European Network of
Transmission System Operators
for Electricity

DYNAMIC MODEL OF CONTINENTAL EUROPE V2

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ENTSO-E Mission Statement

Who we are

ENTSO-E, the European Network of Transmission System Operators for Electricity, is the association for the cooperation of the European transmission system operators (TSOs). The 39 member TSOs, representing 35 countries, are responsible for the secure and coordinated operation of Europe's electricity system, the largest interconnected electrical grid in the world. In addition to its core, historical role in technical cooperation, ENTSO-E is also the common voice of TSOs.

ENTSO-E brings together the unique expertise of TSOs for the benefit of European citizens by keeping the lights on, enabling the energy transition, and promoting the completion and optimal functioning of the internal electricity market, including via the fulfilment of the mandates given to ENTSO-E based on EU legislation.

Our mission

ENTSO-E and its members, as the European TSO community, fulfil a common mission: Ensuring the security of the inter-connected power system in all time frames at pan-European level and the optimal functioning and development of the European interconnected electricity markets, while enabling the integration of electricity generated from renewable energy sources and of emerging technologies.

Our vision

ENTSO-E plays a central role in enabling Europe to become the first climate-neutral continent by 2050 by creating a system that is secure, sustainable and affordable, and that integrates the expected amount of renewable energy, thereby offering an essential contribution to the European Green Deal. This endeavour requires sector integration and close cooperation among all actors.

Europe is moving towards a sustainable, digitalised, integrated and electrified energy system with a combination of centralised and distributed resources. ENTSO-E acts to ensure that this energy system keeps consumers at its centre and is operated and developed with climate objectives and social welfare in mind.

ENTSO-E is committed to use its unique expertise and system-wide view – supported by a responsibility to maintain the system's security – to deliver a comprehensive roadmap of how a climate-neutral Europe looks.

Our values

ENTSO-E acts in solidarity as a community of TSOs united by a shared responsibility.

As the professional association of independent and neutral regulated entities acting under a clear legal mandate, ENTSO-E serves the interests of society by optimising social welfare in its dimensions of safety, economy, environment, and performance.

ENTSO-E is committed to working with the highest technical rigour as well as developing sustainable and innovative responses to prepare for the future and overcoming the challenges of keeping the power system secure in a climate-neutral Europe. In all its activities, ENTSO-E acts with transparency and in a trustworthy dialogue with legislative and regulatory decision makers and stakeholders.

Our contributions

ENTSO-E supports the cooperation among its members at European and regional levels. Over the past decades, TSOs have undertaken initiatives to increase their cooperation in network planning, operation and market integration, thereby successfully contributing to meeting EU climate and energy targets.

To carry out its legally mandated tasks, ENTSO-E's key responsibilities include the following:

› Development and implementation of standards, network codes, platforms and tools to ensure secure system and market operation as well as integration of renewable energy;

› Assessment of the adequacy of the system in different timeframes;

› Coordination of the planning and development of infrastructures at the European level (Ten-Year Network Development Plans, TYNDPs);

› Coordination of research, development and innovation activities of TSOs;

› Development of platforms to enable the transparent sharing of data with market participants.

ENTSO-E supports its members in the implementation and monitoring of the agreed common rules.

ENTSO-E is the common voice of European TSOs and provides expert contributions and a constructive view to energy debates to support policymakers in making informed decisions.

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EXECUTIVE SUMMARY

This report describes version two of the Continental European dynamic model, as developed by the System Protection and Dynamics working group of ENTSO-E. TSOs have a need to have suitable dynamic models in order to analyse the exact behaviour of the current system but also anticipate the challenges of a future power system configuration. ENTSO-E permanently updates the existing model by making use of the latest available dynamic model calibrated by comparison between simulation and measurements from real events. The current version has been developed over the past years and is available in the two major commercial tools being used by TSOs: DIgSILENT PowerFactory and PSS®E. The model has been developed with focus on frequency stability and inter-area oscillation phenomena, by modelling explicitly the behaviour of the synchronous generators and of the loads, based on a TYNPD model representing the year 2027. It has been validated and tuned against measurements as well between the two software tools. The dynamic model is mainly capable to cope with electro-mechanical transients, namely e.g. Frequency Containment Reserve (FCR) activation as well as the main inter-area oscillation modes. The model might also be used as a boundary network for detailed stability studies, if the area of interest is replaced by a detailed dynamic model of that specific region. The Continental European dynamic model itself is not meant to be used for other stability studies, such as voltage stability, transient stability, or even harmonics. Also, the model is not suitable to study other local phenomena such as system protection of lines, special protection schemes, congestions of lines and other specific control schemes.

