

Dynamic Study Model for the Interconnected Power System of Continental Europe in Different Simulation Tools

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Abstract—This paper describes the development process of the Dynamic Study Model (DSM) for the synchronously interconnected power system of Continental Europe in different simulation tools¹. The model was developed by the European Network of Transmission System Operators for Electricity (ENTSO-E) working group System Protection and Dynamics² and the University of Erlangen-Nuremberg within a collaboration. The paper describes the DSM scope, input and necessary steps towards an adequate basis for the novel dynamic data enhancement process by means of standard dynamic models for generation units and allocation criteria. Through a parameter variation process the DSM has been successively tuned to match a frequency measurement of a system event with respect to system inertia, frequency containment reserve and one of the typical oscillation modes within Continental Europe. Finally, the DSM behavior has been verified by means of previous experience from operation.

Index Terms—Dynamic Study Model, Power System Stability Studies, Standard Dynamic Models, Frequency Containment Reserves, Inter-Area Oscillation Modes.

I. INTRODUCTION

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. Therefore, transmission system operators, which are responsible for the transmission layer of the power system, provide long-term development plans (e.g. in [1]) in order to have a common basis among each other and to inform third parties about their intentions. The plans are based on forecasts concerning changes in generation structure, electricity markets, transmission projects etc.

The operation and planning of the transmission system is supported by stability studies done by each TSO with different simulation tools to evaluate the dynamic impact of future

changes. These kind of stability studies need to be done with consistent detailed models of generators. Depending on national regulations the generator owner has different obligations to provide his TSO with data for this modelling task. Apart from that, the results of this kind of studies normally are affected by the modeling of the neighboring countries. At this point, data acquisition, reliability and confidentiality issues may arise. Therefore, new concepts for modeling of power system dynamics are needed to cope with these challenges.

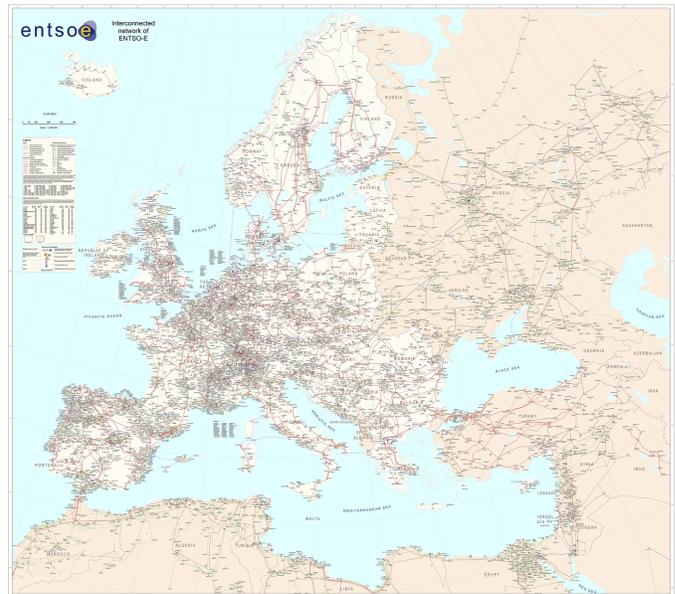


Fig. 1: Interconnected network of ENTSO-E³

This paper presents a novel approach for dynamic modeling of large power systems with the focus on the synchronously interconnected power system of Continental Europe as shown in figure 1 as part of the entire ENTSO-E network. The concept and the development process of the Dynamic Study Model can also be applied to other power systems.

¹The Dynamic Study Models in different simulation tools are available for stability studies from ENTSO-E on request: <https://www.entsoe.eu/publications/system-operations-reports/continental-europe/Initial-Dynamic-Model/Pages/default.aspx>

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³Map for 2013, provisioned by ENTSO-E (<http://www.entsoe.eu>)

The main target was to set up a robust, transparent and easily transferable dynamic model to reproduce the same results in different simulation tools. For this purpose a novel development process was applied. It includes a verified load flow model, standard dynamic models for generation units and the appropriate control as well as a parameter variation process to approach the model for the real system behavior. Since the East-West oscillation mode is typically the dominant one in the synchronously interconnected power system of Continental Europe [2], which implies the interaction of the two most distant borders and which is the one with the most oscillatory energy, the Dynamic Study Model is primarily tuned to a plant outage, which excites such a power oscillation. Once this oscillation mode is tuned, it has been checked that the other known modes are also reproduced by the system model.

