European Network of
Transmission System Operators
for Electricity

DOCUMENTATION ON CONTROLLER TESTS IN TEST GRID CONFIGURATIONS

26.11.2013

ENTSO-E SG SPD REPORT

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1 TESTING OF FUNDAMENTAL MODELS IN DIFFERENT SIMULATION TOOLS

The entso-e sub-group “System Protection and Dynamics” (SG SPD) is going to release a dynamic model for the transmission system of Continental Europe (CE) in 2014. This model will be based on a systematically reduction of machines in the system to a reasonable amount. The aim is to develop a common dynamic model which delivers similar results in all simulation tools used by the Continental European transmission system operators (TSOs) for dynamic simulation.

In order to ensure comparable results in the different simulation tools for studies with the entire dynamic model of the transmission system, it is essential to ensure similar behaviour of standard models for machines, their controllers and other elements as well as to introduce consistent standards regarding simulation and element parameters as a first step. For this purpose a comparison of results obtained from six different simulation tools (anonymously named a, b, c, d, e and f) for defined elementary tests was carried out by the SG SPD. This document describes this test procedure.

2 BASIC TEST GRID CONFIGURATION

The following network scheme (Fig. 2-1) is used as the basic test grid configuration with the purpose to compare the stationary and dynamic performance of a standard machine model equipped with standard controllers and connected to an infinite source within the different simulation tools.

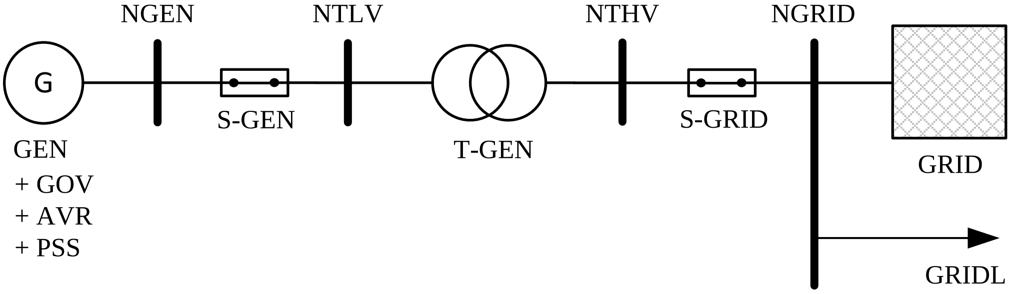

FIG. 2-1: NETWORK SCHEME FOR THE BASIC TEST GRID CONFIGURATION

The four node (NGEN, NTLV, NTHV and NGRID) test grid consists of a synchronous machine (GEN) with its appropriate control (governor (GOV), automatic voltage regulator (AVR), power system stabiliser (PSS)), a machine side switch (S-GEN), a unit transformer (T-GEN), a grid side switch (S-GRID), an infinite source (GRID) with fixed frequency and an adjustable short-circuit power level as well as a constant impedance load (GRIDL). The nominal voltages are 21 kV for the nodes NGEN and NTLV and 380 kV for the nodes NTHV and NGRID respectively. The nominal frequency is $\omega_\mathrm{n} = 2\pi f_\mathrm{n} = 2\pi 50\,\mathrm{Hz}$.

The particular elements, their corresponding models and their parameters will be explained in the following sections.

2.1 SYNCHRONOUS MACHINE GEN WITH CONTROL

In every simulation tool the standard model of a 500 MVA synchronous machine is used to perform the basic load flow case and the controller test cases. The values for its characteristic parameters are given in Table 1. Saturation of the machine and losses due to stator resistance are not taken into account.

TABLE 1: PARAMETER SET FOR THE MODEL OF THE SYNCHRONOUS GENERATOR

Parameter	Value	Base unit	Description
$S_\mathrm{r,G}$	500	MVA	rated apparent power of the machine
$U_\mathrm{r,G}$	21	kV	rated voltage of the machine
$\cos\varphi_\mathrm{r}$	0.95		rated power factor of the machine
f_r	50	Hz	rated frequency of the machine

