PEGASE R&D project: advanced algorithms for state estimation and simulation of the Pan-European power system

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SUMMARY

The PEGASE project aims at grid management tools to achieve an integrated security analysis and control of the European Transmission Network (ETN). Today the paradigm of this system has changed: interconnections are reinforced for market reasons and not any more just for reserve sharing. Moreover, new interconnections are planned (Turkey) or contemplated (for instance the Mediterranean ring or the Russian system) leading to the most extended interconnected system in the world. On top of these structural changes, the following internal evolutions are impacting the operation of the ETN:

- An already massive penetration of wind power and the growing installed capacity of distributed generation;
- Difficulty to build new Extra High Voltage transmission lines and development of more and more special control devices such as phase shifting transformers;
- New power electronic technologies are increasingly used in interfaces between the network and new energy sources (variable speed windmills, Photovoltaic generation);
- Higher power exchanges between countries and the future development of electricity highways to transfer bulk power over long distances across the continent make the national grids more interdependent and increase the need for an integrated operation of the ETN.

Because of these changes in the physical behavior of the system, its mode of monitoring and control must be reviewed. It is thus needed to develop new tools capable of simulating the whole ETN to support the daily operation. The four-year R&D PEGASE project ending in June 2012 addresses this challenge. It was funded by the 7th Framework Program of the European Union and implemented by a consortium composed of 21 Partners which included Transmission System Operators, expert companies and leading research centers. The heart of the PEGASE project involved developing advanced algorithms, building prototype software and demonstrating feasibility of real-time state estimation, constrained multi-objective optimization and detailed time domain simulation of a very large model representative of the ETN, taking into account its operation by multiple TSOs. Looking at the achievement of the project, the European, Russian and Turkish origin of the consortium partners allowed to cover various structural system needs but also organizational schemes from very centralized to decentralized ones. In this context, unbiased recommendations in terms of architecture and associated software application specifications were issued by the project. These paved the way for an optimally integrated security analysis and control of the ETN.

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Next, the *scientific contribution* of the PEGASE project was significant in the field of state estimation, steady state optimization, time domain simulation and modeling, for very large and interconnected power systems. In all these fields, the project went well beyond the state-of-the-art as highlighted in the bibliography.

The *developed prototypes* constitute the elementary blocks of the common platforms to be set up by the TSOs in their operational environment allowing ultimately to operate the ETN closer to its limit and hence *support the integration of large shares of Renewable Energy Sources and the internal electricity market in Europe.*

Finally, the soundness and efficiency of all developed solutions are demonstrated by running large scale test cases representative of the ETN. These tests will be carried out by the TSOs of the project *to ensure the compliance between the TSO needs and the proposed solutions.*

**KEYWORDS**

1. Specification and Architecture

The objective of this first activity of the project is to produce specifications and requirements for the different functions developed in the PEGASE project (state estimation, steady state optimization, time simulation) and to analyse different possible organizations and architectures for their implementation. PEGASE defined new tools to address current and future challenges for the operation the ETN. Over the last 10 years, it was so often heard that the power system would soon be operated very near its limits that this statement became a cliché. Nevertheless, this is now a reality. More precisely, it is no longer possible to respect the classical preventive security standards during all hours in a year. More and more corrective (i.e. post-fault) actions are defined and prepared to maintain the security as the system becomes increasingly complex.

First of all, the needs for the different functions of the PEGASE project were analyzed: State Estimation, Steady State Optimization, Full Time Scale Simulation, Simplified Simulation and Training Simulation and the specifications and requirements for these functions were then defined. These were analysed at the level of the TSO’s with the global objective of improving Pan European coordination. In order to collect the needs, interviews of all the major European TSOs were organized by the project.

In a second stage, different possible architectures for the Pan European functions were defined and analyzed. The objective was primarily to define the specifications and requirements for computational engines (organizational structure and IT architecture) instead of defining the “best” architecture. High-level criteria were first defined to assess combinations of organizational structures and IT architectures. High-level architectures to be analyzed were then defined: organizations, IT architectures, state-estimation/optimization/time-simulation functions, decomposition and coordination of decision making.

