measurements and pseudo-measurements) have to be located in a single Excel spreadsheet document. The structure of this document is detailed in “Description\_of\_the\_input\_data.docx” as part of this tutorial package. See also the spreadsheet in the tutorial code folder for an example, which may be used as template for other networks. It is important to note that all data is expected in basic physical units (W, V, A) and not per unit (p.u.) or multiples of the basic units (e.g. kW).

The required spreadsheet should also contain the topology information of the network in terms of bus numbers, branches, line impedances and so on. See the spreadsheet document in the training example folder for further details.

# Getting started

The best start is to run the Matlab file *run\_NLO.m* located in the training example folder. The output of this script is only on the command line showing the iteration counts for the Kalman filter. Once the script finished, one may plot various combinations of measured and estimated data. A good starting point would be to have a look at a comparison between pseudo-measurement of bus power and the corresponding estimated measurement to see how the NLO adjusted the pseudo-measurement.

The Matlab script creates an additional spreadsheet document which holds the chosen scenario of where pseudo-measurements are to be considered in the network. Hence, the next step could be to compare the estimated measurements from the original spreadsheet file with the corresponding estimate from the considered scenario.

# Further steps

Once familiar with the NLO Matlab script, one can start to adjust the scenario of where pseudo-measurements are considered. For instance, one may analyse scenarios where certain parts of the network are completely non-instrumented and where, thus, only pseudo-measurements are available. One can also consider scenarios with just a very few number of pseudo-measurements and compare the outcome to ones with a larger number of pseudo-measurements.

# Going forward

The complete training example is written in a way that it can be used as a template for other networks. The important elements that have to be provided are given in the spreadsheet. If the structure of this document is maintained, any other network can be analysed with this NLO implementation. For more advanced analyses, one may also consider calculating other state variables from the nodal voltages calculated inside the Kalman filter.