n_{r}	3,000	1/min	rated synchronous speed of machine
$x_{\mathrm{a}\sigma}$	0.15	$U_{\mathrm{r,G}}^2 / S_{\mathrm{r,G}}$	armature leakage reactance
r_{a}	0	$U_{\mathrm{r,G}}^2 / S_{\mathrm{r,G}}$	armature resistance
T_{A}	8	sec	starting time of complete aggregate referred to $S_{\mathrm{r,G}}$
x_{d}	2	$U_{\mathrm{r,G}}^2 / S_{\mathrm{r,G}}$	synchronous reactance in d-axis
$x_{\mathrm{d}}^{'}$	0.35	$U_{\mathrm{r,G}}^2 / S_{\mathrm{r,G}}$	transient reactance in d-axis
$T_{\mathrm{d}}^{'}$	0.9	sec	transient short circuit time constant in d-axis
$x_{\mathrm{d}}^{''}$	0.25	$U_{\mathrm{r,G}}^2 / S_{\mathrm{r,G}}$	subtransient reactance in d-axis
$T_{\mathrm{d}}^{''}$	0.03	sec	subtransient short circuit time constant in d-axis
x_{q}	1.8	$U_{\mathrm{r,G}}^2 / S_{\mathrm{r,G}}$	synchronous reactance in q-axis
$x_{\mathrm{q}}^{'}$	0.5	$U_{\mathrm{r,G}}^2 / S_{\mathrm{r,G}}$	transient reactance in q-axis
$T_{\mathrm{q}}^{'}$	0.6	sec	transient short circuit time constant in q-axis
$x_{\mathrm{q}}^{''}$	0.3	$U_{\mathrm{r,G}}^2 / S_{\mathrm{r,G}}$	subtransient reactance in q-axis
$T_{\mathrm{q}}^{''}$	0.05	sec	subtransient short circuit time constant in q-axis

Some of the simulation tools require some alternative parameters. The following table shows these alternative parameters derived from the above parameters.

TABLE 2: ALTERNATIVE PARAMETERS DERIVED FROM GIVEN PARAMETERS FOR THE MACHINE

Parameter	Value	Base unit	Description
T_{G}	inf	sec	aperiodic time constant
GD^2	162.114	Mp m²	momentum of machine
J	40.528	t m²	moment of inertia
H	4	MW sec/MVA	inertia
$T_{\mathrm{do}}^{'}$	5.143	sec	transient open circuit time constant in d-axis
$T_{\mathrm{do}}^{''}$	0.042	sec	subtransient open circuit time constant in d-axis
$T_{\mathrm{qo}}^{'}$	2.16	sec	transient open circuit time constant in q-axis
$T_{\mathrm{qo}}^{''}$	0.083	sec	subtransient open circuit time constant in q-axis

The synchronous machine is equipped with a GOV, an AVR and a PSS. For those controllers simple models were chosen in a first step.

GOVERNOR

As speed governor the simple model for steam turbines TGOV1 (corresponding CIM-controller: “GOVSTEAM0”) is used. Fig. 2-2 shows the corresponding block diagram.

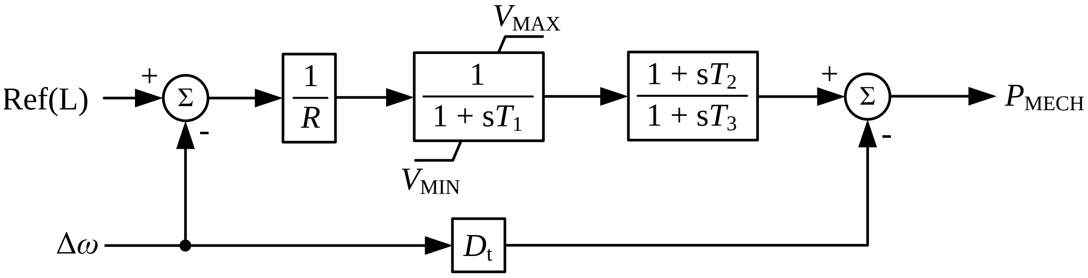

FIG. 2-2: BLOCK DIAGRAM OF THE GOVERNOR TGOV1

Table 3 shows the defined parameters. Those are related to turbine rated power $P_{r,MECH}$ and since the armature resistance r_a is not taken into account they are also related to rated active power $P_{r,G} = \cos\varphi_r \cdot S_{r,G} = 475\,\text{MW}$ of the synchronous machine.

TABLE 3: PARAMETER SET FOR THE GOVERNOR

Parameter	Value	Base unit	Description
R	0.05		controller droop
T_1	0.5	sec	governor time constant
T_2	3	sec	turbine derivative time constant
T_3	10	sec	turbine delay time constant
D_t	0		frictional losses factor
V_{MIN}	0		minimum gate limit
V_{MAX}	1		maximum gate limit

AUTOMATIC VOLTAGE REGULATOR

The simplified excitation system SEXS (corresponding CIM-controller: “ExcSEXS”, here with deactivated PI controller) is used as model for the automatic voltage regulator and the excitation system of the synchronous machine. Fig. 2-3 shows the block diagram of this model with the excitation voltage E_{FD} as output. The input V_S will be set by the PSS output.

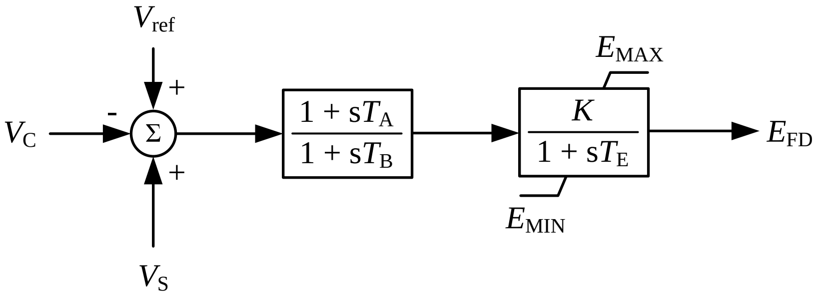

FIG. 2-3: BLOCK DIAGRAM OF THE SIMPLIFIED EXCITATION SYSTEM SEXS

The excitation voltage is based as described in [1] according to the air-gap line. Therefore all of the parameters are valid for this definition. Table 4 defines the parameter set of the simplified excitation system SEXS for the test cases.

