The Two-Step State Estimator has demonstrated its technical feasibility. This opens the way to the TSOs for a superior level of visibility, through a frequently updated picture of the Extra High Voltage (EHV) European network. The development of commercial tools incorporating such methodology could start leaning on the already demonstrated basis.

PDC has been envisaged for usefulness at three different levels: apart from the classical PDC at TSO level, the substation and the ETN levels appear now as really interesting for the next future. New commercial PDCs should be able to receive from and send to other PDCs PMU data.

The use of PMUs and IEDs has been identified as a need from the beginning of the state estimation process: locally at the substation level. Making use of that information, along with the conventional analog and digital measurements currently being sent to the TSO’s SCADA, the quality of the data sent upstream can be improved and, even more important, detection and removal of harmful topology errors can be done before running SE at the TSO level.

An innovative approach to the Local State Estimation has been developed and verified within the project and its implementation in the substation control computers would be quite straightforward.

Minor remaining challenges for future research that should be removed for industrialization of the prototypes are:

- TSO estimators should be suitably modified to be able to cope with filtered information coming from substation-level estimators, which is more accurate but statistically correlated. Diagonal weighting matrices are no longer valid.
- TSO estimators should be modified to allow regional coordination during Stage 2. The border information provided by the coordination level should be handled by the TSO estimator much in the same way as any other pseudomeasurement, in order to refine or compensate the existing estimate of internal variables. The goal is to reuse the existing commercial code as much as possible.
- Computation of residual covariances associated with border magnitudes is currently suboptimal, sometimes providing not very accurate normalized residuals when the redundancy is very low.
- More refined models of some sophisticated components, such as phase shifters, should be considered.

Major remaining challenges for future research that should be removed for industrialization of the prototypes are:

- Ways of implementing the coordination phase (Stage 2) in a distributed manner, without physically resorting to a coordinator entity. This way, border data would only be exchanged between neighbours, instead of being submitted to a central point.
- An in-depth evaluation of accuracy of phasor measurements, which is clearly of prime importance for state estimation. Consequently, an in-depth analysis of the influence of the weights associated to phasor measurements on the SE performances.
- Evaluation of the needed communication infrastructure and corresponding delays.

A list of the most relevant publications on these topics is included below:


The following deliverables present the project results for state estimation and may be downloaded on the PEGASE website:

- D2.1 - Part 1: Algorithm for state estimation of ETN.
- D2.2 - Prototypes for state estimation of ETN.
- D2.3 - ETN information processing for advanced operator display.

A list of the most relevant publications on these topics is included below:


To learn more about the project, visit the official website at http://www.pegase.eu.
The following developments have been undertaken:

> **New mathematical decomposition framework**

Prior to the development of suitable Two-Step State Estimation (TSSE) algorithms for a hierarchical state estimation, development was undertaken in an attempt to improve existing multi-level state estimation schemes. As a result, an elegant and simple factorization scheme was developed, providing the theoretical kernel and implementation steps for the new multi-level hierarchical state estimation paradigm developed in Paseo, spanning, in seamless fashion from individual substation to the ETN. Such factorization exploits the flexibility and optimality of the proposed algorithms, which become particular cases of the general framework.

> **Two-Step Estimation suitable for a Pan-European solution**

A new TSSE algorithm has been developed, dividing the ETN into TSO areas, for which decoupled SEs are handled. Through the exchange of information, it can be ensured that the ETN as a whole is taken care of by means of a coordination process. Conceived to be the basis of the art, the proposed TSSE makes use of the maximum area overlapping that allows all raw measurements to be processed during the first stage, which makes the local state estimation at the substation level becomes linear. Furthermore, sparse weighting matrices are handled throughout the process, reducing the computational effort without sacrificing accuracy. Tests have demonstrated that the proposed scheme indeed fulfills its main requirements, while retaining essentially the same accuracy and reliability of the existing local SE schemes, as well as the conventional estimation of the entire ETN.

> **Phasor Data Concentrator (PDC)**

The use of Phasor Measurement Units (PMUs) appears to be very promising for improving the security and the accuracy of the state estimation of large power systems. The use of Phasor Measurement Units (PMUs) allows all raw measurements to be processed during the first stage by means of a coordination process. A perfectly synchronized snapshot of the whole ETN must be prepared by single calculation procedure, each control centre receiving the phasor; and on the other hand from PDC output streams for SCADA snapshots for conventional measurements properly on real data coming on one hand from measured phasor measurements was proved to perform even higher benefits. These values are then used to update the local SE estimator, global accuracy is improved.

To evaluate their performance and quality of results, the prototypes were put in the hands of actual users of that kind of tools. Several TSOs participated and reviewed the performed tests. REE (Spain), REN (Portugal) and TEIAS (Turkey).

> **Two-Step State Estimation (TSSE) prototype**

A new TSSE algorithm has been developed, dividing the ETN into TSO areas, for which decoupled SEs are handled. Through the exchange of information, it can be ensured that the ETN as a whole is taken care of by means of a coordination process. Conceived to be the basis of the art, the proposed TSSE makes use of the maximum area overlapping that allows all raw measurements to be processed during the first stage, which makes the local state estimation at the substation level becomes linear. Furthermore, sparse weighting matrices are handled throughout the process, reducing the computational effort without sacrificing accuracy. Tests have demonstrated that the proposed scheme indeed fulfills its main requirements, while retaining essentially the same accuracy and reliability of the existing local SE schemes, as well as the conventional estimation of the entire ETN.