II. SCOPE OF THE DYNAMIC STUDY MODEL

First of all it is necessary to define the scope of application for the Dynamic Study Model: It should be able to reflect the main characteristic dynamic behavior of the entire synchronously interconnected power system of Continental Europe. Thereby it represents the mutual impact and interaction of the incorporated areas – the global phenomena (figure 2).

Typically, a specific country or region is the main subject for an investigation. This "observability area" can be modeled in detail while the remote impact from other areas is given by the DSM. In consequence the usage of detailed models within this "observability area" depending on study objectives is required to cover local phenomena. In detail the Dynamic Study Model is suitable for representing:

- mean frequency transients (system inertia, frequency containment reserve) and
- dominant inter-area oscillation modes.

The model is not developed to properly represent local phenomena such as voltage transients, system protection of lines, generators and other devices, special protection schemes and defense plans, specific particular control schemes, dynamic

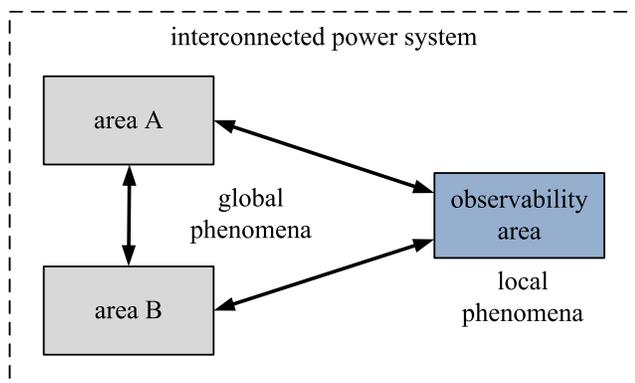


Fig. 2: Definition of an observability area and influencing phenomena

load behavior and specific models of devices connected via power electronic equipment. These phenomena and control

systems can be covered by detailed models within the "observability area" under perpetuation of the global dynamic behavior.

III. DEVELOPMENT OF THE DYNAMIC STUDY MODEL

Figure 3 shows the development process of the Dynamic Study Model in general. In a first step the load flow model of the entire power system is expanded with standard dynamic models for generators and their appropriate control devices by means of allocation criteria. Afterwards the initial parameters

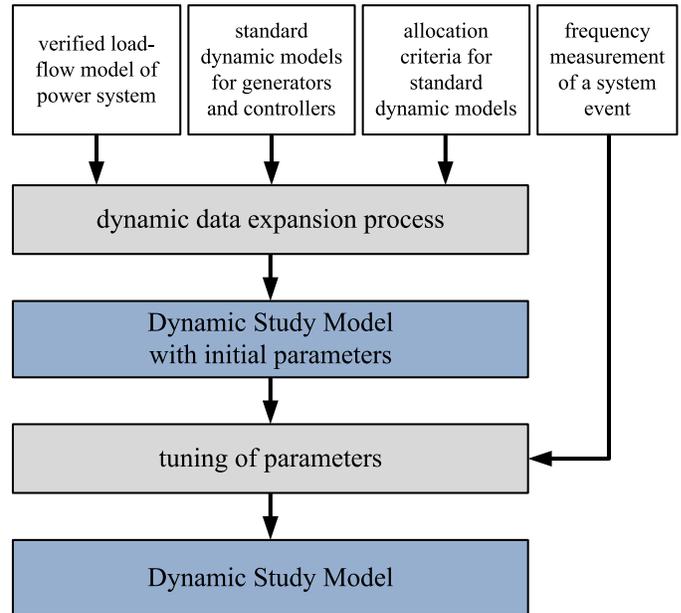


Fig. 3: The development process of the Dynamic Study Model

of the standard dynamic models are tuned on the basis of measurement values of a system event as well as expert knowledge of the power system, so that the Dynamic Study Model reproduces the real power system behavior.