Specific technical coordination issues were finally analyzed in terms of the impact of coordination/non coordination and information exchange (e.g. power-flow control by phase-shifter operation and remedial actions, secondary and tertiary voltage control, ancillary service provision). Based on these specific technical issues, quantitative simulations were defined and run to evaluate the impact of coordination on these issues.

2. State Estimation

One of the PEGASE key targets is to demonstrate the feasibility of a pan-European state estimation, able to provide the state of the ETN in quasi-real time to all TSOs. The research concentrates on the architecture and algorithms of a two-step state estimator TSSE (also identified by bi-level), along with the technologies able to improve the accuracy and convergence of such estimator.

Two hierarchical schemes have been considered, namely:
1) Geographical decomposition: The ETN is split into TSO areas, which locally run the estimation process. Then, boundary coupling among areas is taken care of by means of a coordination process.
2) Voltage level decomposition: The bulk higher-voltage ETN is first solved, followed by the separate solution at the TSO level of the remaining lower voltage transmission networks.

Before dealing with algorithmic developments, an analysis of available scientific literature and reported industrial experiences has been performed [1].
Development of architectures for the two considered schemes was carried out taking into account several possible implementations or levels of simplification. It is important to remark, related to the second scheme (the so-called “Voltage level decomposition”), that the assignment of weights to measurements at boundary nodes required for the second step implies the computation of the complete covariance matrix and, so, the inversion of the gain matrix of the EHV system. This results in a high computational effort. A simplification of this process, being of great importance in the final evaluation, was also considered for assessment.

Besides the development of the TSSE algorithmic prototype, research to assess the best possible use of PMUs in conventional and hierarchical state estimators was carried out. Most results are directly applicable to the existing TSO SE and additional effort has been devoted to assess the benefits of such new measurements in a real TSO system.

Two alternative architectures were identified for making use of the PMUs:

• adapt existing conventional estimator by directly introducing the new information provided by PMUs into the measurement vector, like any other measurement, using polar coordinates for voltage phasors and rectangular ones for current phasors to avoid numerical ill-conditioning problems;
• run SE using only the conventional measurements and handle PMU measurements through a post-processing linear estimation.

The first approach has been adopted for two main reasons: (i) in addition to better filtering capability, observability and bad data analysis, it also takes advantage of the existence of phasor measurements; (ii) the required algorithmic modifications are simpler than with the post-processing scheme. The obtained results show that the addition of phasor measurements provides more accurate estimates and slightly improves the convergence properties of the algorithm.

The devised local substation state estimator relies on the so-called Generalized State Estimator concept [2]. The detailed physical substation model used includes all transformers and circuit breakers that make up the substation. The local state estimation process incorporates all the measurements coming from conventional transducers, protection devices and PMUs. Therefore a greater number of measurements can be used than those usually sent to the SCADA, increasing the local redundancy. The developed algorithm has been tested using model and data of a real substation. The obtained results confirm the feasibility of developing such a local estimation process as well as its ability in detecting and identifying both bad data and topological errors.

Extensive tests have been accomplished for both TSSE schemes with realistic pan-European network models, assessing the impact on the quality of the results, the convergence of the algorithm, the identification of wrong data and the amount of data to interchange between the TSOs and the coordination centre. Preliminary tests with large networks have demonstrated the software prototype adequacy and advantages of the first scheme (geographical decomposition) over the second one (voltage decomposition).

Being aware of the difficulties for dispatchers to deal with the huge amount of information that a pan-European network solution would imply, another important goal within the work package scope was the development of new methods for advanced operator displays design which:

• are capable of representing the complete interconnected area in a very condensed, surveyable way;
• provide information in a situation adapted manner, i.e. presenting selected and pre-processed information relevant to a given operational situation so as to maximize operators awareness.

The work focused on developing a framework for an advanced operator interface that addresses the first two levels of situation awareness, namely the “perception of significant elements”, and “comprehension of situation” thanks to the use of several layers of detailed displays [3]. Prototype implementation was made for several exemplary operational tasks.
3. Steady State Optimization

The objectives of this work is to propose a modelling of the steady state operation conditions as an optimization problem and the appropriate algorithms to solve this latter. Such a modelling requires the proper handling of discrete variables in Security Constrained Optimal Power Flow (SCOPF) problems as well as dealing with a large number of contingencies.