TABLE 4: PARAMETER SET FOR THE SIMPLIFIED EXCITATION SYSTEM

Parameter	Value	Base unit	Description
K	200		controller gain
T_A	3	sec	filter derivative time constant
T_B	10	sec	filter delay time
T_E	0.05	sec	exciter time constant
E_{MIN}	0		controller minimum output
E_{MAX}	4		controller maximum output

POWER SYSTEM STABILISER

The standard model PSS2A is chosen as the power system stabiliser. The following figure shows the corresponding block diagram.

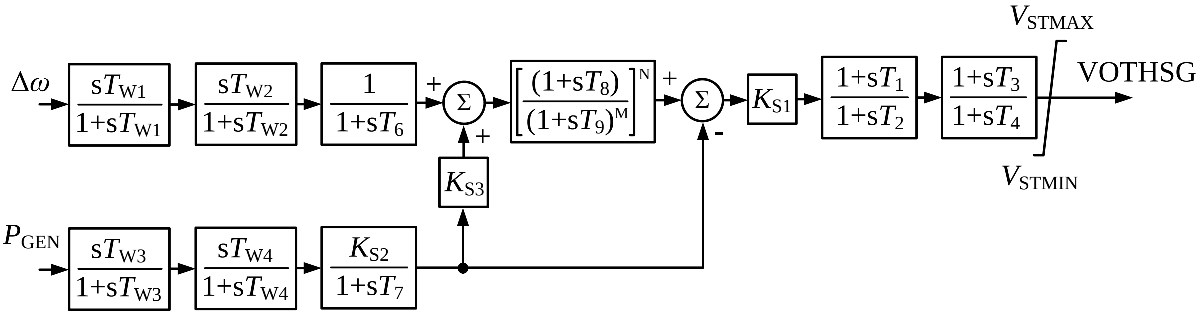

FIG. 2-4: BLOCK DIAGRAM OF THE POWER SYSTEM STABILIZER PSS2A

In Table 5 a parameter set for the power system stabiliser is defined.

TABLE 5: PARAMETER SET FOR THE POWER SYSTEM STABILIZER

Parameter	Value	Base unit	Description
K_{S1}	10		PSS gain
K_{S2}	0.1564		2nd signal transducer factor
K_{S3}	1		washouts coupling factor
T_{W1}	2	sec	1st washout 1th time constant
T_{W2}	2	sec	1st washout 2th time constant
T_{W3}	2	sec	2nd washout 1th time constant

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[1] cf. IEEE Std 421.5-2005: *IEEE Recommended Practice for Excitation System Models for Power System Stability Studies*

T_{W4}	0	sec	2nd washout 2th time constant
T_1	0.25	sec	1st lead-lag derivative time constant
T_2	0.03	sec	1st lead-lag delay time constant
T_3	0.15	sec	2nd lead-lag derivative time constant
T_4	0.015	sec	2nd lead-lag delay time constant
T_6	0	sec	1st signal transducer time constant
T_7	2	sec	2nd signal transducer time constant
T_8	0.5	sec	ramp tracking filter deriv. time constant
T_9	0.1	sec	ramp tracking filter delay time constant
$V_{ST,MIN}$	-0.1		controller minimum output
$V_{ST,MAX}$	0.1		controller maximum output
N	0		ramp tracking filter
M	0		ramp tracking filter
IC_1	1		1st input selector
IC_2	3		2nd input selector

2.2 SWITCHES S-GEN AND S-GRID

For the electrical switches standard models for ideal breakers are used in the simulation tools. In case a dedicated breaker model doesn't exist in a software environment the switches are implemented as very small resistance in case of closed switch and large resistance in case of opened switch.

2.3 UNIT TRANSFORMER T-GEN

The following Table 6 comprises the used values for the unit transformer, which is modelled as an ideal transformer without saturation.

TABLE 6: CHOSEN PARAMETER FOR THE UNIT TRANSFORMER

Parameter	Value	Base unit	Description
$S_{r,T}$	500	MVA	Rated apparent power of unit transformer
$U_{r,THV}$	419	kV	Rated voltage on high-voltage side
$U_{r,TLV}$	21	kV	Rated voltage on low-voltage side
u_r	0.15	%	Re{} of short-circuit impedance, related to $U_{r,THV}^2 / S_{r,T}$
u_k	16	%	Short-circuit impedance, related to $U_{r,THV}^2 / S_{r,T}$

2.4 EQUIVALENT GRID

The equivalent grid is implemented as an infinite source with a defined short-circuit capacity of 2,500 MVA. Its parameters are summarised in Table 7.