An overall phasor measurement architecture has been designed, taking into account that it has to comply with the TSSE developed, a hierarchical structure has been adopted with PDCs at the TSO and ETN levels. A set of minimum requirements specific to the SE application has been defined and a TSSE prototype have been developed according to these requirements.

> **SE algorithm using a mix of conventional and phasor measurements**

Two alternative methods were investigated:

1. To adopt existing conventional estimation by directly introducing the new information provided by PMUs into the classical state estimation, using polar coordinates for voltage phasors and rectangular coordinates for current phasors to avoid numerical ill-conditioning problems;
2. To use SE using only the conventional measurements and handle PMU measurements through a post-processing linear estimator. The latter was shown to be an appropriate representation of state variable and phasor measurements, a slight modification of a conventional Weighted Least Squares (WLS) can easily be obtained and is in addition to conventional measurements. Using those PMUs from the beginning stage provides the added value of increase of observability, improving bad data identification and solving the synchronization of each TSSE solution, reducing the number of iterations required by the incremental state estimation phase. All these conditions confirm the first method as the most convenient.

> **Algorithms for a local state estimation at the substation level**

Making use of all potential real time data available in the substations, like conventional SCADA, PMUs and digital protection devices (IEDs), the developed algorithm performs state and topology estimation at the substation level. Better quality is provided, rather than raw data values are thus sent to upstream estimators (TSSE level) and, even more important, topology errors and some bad data are removed from the beginning in the process of finding the most likely state of the network. Therefore, by exploiting local redundancy, without having to send any extra data to the TSSE estimator, global accuracy is improved.

> **Algorithms for optimal placement of additional sensors**

Some of the problems that have been studied, namely:

1. The optimal PMU location for full observability;
2. The incremental enhancement of an existing measurement configuration;
3. The influence of the maximum number of PMU only, while the second one is oriented to evaluate the SE of the entire ETN. The development of the existing conventional SCADA measurements will be kept.

A new TSSE has been developed according to these requirements. The local SE estimator, global accuracy is improved.

Tests on real data illustrate the improvements brought to state estimation performance by the SE algorithm. The selected tests have been performed on the 400/220 kV Spanish system, using the actual number of PMUs as well as the influence of the weights associated to the phasor measurements. The most important advantage of PMUs over conventional measurements is that they provide a direct measurement of the phasor out of the measurements instead of the original (unfiltered) measurements; this leads to higher estimates accuracy, particularly in the direct neighbourhood of the PMUs, but tend to saturate when 100 units are considered.

The SE algorithm using a mix of conventional and phasor measurements was proved to perform even higher benefits. These values are then used to update the local SE estimator, global accuracy is improved.

> **Synchrophasor and Phasor Data Concentrator (PDC) prototype**

Tests on real data illustrate the improvements brought to state estimation performance by the SE algorithm. The selected tests have been performed on the 400/220 kV Spanish system, using the actual number of PMUs as well as the influence of the weights associated to the phasor measurements. The most important advantage of PMUs over conventional measurements is that they provide a direct measurement of the phasor out of the measurements instead of the original (unfiltered) measurements; this leads to higher estimates accuracy, particularly in the direct neighbourhood of the PMUs, but tend to saturate when 100 units are considered.

To the advantage of this medium size scenario (over 2500 buses) it can be solved as well by a TSSE prototype, which reduces the runtime solution to compare with, in terms of accuracy, phasor measurement configuration as well as for the availability of the speed-up of the TSSE prototype and its ability to handle simultaneously with the correct size of the Portuguese system, in the case of small size of the Portuguese system, for instance the runs under 2 sec. for the low redundancy case, is dominated by stage 1 in all cases.

> **State Estimation Prototype**

The prototype has been extensively tested to ensure the quality of results provided by this kind of tools, as well as its suitability for real life data that exists between TSOs. The following scenarios have been tested:

1. France-Spain-Portugal TSO subsystem:
2. Trans-European network: The TSSE prototype has been extensively tested to ensure the quality of results provided by this kind of tools, as well as its suitability for real life data that exists between TSOs. The following scenarios have been tested:

Tests on real data illustrate the improvements brought to state estimation performance by the SE algorithm. The selected tests have been performed on the 400/220 kV Spanish system, using the actual number of PMUs as well as the influence of the weights associated to the phasor measurements. The most important advantage of PMUs over conventional measurements is that they provide a direct measurement of the phasor out of the measurements instead of the original (unfiltered) measurements; this leads to higher estimates accuracy, particularly in the direct neighbourhood of the PMUs, but tend to saturate when 100 units are considered.

> **A new TSSE algorithm has been developed, dividing the ETN into TSO areas, for which decoupled SEs are handled. Through the exchange of information, it can be ensured that the ETN as a whole is taken care of by means of a coordination process. Conceived to be the basis of the art, the proposed TSSE makes use of the maximum area overlapping that allows all raw measurements to be processed during the first stage, which makes the local state estimation at the substation level becomes linear. Furthermore, sparse weighting matrices are handled throughout the process, reducing the computational effort without sacrificing accuracy. Tests have demonstrated that the proposed scheme indeed fulfills its main requirements, while retaining essentially the same accuracy and reliability of the existing local SE schemes, as well as the conventional estimation of the entire ETN.**