KEY RESULTS 2008-2012

- NEW GENERATION OF GROUNDBREAKING ALGORITHMS
- PROTOTYPES DEMONSTRATED ON PAN-EUROPEAN SYSTEMS
- THE WAY FOR FUTURE RESEARCH AND FOR INDUSTRIALIZATION

CONTEXT

The European Transmission Network (ETN) has been developed and operated up to around the year 2000 under the so-called UCPTE (now ENTSO-E) rules. At that time, utilities were usually national monopolies vertically integrated from generation down to the retail distribution. Each utility had the responsibility of balancing the power delivered to their clients by means of their own generation fleet. The interconnection of the national networks basically had the sole role of sharing generation reserve in case of tripping of a generating unit somewhere in the ETN. The savings in generation capacity and the possibility to install larger, more efficient units in the smaller utilities paid for the investment of the interconnection lines.

The consequences of the UCPTE rules at the level of the operation of the ETN were such:

- The flows on the interconnectors were normally low or zero.
- In case of major disturbances, the interconnections were intentionally tripped in order to avoid the extension of a possible blackout.
- The N-1 network security was managed at national level.
- Very few data exchange between countries was needed.

Today the paradigm of the ETN has changed:

- The liberalization of the electricity market and the implementation of the IEM (Internal Electricity Market) make use of the total available cross border transfer capacity and **call for reinforcement of the transmission network**. But new investments are late.
- **The integration of a large amount of intermittent renewables**, either dispersed in the distribution system or remotely located far away from the load centres call for network reinforcement (possibly a supergrid), cross border load balancing, much more sophisticated grid operation and operation planning, and smarter distribution grids.
- New technologies in the domains of ICT and power electronics are available to help the ETN to become smarter. This requires new models for generating units, wind farms, **FACTS and electrical interface of load with the system and is a major difficulty managed in this project**.
- For political and security of supply reasons, **further extensions of the ETN are planned (Turkey) or contemplated (Russia, Mediterranean ring)** leading to the most extended interconnected system in the world.

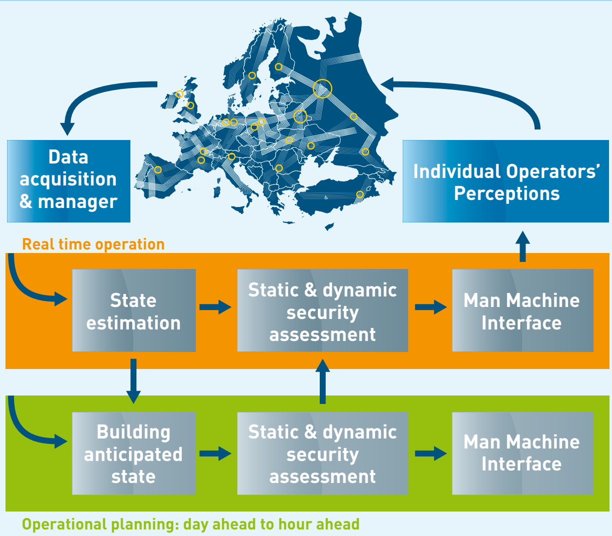
THE PEGASE PROJECT

As a consequence, the organization of the operation of the ETN must adapt and become much more integrated and smart. The way the ETN operation was decoupled into national grids is far away. The ETN shall be, and already is, operated much closer to its physical limits. The awareness of the state of the system by the operator must be much more accurate and extended to all system wide phenomena putting the ETN possibly at risk.

The PEGASE project aimed at removing algorithmic barriers related to the monitoring, simulation and optimization of very large power systems. The project has produced powerful algorithms and full-scale prototypes validated on the European Transmission Network to enhance the cooperation among transmission system operators for the real time control and operational planning of the system.

PEGASE REPRESENTATIVE DATA OF THE ETN

- **16578 NODES**
- **14044 LINES**
- **9654 TRANSFORMERS**
- **3240 GENERATORS**
- **707 WIND FARMS**
- **HVDC: 2 VSC, 1 LCC**
- **TOTAL LOAD: 400 GW**



POWER SYSTEM OPERATION PARADIGM

The four-year R&D project ending June 2012 has developed new powerful algorithms and full-scale prototypes able to run the whole ETN model for state estimation, dynamic security analysis, optimization and real time dispatcher training. It was funded by the **7th Framework Program of the European Union** and implemented by a consortium composed of 22 partners which **included Transmission System Operators, expert companies and leading research centres**.

The project demonstrated the absolute need of coordination beyond the borders between TSOs when operating the ETN and the actual implementation of this coordination is to be agreed between the TSOs as exemplified by the regional coordination centres already set up.

DISCLAIMER

The PEGASE project focused on removing algorithmic barriers to enable real time control and operational planning of the European Transmission System.

1. Non technical barriers were not the focus of this project. They will have to be addressed to enable the deployment of the proposed solutions that proved technically feasible.

2. No real set of data of the ETN were used in the PEGASE project but instead realistic data representative of the ETN. The objective was indeed to test the adequacy and performances of the prototypes and not to carry out a study on the European system.