The process is currently performed synchronously in different simulation tools. Each tool starts from the same load flow model which is available in a common data format. Based on a pre-defined guideline generic dynamic models, which are available in all simulation tools, are added to each model. As a final step the dynamic parameters are adjusted based on the tuning results from one model implementation. Finally, the simulation results are compared between the tools. In the future it will be possible to exchange dynamic power system models among different simulation tools using the Common Grid Model Exchange Standard [3].

The following chapters of the paper refer to this basic structure and describe the individual steps. The explanations refer to the application of the method for the synchronously interconnected power system of Continental Europe.

A. Load flow model of the power system

The load flow model for the Dynamic Study Model comprises the electrical topology of the synchronously interconnected power system of Continental Europe as shown in figure

1 and steady-state data for all generation units for a peak-demand case in 2020. The model information basis descends from the Network Modeling Database (NMD) of ENTSO-E and serves as the planning basis. The use of this database has the advantages of an agreement between TSOs for system planning purposes and detailed information about generation mix and corresponding energy sources for steady-state analysis. The model is structured into 26 areas corresponding to the included countries. It comprises 21,382 nodes and 10,829 generators.

In order to prepare the model for dynamic studies and avoid sharing confidential information, the load flow model underwent some adaptation steps, before it was distributed:

- adding of step-up transformers for generators directly connected to the transmission level,
- reduction of parallel lines,
- reduction of coupled busbars,
- aggregation of multiple loads at busbars and
- aggregation of multiple generation blocks at busbars.

All these adjustments were done without influencing the load flow result.

B. Standard dynamic models

The representation of system dynamics is accomplished by using standard dynamic models for synchronous machines and their control devices. Table I gives an overview and references for the used standard dynamic models for all generation units, which fulfill the defined criteria. The choice is based on principles with the aim to use commonly-used models with simple structure in order to facilitate the tuning process. The table also specifies the variable model parameters, that will be tuned at a later step to get the desired system behavior.

TABLE I: Standard dynamic models for generation units and controllers

element	model	variable parameter for tuning
synchronous machine (SM)	standard model, as defined in [4]	acceleration time constant T_A for complete rotating units
governor (GOV)	TGOV1, as defined in [5]	droop R , time constants T_{G2}, T_{G3}
automatic voltage regulator (AVR)	SEXS, as defined in [6]	gain K
power system stabilizer (PSS)	PSS2A, as defined in [7]	gain K_{S1}

To guarantee a common basis for the Dynamic Study Model implementation in the different simulation tools, a harmonization process for the standard dynamic models as well as for the load flow model was done at the beginning of the DSM development. For the comparison of the standard dynamic models a one-machine test system as shown in figure 4 was introduced. It comprises a synchronous machine (SM) with a governor (GOV), an automatic voltage regulator (AVR) and a power system stabilizer (PSS). This generation unit is equipped with the defined standard dynamic models from table I with default parameters. There are also a step-up transformer, an infinite busbar, loads and switches for test case selection.

Beside a comparison of initialization values for a given load flow case, this basic configuration of the test system is used in three dynamic test cases as described in table II. The test cases target the verification of the standard dynamic models among the simulation tools. These test cases are: voltage reference step in no-load operation, stepwise load increase in island operation and a 3-phase short-circuit.

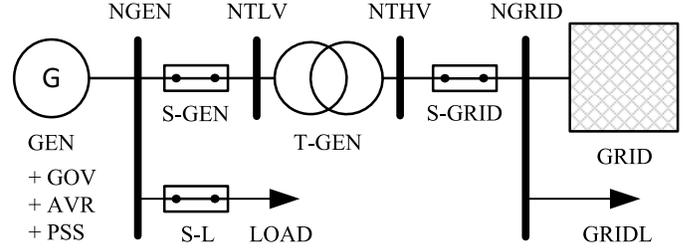


Fig. 4: Test system for the comparison of standard dynamic models

The results of these tests are shown in figure 5 as an array of curves for the five different simulation tools. The results show a good match although some smaller deviations during transients can be seen. In the steady-state condition the curves overlap nearly perfectly. The results of the tests were already published in [6]. In this reference all the parameters for the branches and controllers are listed.