General description

Power systems have to be enhanced continuously in order to ensure a secure and sustainable electricity supply as a backbone of the modern technology society. Power system operation is becoming more and more challenging due to the dramatic changes with respect to the shift of power generation from big generation units based on synchronous generators to small and high in number distributed generation linked via power electronic devices to the power system. Consequently, there is a need to have available suitable dynamic models in order to analyse the exact behaviour of the current system but also anticipate the challenges of a future power system configuration. ENTSO-E permanently updates the existing model by making use of the latest available dynamic model calibrated by comparison between measurement and simulation. The first model was published in 2015 and is described in [1]. The current model is the second one for the entire CE power system and tailored on the main needs and available standard tools of the continental European (CE) TSOs.

Compared with version one, the complexity and accuracy of the model has been increased as the synchronous generation is now divided into four categories, each represented by a generic model, while in the first model only one generic model type was used for all synchronous generators.

However, this dynamic model is not able to cope with all kinds of transients, see Figure 1 below, where the main application fields are marked accordingly. The model has been developed with focus on frequency stability and inter-area oscillation phenomena, by modelling explicitly the behaviour of synchronous generators and loads. It has not been tuned or validated for other kind of stability that may have a more local, less synchronous-zone wide impact. As generic models are used, the property of the modes can be different from reality in some operating conditions. Specifically exact damping of the modes and the mode shape can be different in reality depending on the current generation dispatch. In version two of the model, the main focus has been on improving the representation of the synchronous generation models. Development and implementation of RES models suitable for a large scale as the continental European dynamic model is still ongoing and will be further integrated in the next version 3. As anticipated, the model might also be used as a boundary network for detailed stability studies, if the area of interest is replaced by a detailed dynamic model of that specific region. The Continental European dynamic model itself is not meant to be used for other stability studies, such as voltage stability, transient stability or even harmonics.

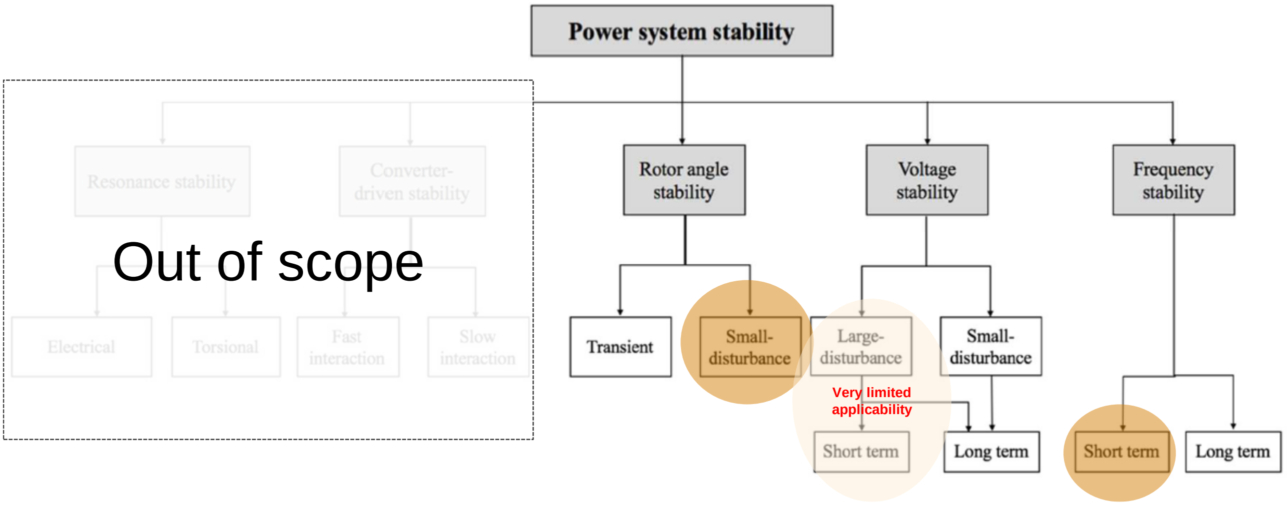


Figure 1: Dynamic phenomena fitting with the dynamic model [2]

The model developed represents a future condition (year 2027) for which limited information was available at the time of the implementation. The model is built upon a long-term load flow simulation in which the dispatch has been defined within the TYNDP2018, in an aggregated way per type of fuel. This means that the dispatch is realistic for load flow studies at CE scale, but much less on a local scale as it may not consider some technical minimum and optimal operational point of units. In the applied methodology it has been chosen to keep the initial dispatch and to adapt the governor **droop** of all the generators and their **inertia** value to increase the adherence of the simulations against the real data.