The small number of papers presenting results on very large systems often uses simplified models (e.g. the DC power flow approximation) or techniques (e.g. successive linear programming) which generally have a limited scope (e.g. optimization of active power flows only). We proposed in [4] a generic approach for solving very large-scale SCOPF problems, which combines an iterative contingency selection algorithm and a network compression method, both aiming together to identify automatically suitable and effective ways to relax a large portion of the inequality and equality constraints. In the framework of the PEGASE project, we use a very large-scale scenario (stemming from the whole ETN) that considers a system of around 10,000 buses and handles about 10,000 contingencies. Thanks to the combination of both constraint relaxation strategies, this problem is reduced to a size that is manageable with conventional computing architectures. Moreover, the method allows considering the AC network model in both pre- and post-contingency states. Our approach enables solving problems within computing times compatible with day-ahead operational planning as well as real-time operation.

Concerning the treatment of discrete variables, three different kinds of problems were investigated: problems related to the modelling of physical equipments, problems involving the mitigation of corrective actions with respect to expensive preventive actions and a new approach to consider the increasing level of operational uncertainty due to the growing number and size of renewable energy sources. For the first kind of problems, the use of MPEC (Mathematical Programs with Equilibrium Constraints) approach, which consists into substituting the discrete variables by continuous variables with complementary constraints, shows that approximated solutions can be found when applied to the ETN. The second kind of problems led to an innovative approach that was illustrated through demonstrative tool on academic test cases. Given that the third kind of problems is not solvable for very large-scale power systems with current computational resources and state-of-the-art optimization methods, we proposed in [5] a sequence of simplified problems (e.g. by considering only one contingency at a time together with branch overloads) in order to determine a reasonable worst-case scenario and its associated combination of preventive and emergency controls. Even if limited in scope, the proposed algorithm constitutes a major progress, since it allows identifying in a systematic way the constraining scenarios for the next day.

4. Time Domain Simulation

Another objective of the PEGASE project is to produce calculation engines able to run system-wide dynamic simulations at the European level reproducing, possibly in real time, any kind of scenarios. These calculation engines can be used for three different purposes: detailed simulations to have an accurate representation of the system evolution, real time simulation to be used for dispatcher training simulators (DTS) environments and simplified simulations for Security Assessment (SA) where many simulations must be performed in a limited time on models of very large scale power system.

To predict the evolution of a system, it must be first formulated as a mathematical problem. In the field of power system this formulation leads to a set of very complex differential and algebraic equations (very large, stiff, strongly non-linear, suffering discontinuities…). Up to date industrial software are currently not efficient enough to simulate accurately a European-wide transmission system within a reasonable time for operation, planning or studies. Improving and developing new algorithms is therefore needed.
Different research orientations were considered:

- In order to exploit the new parallel computers which are nowadays more and more widespread, parallelization at different levels have been investigated ranging from very fine grain to very coarse grain:
  - Parallelization of the function and Jacobian evaluations using a technology like OpenMP is particularly suitable to exploit shared-memory computer. Even if it is difficult to achieve a good scalability above a given speedup (around 7 in our experiments) due to the low “computation/memory access” ratio, this parallelization still allows reducing significantly some of the most time consuming parts of the simulation process.
  - Schwarz approach has also been considered. Using this technique the parallelization is introduced at a higher level which allows to parallelize not only the function and the Jacobian evaluations but also the LU factorization and the corresponding backward/forward substitutions. The idea is to decompose a large system in small subsystems and to solve each of these subsystems on different processors in parallel. An iterative procedure is added to ensure that the appropriate conditions are set-up on the boundaries. The challenge of the implementation was to limit the number of additional iterations. This can only be done by introducing a preconditioner between two iterations in order to propagate, as fast as possible, information between all subdomains. More informations can be found in reference [6].
  - Waveform Relaxation algorithm allows to parallelize the integration at the higher level. It is particularly adapted for distributed architecture. As for the Schwarz approach a preconditioner is needed in order to limit the number of additional iterations. This approach was not able to outperform a “less distributed approach” such as the Schwarz method but it is more suitable if data exchanges are limited due to political/economical/practical reasons.
- One of the most time consuming part of a time domain simulation is related to the resolution of the linear systems arising during the Newton iterations. Many techniques exist to solve linear systems. They are usually classified in two categories: either direct (LU factorization) or iterative (like GMRES) methods. It turns out that the matrices arising in power system are so sparse that direct sequential methods which exploit this property are able to compete with parallel iterative methods. This is discussed in [5]. The selection of the most appropriate LU factorization toolbox is very important for very large power systems. It is possible to face very large differences of performances between the available sparse LU factorization toolbox.
- A multirate algorithm was developed to allow the stepsize to automatically adapt not only with time but also with space. This approach is explained in [7]. During a simulation, some variables can behave fast while other ones are slow. In contrast with a classical integration scheme where an identical timestep is used for all variables, in a multirate algorithm a small timestep is used only for fast variables while large timesteps are used for slow variables to decrease the total number of calculations and therefore achieve faster performances. It has been found out that this algorithm behaved particularly well to simulate fast dynamics inside a component with no strong impact on the whole network.
- An algorithm dedicated to simplified simulations has been developed. This algorithm is based on two concepts:
  - The use of a stiff-decay method (such as Backward Euler method) with a very large stepsize (around 500 ms) which allows to filter numerically the fast dynamics. The main difficulty is to handle the discrete transitions without reducing the stepsize.
  - A latency exploitation technique which replace components having negligible impacts on the system by static equivalent. This technique is detailed in [8].

These algorithms have been combined in three different prototypes dedicated to the full accuracy simulation, to a DTS and to simplified simulation to be used for SA. Depending on the prototype, the best “combination” of algorithms can be different.
For example:

- The parallelization which can bring significant performance improvement has not been selected for the simplified simulation prototype. This prototype being dedicated to SA where a large number of simulations must be performed, it is much more efficient to introduce the parallelization at the very top level (i.e. associating only 1 processor per simulation).
- For the full accuracy prototype, variable stepsize is needed to guarantee that the integration error remains below a given threshold. For a DTS where it is desirable to be as close as possible to realtime, one prefers to use fixed stepsize which leads to more predictable computation time.
- A particular decomposed Newton scheme can be used which allows to update/factorize independently the machine Jacobians. This technique leads to a very important speedup in the simplified simulation prototype where nearly fixed stepsize is used. However the benefit in a full accuracy simulation is more limited since after each significant stepsize change all machine Jacobian must be re-factorized since the stepsize appears in the algebraized differential equations.

The three prototypes combining these algorithms are at the end of their development phase at the time of writing this report. Preliminary tests show already promising results on very large scale system (such as the ETN):

- For the simplified simulation: the simulation of a line opening can be carried out in 16 seconds.
- For the full accuracy simulation: very complex scenarios like the opening of a line leading to a cascade and the split of the network can be simulated with high accuracy in a limited time (8 minutes simulated in 3 minutes of computation time)
- For the DTS: the real time can be considered as hold even for difficult scenario like a strong short-circuit leading to the loss of synchronism of some machines (10 seconds simulated in 10.8 seconds of computation time).

5. Modelling issues in large scale system studies

The number of new power electronic based devices and systems such as electronic interfaces, FACTS, active distribution networks, digital controllers and protection systems in European power systems is increasing rapidly. As a result, the PEGASE project also focused on issues related to modeling, including the development of a validation procedure to assess the accuracy of the models in dynamic simulations and a computational platform for exchanging models and comparing results. An important activity carried out in this field was the modeling of wind turbine (WT) and wind farm (WF) for dynamic stability studies.