TABLE II: Test cases for comparison of standard dynamic models

test case 1	test case 2	test case 3
opened S-GRID, opened S-GEN, opened S-L	opened S-GRID, opened S-GEN, closed S-L	closed S-GRID, closed S-GEN, opened S-L
step of AVR voltage reference $\Delta U_{NGEN,sep} = +0.05$ p.u.	increase of demand in LOAD $\Delta P_{LOAD} = +0.05$ p.u.	3-phase short circuit at NTHV

The applied parameters for the standard dynamic model tests represent the basis for the parameter variation process in a further step of the DSM development process. In the next step the tested and compared standard dynamic models are systematically assigned to generation units.

C. Dynamic data expansion process

The dynamic data are added in each simulation tool by scripts as shown in algorithm 1 as pseudo code. Every generator i of n generators in the load flow model pass through this procedure. There are two mandatory conditions concerning the maximum active power $P_{max,i}$ of a generator i and its initial power $P_{init,i}$ in the load case.

The first condition assures that only large generation units above $P_{max,ref} = 250$ MW are modeled as synchronous machines. Otherwise they are modeled as constant impedances. The second condition, if the first one is fulfilled, guarantees that only generators i with an initial active power greater than $P_{init,ref} = 0$ MW are equipped with the full appropriate control models. Otherwise they only get an AVR model. In the case of the Dynamic Study Model the conditions particularly aim at