The model has been implemented in the two major commercial tools being used by TSOs: DIgSILENT PowerFactory and PSS®E. The main model was developed and tuned in PowerFactory and the PSS®E derived from that. Behaviour of the PowerFactory model is there for most representative and results from PSS®E should be treated with care.

The aim of the model is not to represent the exact behaviour of past incidents, for which the load flow and dispatch can enormously differ from the one in the model, but to rather represent one of the possible future conditions. The user of the model should take the above mentioned into account when using the model and analyse the results with a critical expert eye and consider possible sensitivities in the parameters and in the system dispatch to increase the realism of the simulation. This dynamic model is mainly capable to cope with electro-mechanical transients, namely e.g. FCR activation as well as the main inter-area oscillation modes. It includes all countries, which were connected to the Continental European system at the time the development of the model started, see Figure 2. In the context of emergency synchronization Ukraine was connected to CE in the meantime, which is however not represented by the dynamic model.

Figure 2: Perimeter of dynamic model for continental Europe v2, in yellow (source ENTSO-E)

Methodology for the development of the model

The diagram below summarizes the approach to model development, validation and implementation of models in different platforms. The “reference” model has been developed in DIgSILENT PowerFactory software and was tuned by comparing its behaviour with past events to assess its realism. The model has been then exported to PSS®E to establish an equivalent model. Validation and comparison of the results between the platforms has been performed along the way.

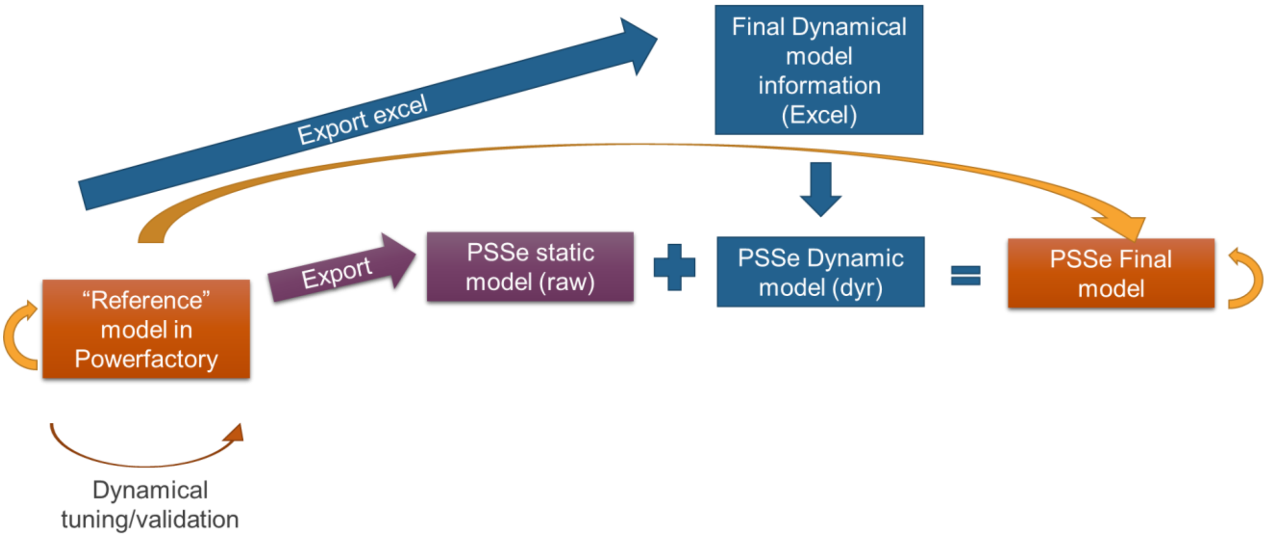


Figure 3 : Methodology of creation of the dynamical models.

PowerFactory model

The initial "steady-state" model of Continental Europe has been built based on all European TSOs planning grid models provided in the CGMES format. To adopt this model for time domain simulations, several model adjustments had to be undertaken to make it compatible with dynamical simulation, improve convergence and ease conversion to PSS®E tool. This has been performed maintaining the initial load flow.