3. Data management issues were not the main focus of the PEGASE project and they will be addressed in a dedicated R&D project: iTesla.

3 ACHIEVEMENTS

SMART TOOLS FOR TRANSMISSION GRID

The PEGASE project succeeded in developing smart tools for managing the transmission grid. The project achievements can be summarized as follows:

1

Having developed a new generation of ground breaking algorithms

ACHIEVEMENT 1: NEW GENERATION OF GROUND-BREAKING ALGORITHMS

The PEGASE project developed a new generation of ground-breaking algorithms for state estimation, dynamic simulation and optimization of the Pan-European power system. **These new algorithms are well beyond the state-of-the art. Their validity, applicability and scientific soundness have been acknowledged by the international scientific community.** A large number of journal and conference papers have been welcome and exciting discussions at various technical workshops, seminars and panel sessions at major international conferences demonstrated the quality and the timeliness of the project results. Developed algorithms are suitable for dealing with new challenges in all aspects of power system operation, particularly in case of very large power systems incorporating a range of new power electronics based equipment.

2

Having developed prototypes that integrate new algorithms demonstrated on Pan-European systems

ACHIEVEMENT 2: PROTOTYPES DEMONSTRATED ON PAN-EUROPEAN SYSTEMS

The PEGASE project selected, combined and implemented the developed algorithms into full scale prototypes of power system applications.

The soundness and efficiency of developed solutions are demonstrated by running large scale test cases representative of the ETN. The tests were carried out by the TSOs involved in the project such ensuring the compliance between the actual needs of the profession and the developed solutions.

The PEGASE project proved therefore that the existence of adequate tools is no longer a technical barrier for moving towards an integrated Pan-European power system operation that will ultimately allow operating the ETN close to its physical limits. This added flexibility in ETN operation strongly supports the integration of large shares of Renewable Energy Sources into the electricity market in Europe.

3

Having paved the way for future research and for industrialization

ACHIEVEMENT 3: PAVING THE WAY FOR FUTURE RESEARCH AND FOR INDUSTRIALIZATION

The PEGASE project succeeded in demonstrating the feasibility of the computation of any huge power system. The prototypes having been tested by end users, a better specification of the future industrial versions of the PEGASE applications can be produced, reducing the financial risk of commercialization.

As regards the algorithms, new tracks have been identified but not fully developed, like distributed computation or discrete variables management. There are no doubts that the PEGASE results will boost the research in these fields, in power system or other domains.

But the main repercussion of PEGASE could possibly be the deep knowledge of the power system gained through the use of more powerful simulation and optimization tools. This knowledge is necessary to develop new smart applications for control systems, self-healing capabilities or for speeding up the deployment of new technologies

4 TOPICS

In order to ensure an efficient and safe operation of the power system, various computational tools are used by the TSOs. Most of those tools must adapt to the needs of a more integrated operation of the ETN. In particular the model of the system used at the national level must be extended possibly to the whole ETN and updated in real time.

STATE ESTIMATION

A SINGLE ENTRY POINT OF ALL ON-LINE GRID APPLICATIONS AT THE CONTROL CENTRE

State Estimation (SE) determines the most likely state of a power system from a set of real time data captured at the substations.

Today, the SE is run independently by each TSO, on its own grid. To accept the new challenges of the ETN, a fully synchronized global SE must be implemented.

The PEGASE project has determined the best architecture of a **two-step hierarchical SE prototype** running the entire ETN and maximizing the accuracy and robustness of the procedure when minimizing the exchanges of data.

But a sound architecture of the SE will not be enough to master the complexity of the ETN. That is why the use of new ICTs has been considered:

- Synchronized Phasor Measurement Units (PMU) have been optimally placed in the grid
- PMUs have been introduced in the two-step SE algorithm using the developed **Phasor Data Concentrator (PDC) prototype**. Results confirm their usefulness in terms of accuracy and robustness.
- A local SE at the substation level, including topology estimation and using IED's data, has notably improved the global SE procedure.

All the developed algorithms have been tested on pan-European systems

STEADY STATE OPTIMIZATION

SIMULATION OF OPERATIONAL POLICIES

Anticipating the power system state is an essential step of the operational process. Steady State Optimization aims at creating these anticipated states of the system

Today, Each TSO is operating its own network close to the limits with more and more corrective actions in a context of higher uncertainties due to renewable energy sources and increased interactions between neighbouring networks. An optimization of the whole ETN must be considered.

The PEGASE project produced several conclusions and achievements:

- A **Security Contrained OPF (SCOPF) prototype** has been created, based on constraints filtering and network reduction methods. A full size prototype able to run huge systems with a huge amount of constraints (typically 10000 nodes and 30000 constraints) has been set up and tested on the ETN.
- A **discrete variable prototype** able to manage an ETN model with large number of discrete variables modelling the discrete behaviour of equipment has been developed considering some approximations.
- New formulations of the actual operating practices, favouring corrective actions against preventive actions, have been proposed.
- A "Worst-case" approach has been developed as a screening method to anticipate possible unsecure states of the system.