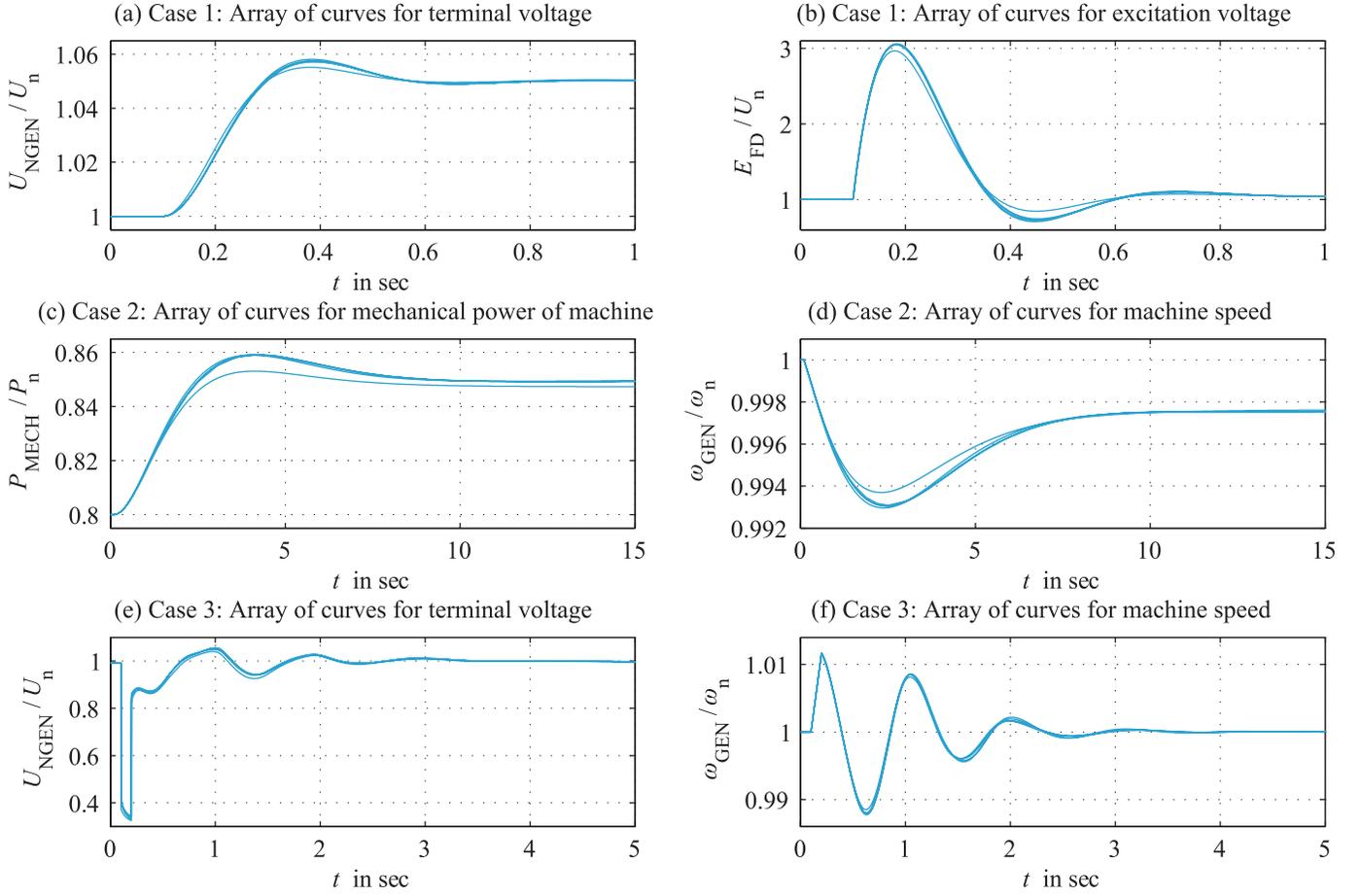


Fig. 5: Selected results from the comparison of standard dynamic models in three test cases

Algorithm 1 Dynamic data expansion process

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1: for generator  $i = 1 \rightarrow n$  do
2:   if  $P_{\max,i} \geq P_{\max,ref}$  then
3:     assign synchronous machine model to generator  $i$ 
4:     if  $P_{\text{init},i} \geq P_{\text{init},ref}$  then
5:       assign GOV, AVR and PSS models to generator  $i$ 
6:     else
7:       assign AVR model to generator  $i$ 
8:     end if
9:   else
10:    model generator  $i$  as negative constant impedance
11:  end if
12: end for

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generators with negative initial power, to avoid deviations as a result of standard model choice for the governor for thermal power plants. For instance it concerns pumped-storage hydro power plants or synchronous condensers. The machines were identified by maximum active power rather than rated apparent power due to insufficient information in the load flow model.

Executing this procedure, one obtains 1,013 synchronous machine models out of 10,829 generators in the load flow model. Just 17 of them have only an AVR model. The remained 9,816 generators are modeled as negative constant impedances. The obtained Dynamic Study Model with initial

parameters for the standard dynamic models was checked for control limitation violations and stable time-domain simulation without any system event. In the next step, the parameters are tuned to influence the model behavior.

D. Parameter variation process

For the next step the parameters from the tests of the standard dynamic models were used as default [6]. The parameter variation process is merely done in one simulation tool. Therefore frequency measurements of the Wide Area Measurement System (WAMS) for a plant outage in Spain in October 2011 are used, see the black curves in figure 6. The outage was a loss of active power $P \approx 1$ GW. The measured steady-state frequency deviation is $\Delta f \approx 26$ mHz, before the frequency restoration reserves are activated. The gradient of the frequency immediately after the outage varies up to the maximum of $|\Delta f / \Delta t| \approx 63$ mHz/sec in Western Europe and $|\Delta f / \Delta t| \approx 9$ mHz/sec in Central Europe. The electromechanical wave propagation from Western to Eastern Europe needs approximately two seconds. In consequence of the outage electromechanical oscillations occur in the East-West axis of the power system with Central Europe as non-swinging area.

The parameter variation process is primarily based on a

successive approximation of dynamic model behavior to that measurements of the system event considering results of the eigenvalue analysis and mode knowledge of the power system [2], [8]. Generally the applied tuning method can be divided into the following steps:

- adaptation of steady-state frequency deviation,
- adaptation of moderate dynamics,
- adaptation of faster dynamics and
- adaptation of damping.

The variable tuning parameters of the standard dynamic models were already defined in table I. The variation of the parameters in the first steps is done simultaneously for all areas.