Some of the modifications that have been performed in PowerFactory are presented below:

- Element modelling – to allow correct conversion to other tools and improve convergency
    - Adaptation or conversion of equivalent branches, ideal voltage sources, some type of shunt compensator and ideal voltage sources to PowerFactory elements
    - Conversion of LCC/VSC models into equivalent static sources/sinks
    - Adding step-up transformers for synchronous generators directly connected to EHV and HV voltage level
    - Disable voltage control for synchronous generators with unrealistic reactive power limits (e.g. maximum limit equal to minimum.
- Reduction of non-relevant number of generators – to speed up dynamical simulation
    - Conversion into passive elements or disabling the synchronous generators with very small active power contribution
    - Disabling of units running at zero active and reactive power (excluding synchronous condensers)
    - Conversion of renewable energy sources into equivalent static injectors
- Adaptation of parameters of the synchronous generators – to have a more realistic model
    - Update of synchronous generator type model and park parameters to match standard and typical ones
    - Correct physically not plausible capability curves of synchronous machines
- Adding dynamic models for large generating units
    - Adding governor and exciter to all synchronous machines
    - Adding of dynamic load model
    - Adaptation of some per uniting and controller parameters

  - Tuning of some unit operational point and relative PSS

- Tuning of model parameters - to match the selected incidents
  - Modification of the FCR droop constants and inertia values of generators.

- For some limited cases, the parameters of some units with too high internal load angle have been modified to avoid loss of synchronism.

The scripts developed in PowerFactory in order to adopt the “steady-state” model of Continental Europe into “dynamic” model are available for download from Energinet’s GitLab homepage: https://gitlab.com/energinet/powerfactoryscripts

PSS®E model

Based on the Continental European model in PowerFactory a model in PSS®E was developed. To translate the PowerFactory data to PSS®E the following steps were taken:

- Preparation of a database in Excel to allow the conversion of the dynamic model by mapping the corresponding elements in Powerfactory and PSS®E
- Conversion of the steady state file from Powerfactory to PSS®E and relative check of flows and voltages
- Parameterisation of the PSS®E models was done in a previous stage when tuning the models.
- Initialisation model in PSS®E
- Disabling of islanded networks
- Adaptation of operation of few initial values of the generators, including the slack to go below the limit of the capability curve to allow initialization below limits from a numerical point of view.
- For the nuclear generators adaptation of their step-up transformer

Validation of the model

Time domain simulations

The base load flow used for the construction of the dynamic model is based on the TYNDP model that represents a credible future grid topology for 2027. In this respect, there are no recordings of incidents to be used as reference to assess the future behaviour. Hence, it has been chosen to validate the model with respect to a past incident involving 1.8 GW power plant outage in Turkey.

More specifically, the model dynamic response and its sensitivity to changes in its fundamental parameters (namely, inertia, governors droop and dead band) will be compared to WAMs recordings during the incident.

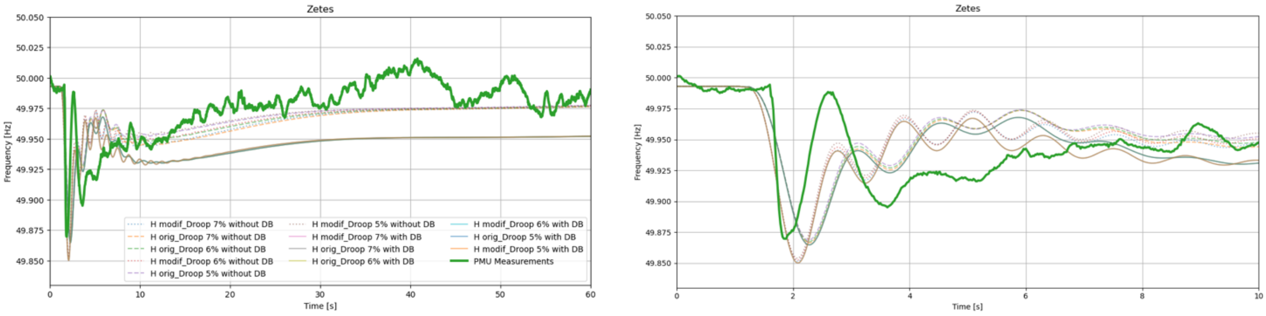


Figure 4: Comparison of simulations with the measurement of Zetes incident.

It is important to highlight that it is not possible to discern the pure effect of FCR and aFRR as both of them are acting at the same time on the system, while the model does not include the aFRR.

