Outline

PEGASE general presentation
- Context
- Project description
- Project main achievements

Focus on time domain simulation
- Objectives
- Algorithm improvements
- Prototypes demonstration

Conclusions
CONTEXT
Historical background up to year 2000

Power sector characteristics

- Utilities were most of the time national monopolies vertically integrated
- Interconnection of national networks used mainly for generation reserve sharing

Consequences

- 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

- Liberalization of the electricity market pushes to the use of the total available cross border transfer capacity

- Integration of a large amount of intermittent renewables

- Introduction of new ICT to improve the awareness of the system and its commandability

- Further extensions of the ETN considered

Need for new solutions
PROJECT DESCRIPTION
The PEGASE project addressed these issues and aimed at removing associated technical barriers

- By developing new tools to be capable of
  - Monitoring
  - Simulating
  - Optimizing
- The ETN as a whole.
- To support its real time control and its operational planning.

Development of powerful simulation and optimization tools able to run the entire European Transmission Network
Power System Operation Paradigm

Real time operation

Single Country with limited neighbouring areas (external equivalents)

Data acquisition & manager

Individual Operators’ Perceptions

Operational planning: day ahead to hour ahead
Power System Operation Paradigm

Real time operation

State estimation → Static & dynamic assessment → Man Machine Interface

Building anticipated state → Static & dynamic security assessment → Man Machine Interface

Data acquisition & manager

Individual Operators’ Perceptions

Operational planning: day ahead to hour ahead
The PEGASE consortium structure

Consortium Nature
- 9 TSOs & Expert Companies
- 1 Manufacturer
- 11 Research Centers & Universities

Project duration:
- 4 Years
- June 2008 – June 2012

Funding:
- EU: 8.6 M€
- Total: 13.6 M€
Smart Tools for Transmission Grid

1. New generation of groundbreaking algorithms
2. Prototypes demonstrated on Pan-European systems
3. Paving the way for future research and for industrialization

Power System Operation

- State Estimation
- Steady State Optimization
- Time Domain Simulation
- Dispatcher Training Simulator
Special focus on time domain simulation

1. New generation of groundbreaking algorithms
2. Prototypes demonstrated on Pan-European systems
3. Paving the way for future research and for industrialization

Power System Operation

- State Estimation
- Steady State Optimization
- Time Domain Simulation
- Dispatcher Training Simulator
Context

- Increasing need for time domain simulation on Pan-European model
  - The system is operated closer to the limits
  - More protections and controllers
  - Poorly damped inter-area power oscillations can occur in large synchronous power system

Objective

- Develop new algorithms to
  - Simulate the time electro-mechanical evolution of very large power system
  - Decrease sufficiently simulation time for:
    - Full accuracy simulation for reference and offline studies
    - Dynamic Security Assessment by computing approximate trajectories
    - Real time simulation for DTS purpose

PEGASE target: develop and integrate these new algorithms in three prototypes
ACHIEVEMENT 1: NEW GENERATION OF GROUND-BREAKING ALGORITHMS
Target problem

- Simulation of the electro-mechanical evolution of very large power system
  \[ \dot{y} = f(y, t) \]
  \[ 0 = g(y, t) \]

- Very though mathematical problem
  - Very large: +/- 140,000 variables for the European system
  - Non-linear: park’s equations, loads,…
  - Discontinuous: relay/switch in controllers
  - Stiff
  - Oscillating and badly damped

- Need of new advanced algorithms to reduce computation time
New generation of ground-breaking algorithms
Multi rate algorithm

Many disturbances impact only a small part of the system

- Use of small stepsize for “fast variables” and large stepsize for “slow variable”

### Multi rate computation for two components

<table>
<thead>
<tr>
<th></th>
<th>single-rate</th>
<th>multirate</th>
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<tbody>
<tr>
<td>|error|_\infty</td>
<td>7.64 \cdot 10^{-2}</td>
<td>5.28 \cdot 10^{-2}</td>
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<tr>
<td>|error|_2</td>
<td>4.22 \cdot 10^{-5}</td>
<td>4.22 \cdot 10^{-5}</td>
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<tr>
<td># func evals</td>
<td>184 326</td>
<td>47 102</td>
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<tr>
<td>Simulation time</td>
<td>0.045</td>
<td>0.026</td>
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</table>

Fast variable: 26 steps

Slow variable: 5 steps
Error control management

In time domain simulation, a guarantee on the accuracy can be obtained only by adapting dynamically the stepsize length.

The step size selection depends on the *norm* of a local error estimation.