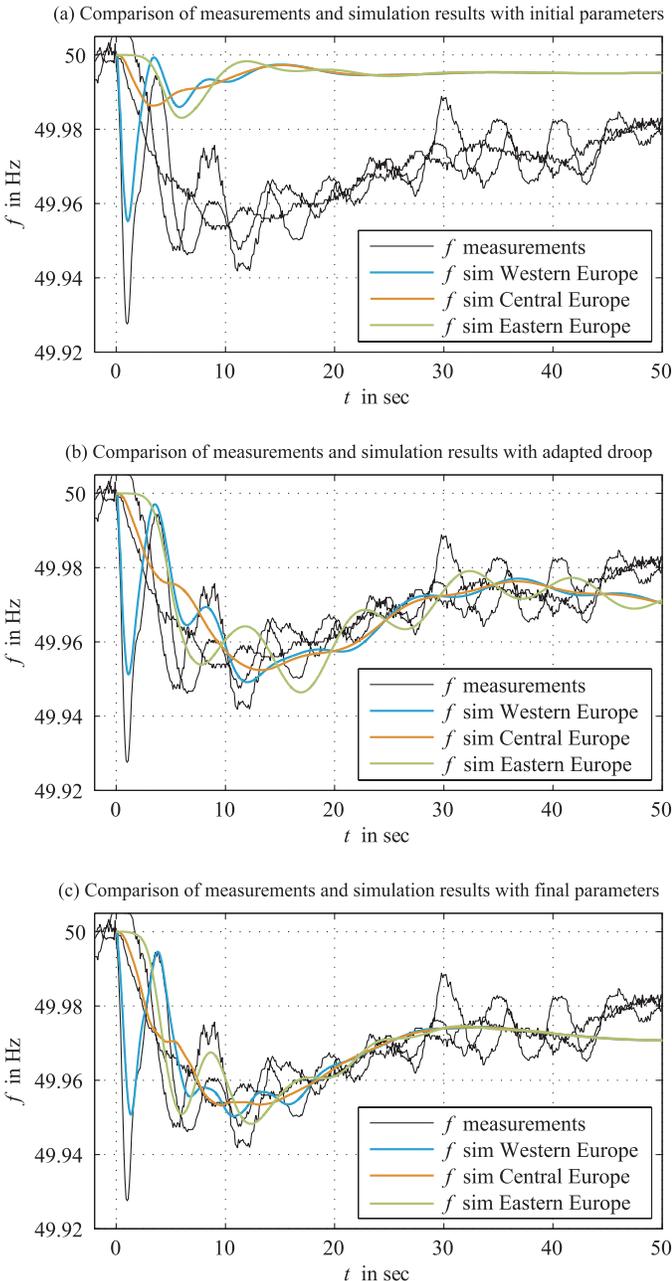


Fig. 6: Measurements and simulation results for parameter variation process

Subsequently the variation is done individually for pre-defined areas. Figure 6 (a)-(c) shows the successive approximation of the model behavior for three frequency signals, in Western, Central and Eastern Europe. In black color one can see the frequency measurement signals of these locations.

In the first diagram (a) the comparison between the simulation results with initial parameters and the measurements is shown. It can be seen, that regarding the tuning method the droop R of the governors has to be increased to get closer to the measurements. The droop mainly affects the steady-state frequency deviation. But increasing the droop influences the dynamic behavior of the governors and in consequence of the system. This can be seen in the simulation results of the second diagram. Therefore an adaptation of the moderate dynamics by changing the turbine time constants T_{G2} and T_{G3} is needed. In further steps the faster dynamics and damping of the system are tuned using the other variable parameters T_A , K and K_{S1} . The frequency response in (c) shows the final tuning result, that satisfies the requirements. It is a good approximation for the system inertia, frequency containment reserve and the stimulation of electromechanical oscillations. The time constants of the oscillations correlate with the measured ones. The oscillation damping of the system cannot be modeled adequately as it is a non-constant value for the real system.

The analysis of the electromechanical oscillations is also performed in the linearized model by means of eigenvalues of the system. As figure 7 shows, the characteristic modes as presented in [8] are adequately modeled in the DSM.

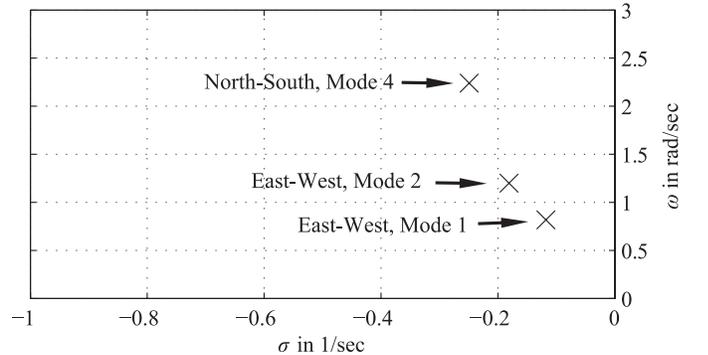


Fig. 7: Selected oscillatory eigenvalues for the DSM

After tuning the system behavior in one simulation tool, the final parameters for all areas are distributed to users of different simulation tools. Afterwards a comparison of all tools is performed. Figure 8 shows this comparison between the measured and simulated frequencies for nodes in Western, Central and Eastern Europe, again as array of curves for the five different simulation tools.