This incident has been selected since the initial conditions are quite close to steady state and raw measurement data were available for effectively visualizing differences with respect to the simulated trajectories.

Figure 4Figure 4 shows the comparison between model simulations and real-world WAMS registrations. Considering the above, it is possible to say that the model reasonably represent the dynamic behaviour of the CE grid.

Small signal stability

It is extremely important that the simulation models reflect properly the dynamic behaviour of the real power systems. The accuracy of the simulation model has been verified by comparing the simulated response and the real measurements in the time domain against some reference incidents occurred in CE. Outcomes from a model-based analysis carried out using the full dynamic model of the European network (i.e. Continental Europe) in DIgSILENT PowerFactory, are compared with the ones coming from a measurement-based analysis, which employs synchrophasors data collected by PMU disseminated along the power system.

The correlation between the simulated and measured results provides an indication of whether the modelling and data analysis techniques have aligned each other with respect to the inherent power system dynamics.

The real measurements relating to the reference incident were processed by performing a Dynamic Mode Decomposition (DMD) [3]. Once feed by an adequate set of measurements, the DMD can provide the fundamental descriptive parameters of the inherent modes of evolution of the system. Specifically, if the set of measurements is adequately filtered, the DMD can make an accurate estimate of the fundamental parameters of the oscillatory modes.

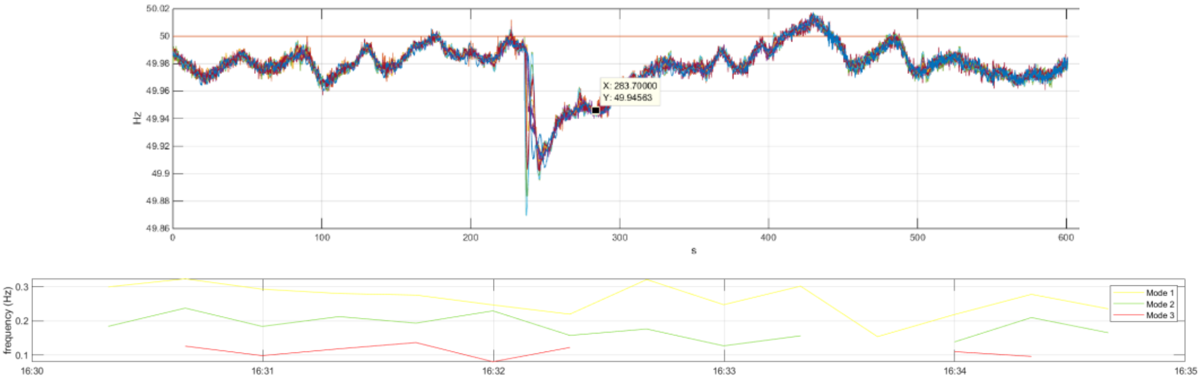


Figure 5: DMD outcomes – Modal frequencies.

As shown in Figure 6, CE is characterized by three main inter-area modes.

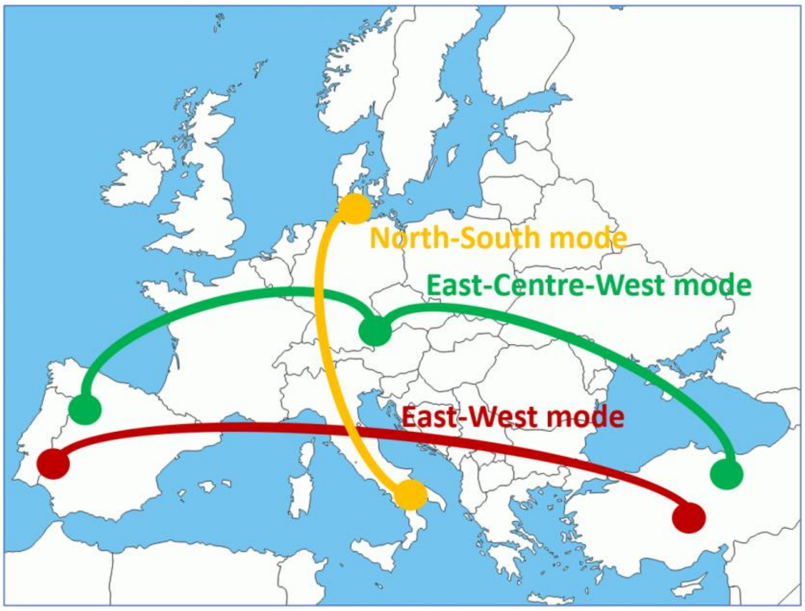


Figure 6: RGCE inter-area modes.