TABLE 7: PARAMETERS FOR THE GRID EQUIVALENT

Parameter	Value	Base unit	Description
S_k''	2,500	MVA	short-circuit capacity
U_r	380	kV	rated voltage of grid
R / X	0.1		ratio of resistance to reactance of grid
c	1.1		c-factor for calculation of short-circuit capacity

Some of the simulation tools require some alternative parameters. The following table shows these alternative parameters derived from the given parameters above.

TABLE 8: ALTERNATIVE PARAMETERS FOR THE GRID EQUIVALENT

Parameter	Value	Base unit	Description
R	6.322	Ω	resistance of grid
X	63.22	Ω	reactance of grid

2.5 CONSTANT IMPEDANCE LOAD GRIDL

The load GRIDL connected to the node NGRID is defined as a constant impedance load. That means, it has exact active and reactive power consumption in the load flow calculation and is represented as constant impedance for the time-domain simulation. This includes a voltage dependent $(P, Q \propto u^2)$ and frequency independent behaviour. The initial values for active and reactive power are referred to a terminal voltage of one pu.

3 BASIC LOAD FLOW CASE

A basic load flow case for the test grid is defined for a stationary comparison and as initial condition for the time-domain simulation. The initialization of the set-points includes the slack bus NGRID and the generator bus NGEN.

$$\begin{aligned} P_{\mathrm{G,setp}} &= 475\,\mathrm{MW} & U_{\mathrm{NGRID,setp}} &= 1.05\,\mathrm{pu} \\ Q_{\mathrm{G,setp}} &= 156\,\mathrm{MVar} & \delta_{\mathrm{NGRID,setp}} &= 0^{\circ} \end{aligned} \tag{3.1}$$

Additionally the constant impedance load GRIDL is initialized with active and reactive power consumption, voltage independent for the load flow:

$$P_{\mathrm{GRIDL,setp}} = -475\,\mathrm{MW} \qquad Q_{\mathrm{GRIDL,setp}} = -76\,\mathrm{MVar} \tag{3.2}$$

Coincident results for the load flow calculation were generated in all simulation tools. Fig. 3-1 shows the obtained values.

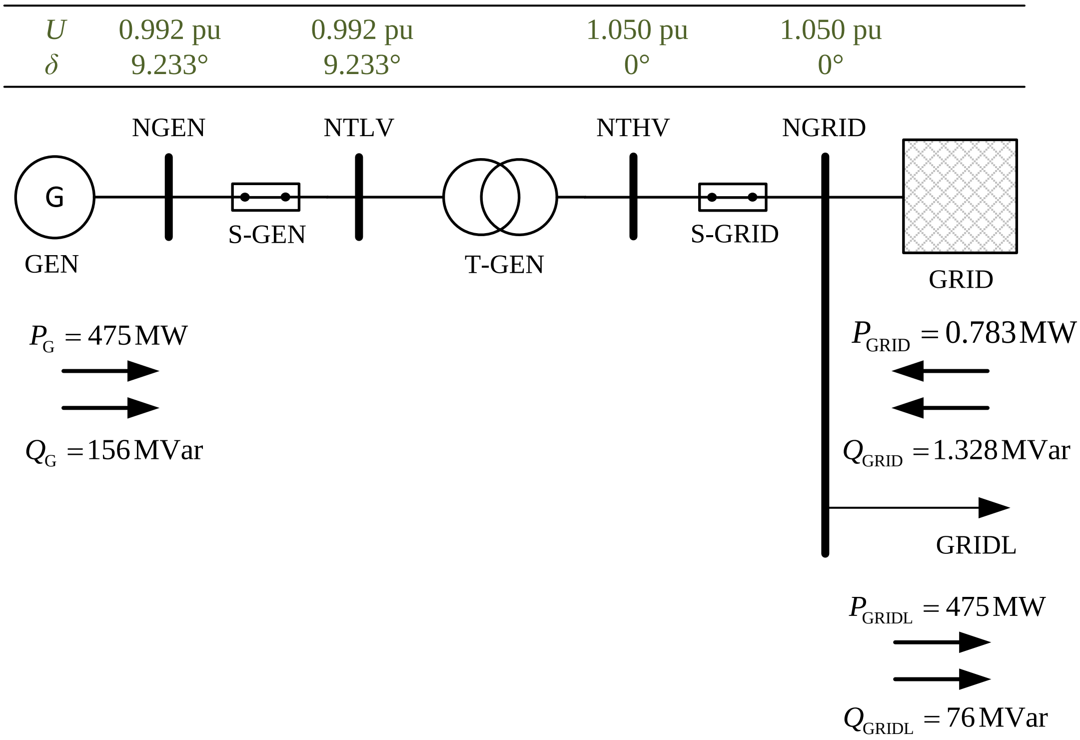

FIG. 3-1: RESULTS OF THE BASIC LOAD FLOW CASE

4 DEFINITION OF TEST CASES

Three test cases for time-domain simulation were defined in order to gain representative results for the dynamic performance of the synchronous machine and its control devices. Test case 1 aims at the dynamic performance of the synchronous machine and its AVR, whereas test case 2 compares the behaviour of the synchronous machine and its speed governor. Finally, test case 3 reveals the overall dynamic characteristic with the entire control system (AVR, governor, PSS) connected.