TIME DOMAIN SIMULATION

FOR SECURITY ANALYSIS OF THE SYSTEM

As a result of the change of paradigm, the ETN is operated close to its stability limits. Moreover, it has been shown that system wide detrimental phenomena may lead to the total black-out of the system.

The terms of references of PEGASE project concerning dynamic simulation were far reaching:

- To detect any unstable phenomenon somewhere in the ETN, a detailed electromechanical model of the whole ETN had to be used, the size of such model being at least 125000 state variables.
- The dynamic simulation must be fast enough to replace the classical on-line (N-1) security assessment based on a static model

An impressive research effort has been delivered. Different approaches were investigated: Fine grain parallelization, advanced linear algebra, domain decomposition methods, multirate algorithms, localization techniques, etc.

World-class results were obtained: A relevant combination of the research outcomes allowed a speed up of 10 to be reached on the detailed ETN model.

For on-line security assessment, a specific integration algorithm has been developed having the capability to filter the faster stable phenomena and offering a good trade off between speed and accuracy.

A **full accuracy prototype** and a **simplified simulation prototype** have been produced and successfully tested on systems of up to 140000 state variables.

DISPATCHER TRAINING SIMULATOR

TRAIN OPERATORS ON CROSS BORDER COOPERATION AND CRITICAL SCENARIOS

The role of the dispatchers is central in the operation of the European Transmission Network (ETN) and is one of the major components of the security of the overall system. It is crucial to train system operators on multilateral cross border operational issues and events that might lead to large-scale blackouts if not timely tackled.

The present state of the art of DTS consists in using a replica of a single control centre linked to a quasi steady state power system model. This is no longer satisfactory.

The PEGASE **prototype** has developed a **real time simulation engine** meeting the requirements of the project: capable of simulating the entire ETN with high fidelity, whatever the electromechanical behaviour of the system, up to the complete blackout and the subsequent restoration. This simulation engine capitalizes on the deep knowledge of the algorithms gained along the project.

A DTS prototype made of the ETN simulation engine connected to a replica of the control centre of a consortium member and to a generic operator station has been built and tested on realistic scenarios.

SUMMARY TABLE

	STATE ESTIMATION	STEADY STATE OPTIMIZATION	TIME DOMAIN SIMULATION	DISPATCHER TRAINING SIMULATOR
NEW GENERATION OF GROUND BREAKING ALGORITHMS	■ New mathematical decomposition for multi-area schemes ■ Algorithms mixing conventional and phasor measurements ■ Local state estimation at the substation level ■ Optimal placement of additional Phasor Measurement Units	■ Treatment of potentially huge number of contingencies ■ Treatment of discrete variables in very large power system	■ Fine grain parallelization ■ Direct and iterative linear algebra ■ Domain decomposition methods ■ Multirate ■ Localization ■ Step size control	
PROTOTYPES DEMONSTRATED ON PAN-EUROPEAN SYSTEMS	■ Hierarchical two-step state estimation prototype ■ Phasor data concentrator prototype ■ Test case characteristics: 9200 nodes, 14000 lines, over 50000 measurements,... ■ TSO testers: REE (Spain), REN (Portugal) and TEIAS (Turkey)	■ Iterative security constrained optimal power flow prototype ■ Discrete variable prototype ■ Test case characteristics: 9200 nodes, 14000 lines, 1500 generation nodes,... ■ TSO testers: SO-UPS (Russia), TEIAS (Turkey), HEP (Croatia), Transelectrica (Romania) and RTE (France)	■ Full accuracy prototype ■ Simplified simulation prototype ■ Test case characteristics: 16000 nodes, 13000 lines, 9000 transformers, 3000 synchronous generators, 700 wind farms,... → 140000 variables ■ TSO testers: SO-UPS (Russia), TEIAS (Turkey), HEP (Croatia), Transelectrica (Romania), RTE (France) and LITGRID (Lithuania)	■ Dispatcher training simulator prototype ■ Test case characteristics: 24000 busbars, 12500 lines, 3800 generators,... → 125000 variables ■ Validated by all TSOs of the Consortium
PAVING THE WAY FOR FUTURE RESEARCH AND FOR INDUSTRIALIZATION	■ Prototypes and algorithm bricks developed in the PEGASE project will be integrated in a toolbox developed in the iTesla project			
	■ Two-step state estimation to be incorporated in commercial tools ■ Implementation in substation control computers of local state estimation ■ Integration of PMUs treatment in new commercial SE packages	■ Industrial implementation of ISCOPF including HVDC modeling (CSC and VSC) ■ New optimization formulation to be used for HVDC link between France and Spain ■ Use of MPEC for treating discrete variables ■ Improvement of SCOPF performances for very large networks ■ Reduce the complexity of the security management under uncertainty formulation for efficient implementation	■ Computation engines fully operational and ready for industrialization ■ Some aspects need further investigations before industrialization: hypercomputing, CIM for system dynamics, collaboration framework between TSOs,...	■ Computation engine fully operational ■ To get closer to a real European DTS, a demonstrator project needs to be developed focussing on data issues, model validation issues, vizualization, legal issues and logistic issues