The Modal Analysis provides the eigenvalues and eigenvectors of a dynamic multi-machine system including all controllers and power plant models. After the initial conditions have been calculated successfully, the modal analysis calculates the complete system dynamic matrix using numerical, iterative algorithms.

In the PowerFactory environment, a selective eigenvalue calculation based on the *Arnoldi-Lanczos* method was performed to minimize the computational time that increases significantly when the size of the system increases. The method consists in the computation of a user-definable number of closest eigenvalues around a complex reference point, for instance expected mode frequency.

Modes selections are obtained by analysing mode frequencies, participation factors and identification of groups of synchronous machines oscillating in phase. Table 1 describes the three main inter-area oscillation modes, identified by the application of this methodology to the CE grid model with a 0.238 Hz target frequency.

Table 1: PF modal analysis results

Mode	Real part (1/s)	Imaginary part (rad/s)	Magnitude (1/s)	Angle (deg)	**Damped Frequency (Hz)**	Period (s)	Damping (1/s)	Damping Ratio	Damping Time Const. (s)
East-Centre-West Mode	-0.418	1.762	1.811	103.4	**0.28**	3.56	0.414	0.231	2.389
East-West Mode	-0.258	0.666	0.715	111.2	**0.106**	9.42	0.25	0.360	3.874
North-South Mode	-0.191	2.374	2.381	94.60	**0.37**	2.646	0.191	0.080	5.229

- Mode 1 is the East-Centre-West mode. The mode appears in the simulation model as an oscillation mode with the frequency around 0.28 Hz.
- Mode 2 is the mode with the lowest oscillation frequency. It appears in the simulation model as a 0.1 Hz frequency oscillation mode. It represents an inter-area oscillation between Western Europe and Turkey.
- Mode 3 is the North – South mode. It appears in the simulation model as a mode of oscillation of the frequency of 0.37 Hz. It describes an inter-area oscillation between the central north and the southern part of Europe.

Modal analysis confirms, in terms of mode shape and geographical displacement of the modes the real behaviour that SPD observed thanks to WAMS analysis. In addition, we can note a certain small shift in the dominant frequencies that could be mainly an effect of the simplifications described in the preparation procedure, but don't invalid the physics of the results.

Comparison of model behaviour in different platforms

Step response tests

To ensure a consistent dynamic behaviour across different simulation platforms generic standard models for synchronous generation units are used [4] [5]. For the Dynamic model of CE version 2 the synchronous generation is divided in four categories, each represented by a generic model as shown in Table 2. For the cross-tool validation, a dataset based on a representative machine is selected for each category and test cases are simulated on a single machine system (Figure 7). The test cases that were simulated are summarized in **Error! Reference source not found.** below.

Table 2: Types and models for synchronous generation

Type	Description	Governor	Voltage Control/ Excitation	Power System Stabilizer
Thermal Classic	Classical thermal power plant with steam turbine	GovSteam1	ST4B	PSS2B
Thermal Gas	Gas turbine model for both open and combined cycle	GovCT2	ST1A	PSS2B
Nuclear	Nuclear power plant	GovSteamEU	ST7B	PSS2B
Hydro	Hydro power plant (Francis, Pelton, Kaplan)	GovHydro1	AC6A	PSS2B