The time-domain simulation is applied with a fixed time-step of 1 msec. The event-time is always at 0.1 sec. The simulation time varies due to the object of investigation. The initial condition for the speed is always at one pu referred to synchronous frequency.

4.1 TEST CASE 1

The purpose of the first test case is to compare the dynamic behaviour of the model for the synchronous machine and its AVR by analysing the terminal voltage U_{NGEN} and the excitation voltage E_{FD} inside the machine. Therefore a no-load operation is created by opening the machine side switch S-GEN. For this load flow case without active and reactive power the terminal voltage U_{NGEN} is set to $1\,\mathrm{pu}$ and since there is no saturation characteristic for the synchronous machine implemented, the initial value for the excitation voltage is also $1\,\mathrm{pu}$.

At the event-time the reference value for the terminal voltage is increased by $\Delta U_{\mathrm{NGEN,setp}} = +0.05\,\mathrm{pu}$. The response of the terminal and excitation voltage to this event in different simulation tools can be seen in chapter 5.1.

4.2 TEST CASE 2

The purpose of the second test case is to compare the dynamic behaviour of the model for the synchronous generator and its governor by analysing the terminal voltage U_{NGEN}, the active and mechanical power of the synchronous machine P_{G} and P_{MECH}, the reactive power of the synchronous machine Q_{G} and the speed ω_{G}. The machine side switch S-GEN is still opened. Additionally another constant impedance is implemented at the node NGEN, whose initialisation is related to the terminal voltage of $1\,\mathrm{pu}$ (dependencies as described in chapter 2.5). Due to its undesirable influence the power system stabiliser has to be switched off for this case.

The model is initialised with $U_{\mathrm{NGEN}} = 1\,\mathrm{pu}$ again. This time an initial active power demand in the additional constant impedance of $P_{\mathrm{L}} = 0.8 \cdot S_{\mathrm{r,G}} \cdot \cos\varphi_{\mathrm{r}} = 380\,\mathrm{MW}$ is considered.

At the event-time the active power demand of the additional constant impedance is increased by $\Delta P_{\mathrm{L}} = +0.05\,\mathrm{pu}$ related to the rated active power of the synchronous machine $P_{\mathrm{r,G}} = S_{\mathrm{r,G}} \cdot \cos\varphi_{\mathrm{r}}$. The response to this event can be seen in chapter 5.2.

4.3 TEST CASE 3

The purpose of the third test case is to compare the dynamic behaviour of the model for the synchronous machine with its whole control in operation during and after a three-phase short-circuit by analysing the terminal voltage U_{NGEN}, the excitation voltage inside the generator E_{FD}, the active and reactive power of the synchronous machine P_{G} and Q_{G} as well as speed ω_{G}. The additional constant impedance load used in test case 2 is removed and the machine side switch is closed. For further analysis the behaviour of the constant impedance load GRIDL and the PSS output signal VOTHSG are also observed.

For the initialisation of the system the basic load flow case introduced in chapter 3 is used.

At the event-time a bolted three-phase short circuit occurs at the high-voltage side of the unit transformer (node NTHV). After the fault duration of $T_{\mathrm{f}} = 0.1\,\mathrm{sec}$ the initial system conditions are restored. The response to this event can be seen in chapter 5.3.

4.4 SUMMARISED OVERVIEW

The following table summarises the described test cases.

TABLE 9: SUMMARY OF DESCRIBED TEST CASES

	Case 1	Case 2	Case 3
Test case	voltage reference step	speed reference step	3-phase short-circuit
Grid configuration	- no-load operation - switch S-GEN opened	- isolated operation - switch S-GEN opened - constant impedance load at NGEN	- basic test grid configuration - chapter 4
Simulation time step	1 msec	1 msec	1 msec
Simulation time	2 sec	15 sec	10 sec
LF initialisation	$U_{\mathrm{NGEN}} = 1\,\mathrm{pu}$ $\omega_{\mathrm{G}} = 1\,\mathrm{pu}$ $P_{\mathrm{G}} = 0$	$U_{\mathrm{NGEN}} = 1\,\mathrm{pu}$ $\omega_{\mathrm{G}} = 1\,\mathrm{pu}$ $P_{\mathrm{L}} = 0.8 \cdot P_{\mathrm{r,G}}$ $Q_{\mathrm{L}} = 0$	- see chapter 3
Event-time	100 msec	100 msec	100 msec
Event	voltage reference step $\Delta U_{\mathrm{NGEN,setp}} = +0.05\,\mathrm{pu}$	load demand step $\Delta P_{\mathrm{L}} = +0.05\,\mathrm{pu}$ related to $P_{\mathrm{r,G}}$	bolted 3-phase short-circuit at HV side of transformer, with fault duration $T_{\mathrm{f}} = 0.1\,\mathrm{sec}$