Wind based power generation in its present scope is relatively new and still evolving with a broad spectrum of equipment technology. Standard simulation models are still not available, and this makes representation of wind turbines in large system studies a difficult task. Further compounding the problem is the fact that manufacturer-specific models often contain proprietary information and are not publicly available. Thus the development of simplified wind turbine/wind farm model for use in large system studies was found to be necessary [9]. The model is not manufacturer or technology specific. As usual in modeling, the fundamental issue to be resolved is finding the right balance between the level of detail and complexity of the model on the one hand and the acceptable error in the simulation results arising from the simplification on the other. For validation of the results the quasi steady state (QSS) mathematical model was taken as a basis [10]. Further systematic simplification of the QSS model results in the mathematical basis of the block diagram shown in Figure 1.
A voltage source behind internal impedance (Thevenin model) or alternatively a current source (Norton model) forms an interface to the grid. The voltage source is supplied by two delay blocks (one each for the d, and q components) representing the electrical machine (DFIG) and/or the converter delay. This part of the model is in grid synchronous coordinates. The controllers represented by PI blocks operate in terminal voltage oriented coordinates in which the real component of the current corresponds with the active current and the imaginary component with the negative of the reactive current [11]. Consequently, both controllers perform active and reactive current (power) control.

For simplicity, the reference for reactive current is provided by a terminal voltage controller and the active current reference is calculated from the active power which is assumed constant. This assumption is valid for 1-2 seconds following a grid disturbance. For longer simulation durations modeling of the speed controller including the equation of motion may be necessary. The magnitude of the current reference is limited to a maximum allowed for the converter system. As can be seen from the model, there is no separate representation of machine side or line side converter. Also the parameters do not correspond with any of the real controller parameters, rather characterize the aggregated values.

6. Demonstration on Pan-European and Russian test cases

A major objective of the project is to demonstrate on realistic, European-scale and Russian-scale use cases the capabilities of the functions developed. In order to achieve this, a special emphasis has been put on the following goals:

- Gathering of data for static and dynamic simulations representative of the European, Turkish and Russian transmission grids.
- Involvement in testing activities of real-world users of this kind of tools: mainly Transmission System Operators workers from European countries, Turkey and Russia.

Looking at the UCTE and TEIAS parts of the system as an example, we came up with a representative model comprising:

- 16,000 buses, 14,000 lines and 9,500 transfos
- 100 phase shifters
- 3 HVDC links
  (2 VSCs: France-Spain and Denmark-Netherlands, 1 LCC: Greece-Italy)
- SVCs, STATCOM, TCSC
- 700+ wind farms of 50 to 120 MW
- …

At the time of writing this report (January 2012), testing activities are ongoing, therefore most of the results are still to come.
However, here is an example of test scenario that runs on the DTS prototype. Designed to mimic the well-known incident of November 2006 on the European grid, it consists in a splitting of the network in 3 asynchronous parts, followed by a resynchronization of the different parts to be done by the user:

**Figure 3: splitting of the grid in 3 areas**

**Figure 4: frequency evolution**

### 7. Dissemination of PEGASE results

To encourage and facilitate implementation of the key results of PEGASE project it is indeed essential to make sure that the results and recommendations of the research are fully compatible and in line with the views of wide range of groups of stakeholders.

Convincing stakeholders of the need to implement project results implies that dissemination of the results has to reach not only the engineers and other technical and scientific personnel working for TSOs but also the management responsible for decision making regarding the implementation of these solutions and for overseeing the organizational and procedural changes that this implementation may require.

During 4 years of the project dissemination activity continuously intensified. A wide range of dissemination activities has been undertaken including publication of a large number of scientific papers, organization of international workshops, international training courses, and technical seminars (for TSOs, control centres manufacturers, consulting engineering, generators and traders), organization of special panels within the international conferences and participation in international exhibitions.

Since 2007 more than 40 scientific papers prepared by PEGASE consortium specialists have been published and submitted for publication in leading international journals and large number of technical workshops was held. Additionally, 14 newsletters that present project results and achievements were issued for wider dissemination to all stakeholders and general public. Key research results concerning Pan European Grid Advanced Simulation and State Estimation were presented at PEGASE panel session at IEEE PES International Conferences on Innovative Smart Grid Technologies, IGST Europe 2011, in Manchester, UK in December 2011. Members of PEGASE consortium have initiated Special section on “Analysis and simulation of very large power systems” in leading International journal in the area, IEEE Transactions on Power Systems. Furthermore, 2 EES-UETP courses on “Optimisation of Power System” and “Large power system dynamic simulation and associated modeling of wind turbines/wind farms & of HVDC VSC” based on the project results, are planned to be held in March-May 2012 at National Technical University of Athens (NTUA), Greece and at University Duisburg-Essen, Germany.
BIBLIOGRAPHY