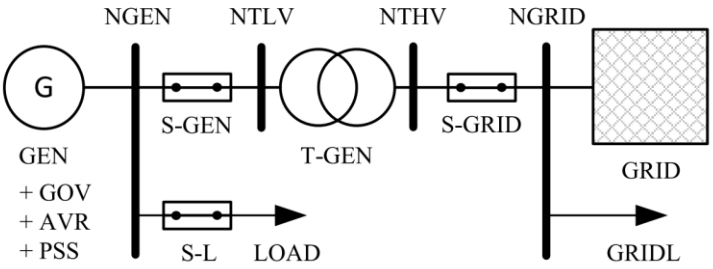


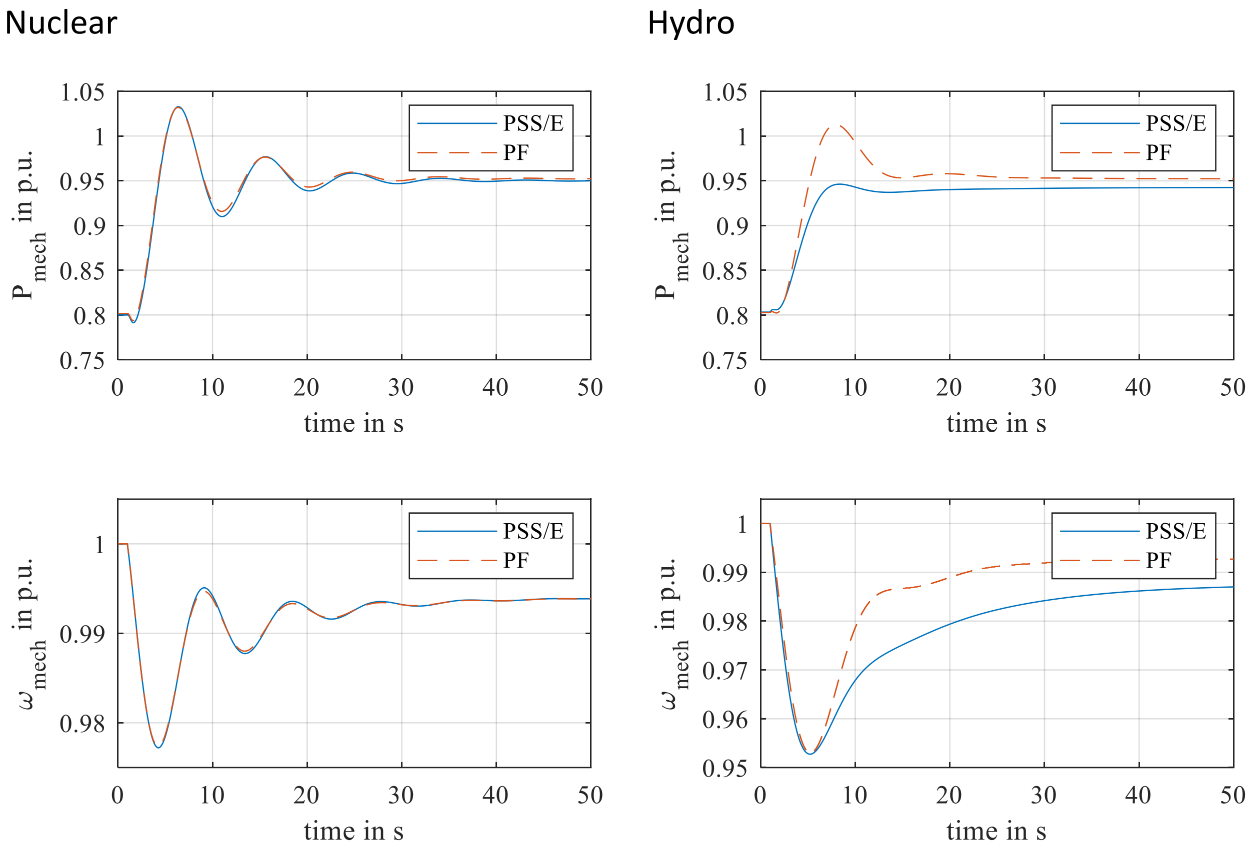
Figure 7: Test system for the comparison of standard dynamic models introduced in [6]

Table 3: Test cases for step response test

	Case 1	Case 2	Case 3
Test case	**Voltage reference step**	**Speed reference step**	**3-phase short-circuit**
Grid configuration	S-GEN is opened (no load operation) PSS and GOV are disabled	S-GEN is opened PSS is disabled Load with constant impedance at Terminal NGEN	Setup Figure 7
Event	Increase of terminal voltage reference to $U_{\mathrm{NGEN,setp}}$ = 1.05 pu	Load demand step $\Delta P_{\mathrm{L}} = +0.05\ \mathrm{pu}$ related to $P_{\mathrm{r,G}}$	3-phase short-circuit at HV side of transformer (NTHV), with fault duration of 0.1 s

When checking the overall system behaviour, it was identified that in case of larger frequency disturbances the results between PF and PSS®E diverged. Step response tests for case 2 where therefore repeated, with different load changes.

The step response test showed misalignments between PF and PSS®E on Hydro and Nuclear turbine governor models. In particular, the Hydro 1 model was used in PSS®E, while Hydro 4 in PowerFactory. In this case, the PF version of the model has been modified, using Hydro1 model for all the Hydro units in the system. Secondly, major differences were in the representation of nuclear units: PSS®E has introduced the GovSteamEU model in the latest versions, hence this has been used adopting a parametrization which solved instability after large perturbations. After these modifications, the transient behaviour of the two software was aligned. The following figures show the results for the Nuclear and Hydro units for a step response of 15% of the generated active Power (Pg). Some minor differences still hold in the initial response of hydro units, these can however be neglected due to the limited impact of hydro on the overall system behaviour.