Values to analyse	U_{NGEN} rel. to $U_{\mathrm{n,NGEN}}$ E_{FD} rel. to $U_{\mathrm{n,NGEN}}$	U_{NGEN} rel. to $U_{\mathrm{n,NGEN}}$ P_{G} rel. to $P_{\mathrm{r,G}}$ P_{MECH} rel. to $P_{\mathrm{r,G}}$ Q_{G} rel. to $Q_{\mathrm{r,G}}$ ω_{G} rel. to ω_{n}	U_{NGEN} rel. to $U_{\mathrm{n,NGEN}}$ P_{G} rel. to $P_{\mathrm{r,G}}$ Q_{G} rel. to $Q_{\mathrm{r,G}}$ ω_{G} rel. to ω_{n} VOTHSG rel to $U_{\mathrm{n,NGEN}}$ P_{GRIDL} rel. to $P_{\mathrm{r,G}}$ Q_{GRIDL} rel. to $Q_{\mathrm{r,G}}$

5 COMPARISON AND ANALYSIS OF RESULTS

5.1 TEST CASE 1

The following diagrams show the comparison of the results for the terminal voltage U_{NGEN} and the excitation voltage E_{FD} of the synchronous machine as response to the voltage reference step.

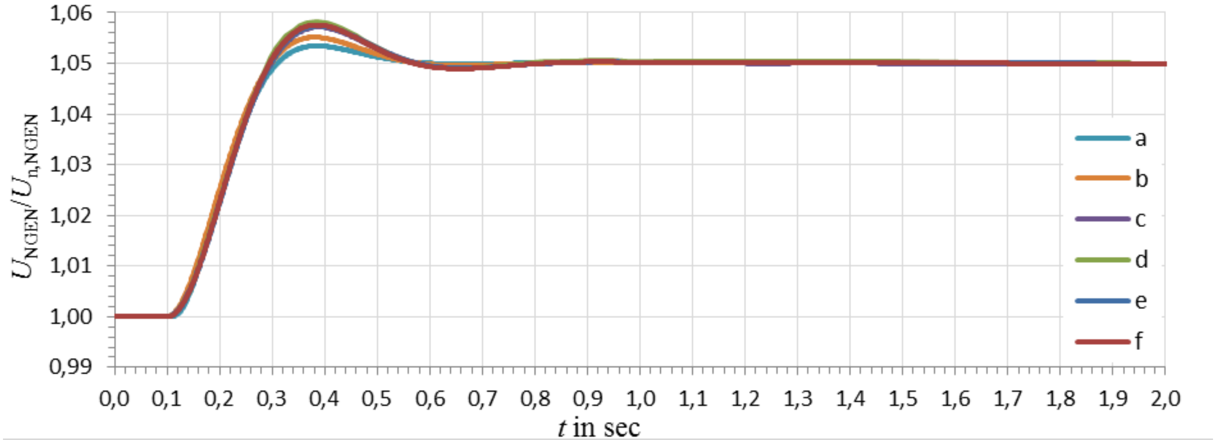

FIG. 5-1: RESPONSE OF TERMINAL VOLTAGE OF MACHINE IN TEST CASE 1

The response of the terminal voltage U_{NGEN} of the synchronous machine shows a stationary precision in all simulation tools. The desired voltage reference step will be fulfilled by all of the tools. The dynamic behaviour shows small deviations. The source of this deviation can be observed in the response of excitation voltage E_{FD} in Fig. 5-2. From stationary point of view, all of the simulation tools have identical behaviour.