- An unsuitable norm can lead to the misdetection of some instabilities.

Development of a new norm suitable for very large system.

- Approach: mixing $L_2$ and $L_\infty$ norm depending on the step size.
- Lead to smaller step sizes allowing to detect instability.
Higher order methods

- An order 4 (Hammer-Hollingsworth) integration scheme investigated
  - Allows to take larger steps but each step takes more time
  - Suitable only when very high accuracy is targeted (tolerance less than 10^-4)
Decomposition methods

- **Coarse grain approach**: parallelize the resolution of the system on different processors

  - **Technique**:
    - Cut the system into $n$ subsystems
    - Solve each system simultaneously on different processors
    - Exchange values on the boundaries and iterate up to convergence
      - Boundary values assumed could have been erroneous. Mandatory to have good accuracy

- **Benefit brought by parallelization** limited by the additional iterations
  - Speedup only if small number of iteration
    - Iteration number depends on many factors
    - Key factor: a **preconditioner** has to be introduced between two iterations
ACHIEVEMENT 2: PROTOTYPES DEMONSTRATED ON PAN-EUROPEAN SYSTEMS
**Full European size testcase**

- **All prototypes validated on a testcase representative of the full European size system**
  - **Static data:**
    - anonymized and noised load flow model of UCTE (now ENTSO/e) EHV grid + Turkish EHV grid provided by TEIAS, which consists in real static data
  - **Dynamic data:**
    - Fictitious data and controllers created to respect ENTSO-E statistics energy source

<table>
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<tr>
<th>Nodes</th>
<th>16578</th>
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<tbody>
<tr>
<td>Lines</td>
<td>14044</td>
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<tr>
<td>Transformers</td>
<td>9654</td>
</tr>
<tr>
<td>Generators</td>
<td>3240</td>
</tr>
<tr>
<td>Wind farms</td>
<td>707</td>
</tr>
<tr>
<td>HVDC</td>
<td>2 VSC, 1 LCC</td>
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<tr>
<td>Total load</td>
<td>400 GW</td>
</tr>
<tr>
<td>Nbr. of variables</td>
<td>140 000</td>
</tr>
</tbody>
</table>

- **Benchmarked on “standard” computer architecture**
  - 2 x Xeon X5690 @ 3.47GhZ CPU
  - 48 GB RAM
Full accuracy prototype demonstrated on pan-European system

Thermal cascade leading to system splitting simulated in full accuracy prototype

A 400 kV line is tripped at the time t = 1s. As consequences nearby lines are overloaded and tripped by thermal protection. System splits at FR-ES border at time t = 6.18s. Frequency in ES and PT part dips and when it reaches 49.5 Hz load shedding is activated at time t = 48 s. At the same time 3x600 MW generating units are shut down in FR area to restore power balance. After frequency restoration interconnection branches between ES and FR are closed causing successful resynchronisation at time t = 150s.

Initial PEGASE target: 15 min

CPU time: 12 min 35 s
Full accuracy prototype demonstrated on pan-European system

Unique combination of
- Performances on very large power systems
  - System splitting and resynchronization: 12 min 35 sec.
  - Voltage collapse: 4 min 42 sec

Flexibility
- For model definition: user defined controllers through block diagrams
- For post-processing: access to all variables even without any pre-selection

Accuracy
- Guarantee on the solution accuracy thanks to the variable step size strategy
DTS prototype demonstrated on pan-European system

- Performance improvements $\rightarrow$ real time achieved
  - Merging of the new investigated algorithms to achieve real-time
  - Difference between simulation time and wall clock time seamless to operators
ACHIEVEMENT 3: PAVING THE WAY FOR FUTURE RESEARCH AND FOR INDUSTRIALIZATION
PAVING THE WAY FOR INDUSTRIALIZATION

- Performances reached are sufficient for time domain simulation of the whole Pan-European system
  - Less than 15 minutes for a full accuracy simulation
  - Around 15 seconds for a simplified simulation
  - Real time simulation for DTS

- Prototypes validated and ready for industrialization

- Prototypes usable by other research projects
  - Full accuracy prototype (based on EUROSTAG) to be used in iTesla project
Conclusions

- PEGASE was a major project addressing four topics in the field of very large power systems
  - State estimation, steady state optimization, time domain simulation and Dispatcher Training Simulator

- Some key figures
  - 150.000+ hours
  - 30+ publications
  - 7 prototypes

- Prototypes demonstrated on an European size testcase
How to remain updated with PEGASE results?

www.fp7-pegase.eu: Public version of the deliverables posted
QUESTIONS
COMMENTS?