It can be seen a good fit of simulated curves among the different simulation tools. The smaller deviations may have the same source as seen in the standard dynamic model tests. Hence the predetermined aims of the Dynamic Study Model concerning the dynamic behavior and the overall conformity of different tools are fulfilled.

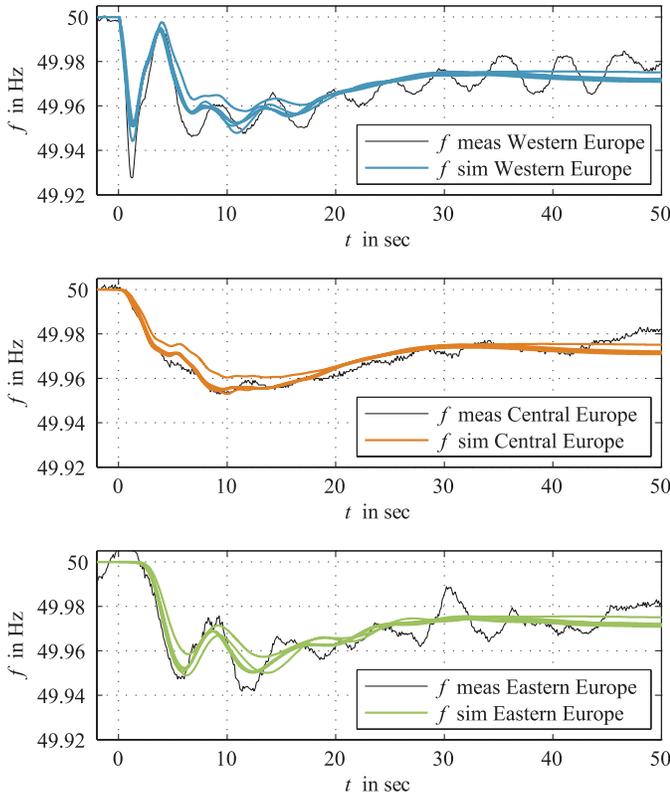


Fig. 8: Measured and simulated frequency after a plant outage in Spain

IV. CONCLUSION AND OUTLOOK

As shown in the paper, the novel approach of the Dynamic Study Model is suitable for the representation of the global dynamic behavior of the synchronously interconnected power system of Continental Europe concerning the system inertia, the frequency containment reserve and the dominant inter-area oscillation modes. It is available in different simulation tools producing similar results. The deviations to measurements and between the simulation tools are insignificant with regard to the objectives of the model.

In future the degree of the model accuracy can be augmented by considering existing standard dynamic models for:

- generation units with respect to their energy source (steam, gas, hydro etc.), e.g. [5],
- loads with dynamic impact, e.g. [9], [10], and
- infeeds connected via power electronics and transmission technologies employing power electronics, with dynamic

impact (wind, HVDC, FACTS), e.g. [11]–[13].

The major benefit of the Dynamic Study Model is the entire topology information of the synchronously interconnected power system of Continental Europe under consideration of dynamics, so that it can be used in analysis of global phenomena in stability studies. For analyzing local phenomena in the defined "observability area" a detailed model can be implemented modularly while keeping the global frequency behavior. It is also possible to transfer the concept and the development process of the Dynamic Study Model to other power systems.

V. ACKNOWLEDGMENTS

The authors gratefully acknowledge the constructive contributions, comments, discussions and technical support of the TSOs Amprion (Germany), ČEPS (Czech Republik), Energinet.dk (Denmark), Mavir (Hungary), PSE (Poland), REE (Spain), RTE (France), Swissgrid (Switzerland), TenneT (Germany), Terna (Italy) and TransnetBW (Germany).

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