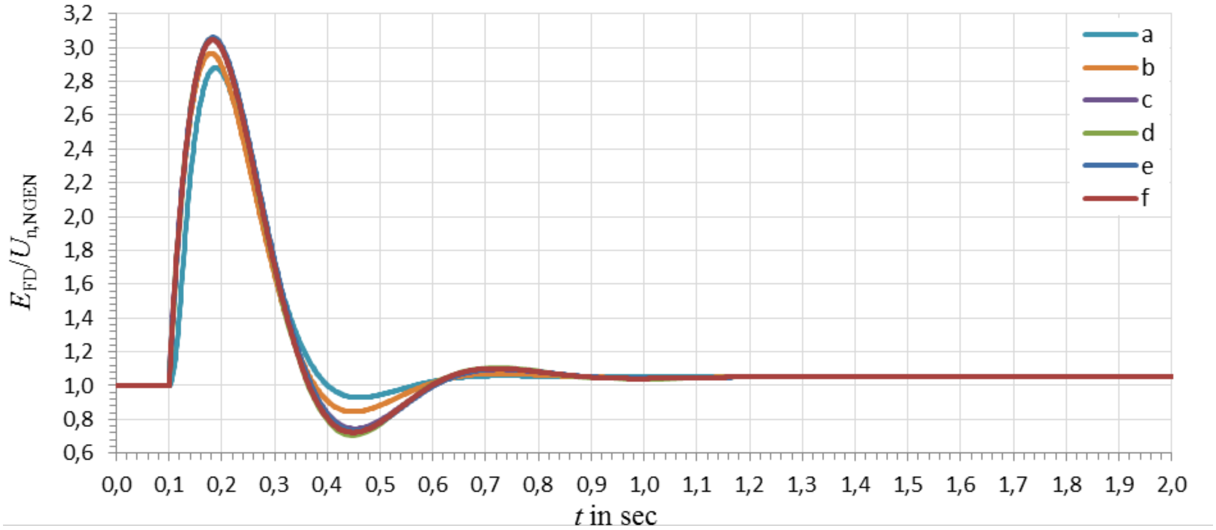

FIG. 5-2: RESPONSE OF EXCITATION VOLTAGE OF MACHINE IN TEST CASE 1

5.2 TEST CASE 2

The following diagrams show the comparison of the results for the terminal voltage U_{NGEN}, active and mechanical power P_{G} and P_{MECH} of the synchronous machine and machine speed ω_{G}. The behaviour of the reactive power of the machine will not be shown. It remains at zero.

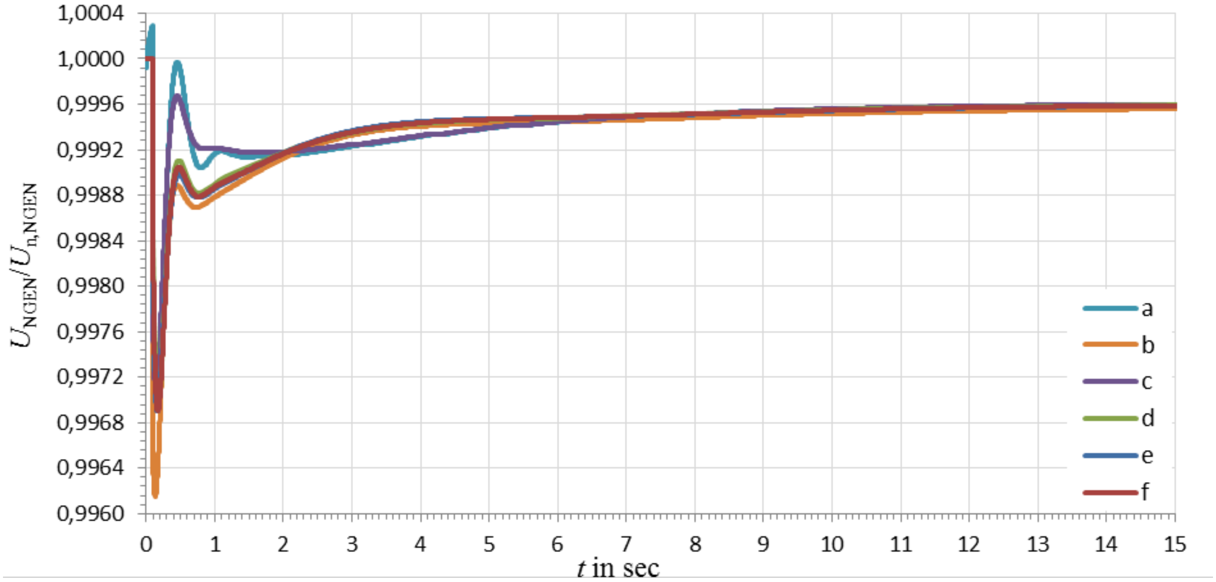

FIG. 5-3: RESPONSE OF TERMINAL VOLTAGE OF THE MACHINE IN TEST CASE 2

The stationary values of the terminal voltage are nearly identical in all simulation tools. The dynamic behaviour differs especially in the second oscillation. Nevertheless the response of the active power in Fig. 5-4 shows almost similar curves.