Nuclear

Hydro

Figure 8: Comparison step response behaviour PSS®E vs PowerFactory

Furthermore, the respective dynamic load models available in PF and PSS®E have been tested and validated for the use in the dynamic model of continental Europe v2. This allows to represent the behaviour of vertical grid loads with constant power, constant current, impedance behaviour and allows to integrate the frequency dependency of loads such as asynchronous machines. A set of standard parameters is derived and proposed for the use in the model.

Overall system behaviour

After the validation of the dynamic models for generation and load a cross tool validation of the full model of CE has been done based on the comparison of the 3 GW reference outage of a nuclear power plant (Chooz). The validation was done in PowerFactory 2020 SP3 and PSS®E 35.2, the frequency trajectories are shown for two locations in the figure below. The results, show a good match of the steady state value, but a significant difference at frequency nadir. The differences between the two software tools were attributed to different mathematical representations of synchronous machines and load models in both software and/or solvers for numerical integration of the differential algebraic equation system. It is planned to bring the system responses for both simulation tool closer in model version 3 by consideration of these tool and solver specific properties.

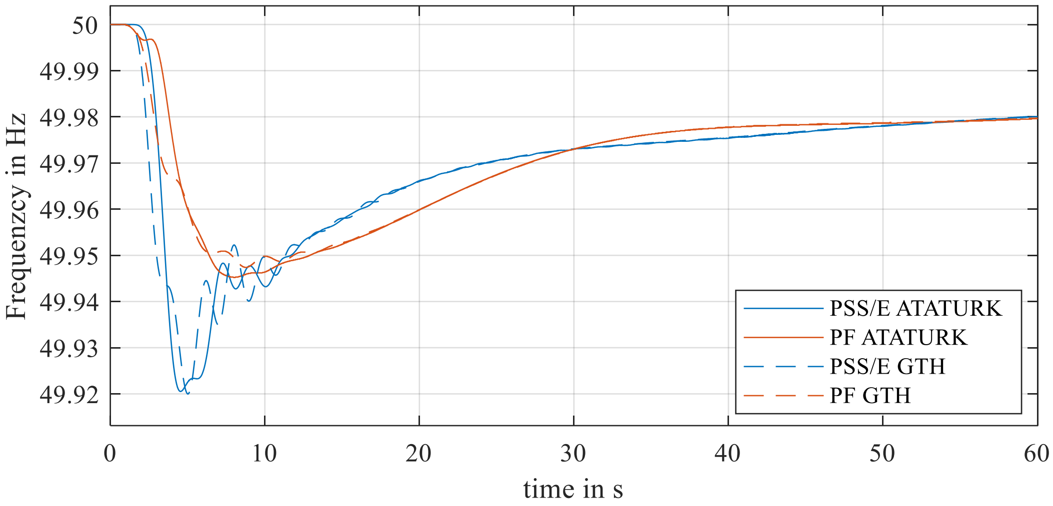


Figure 9: Comparison of full mdel behaviour PSS®E vs PowerFactory

Conclusions and future developments

The model described in this document represents a future condition to support analyses with a focus on frequency stability and inter-area oscillation phenomena, explicitly modelling the behaviour of synchronous generators and loads.

The validation of the model was carried out by comparing the measurements of real events with the outcome of the simulation in PowerFactory. Comparison between measurements and simulation results was made on steady-state rate and nadir for a selected rate measurement point close to the incident. Considering that the model represents a future operating condition and the three main inter-area oscillation modes derived from measurement are confirmed by simulation, the authors agree that the developed model is sufficiently accurate. However, as generic models and parameters are used for generators and PSSs modelling, care should be taken when results are derived from this model.

The comparison of the model behaviour between the two software tools showed up some differences. The investigations on this aspect highlighted some differences in generators modelling between the two tools, which increases with the perturbation severity. Nonetheless, the model performance is very satisfactory, and it is possible to confirm its validity in both the simulation tools.

In the next years, a new model (version 3) will be developed, based on a 2030 load-flow scenario, which will also include HVDC, RES, and other complex equipment models in order to allow for more precise and comprehensive analyses of the dynamic behaviour of the Continental European power system.

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