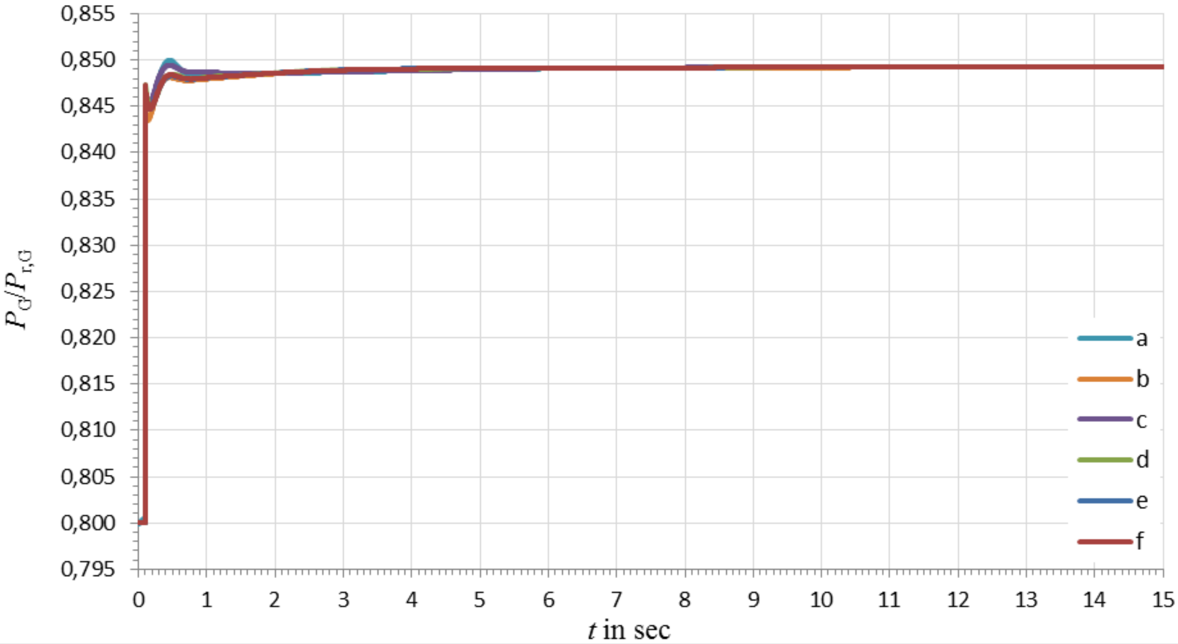

FIG. 5-4: RESPONSE OF ACTIVE POWER OF THE MACHINE IN TEST CASE 2

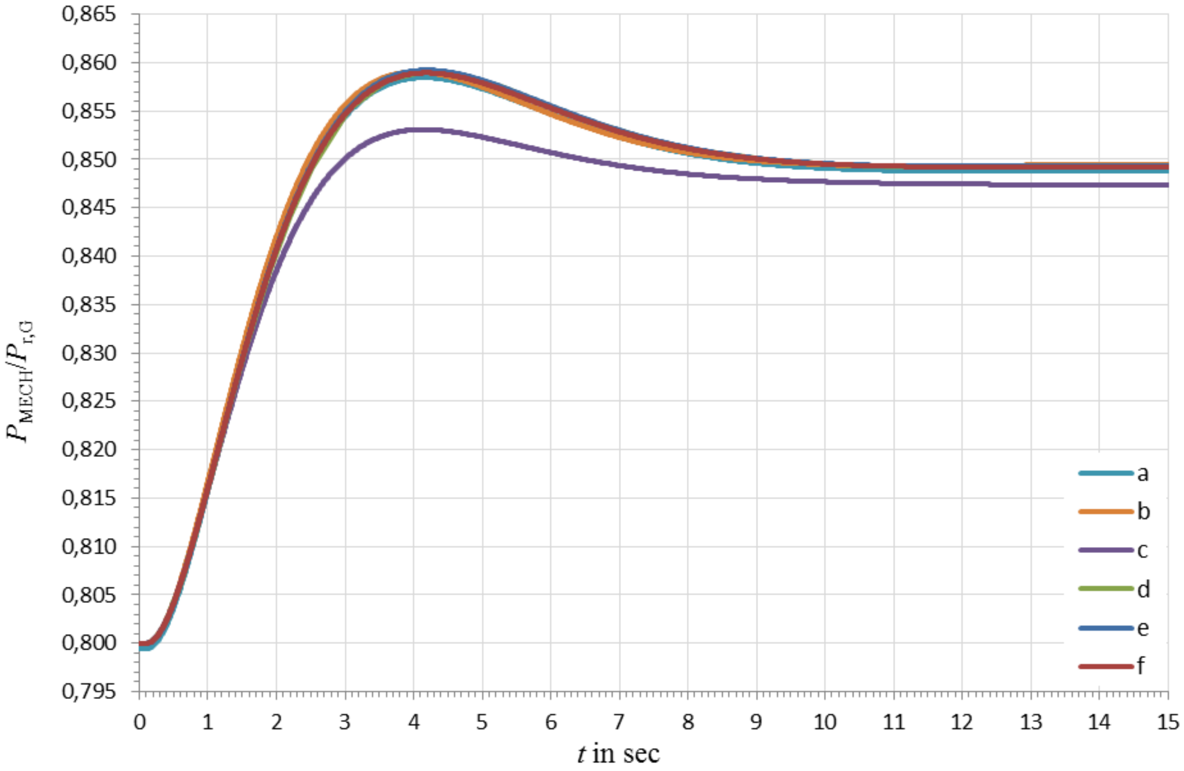

FIG. 5-5: RESPONSE OF MECHANICAL POWER OF MACHINE IN TEST CASE 2

The response of the mechanical power P_{MECH} of the synchronous machine in Fig. 5-5 shows some small dynamic and stationary deviations. This can also be noticed in the response of the machine speed, Fig. 5-6.

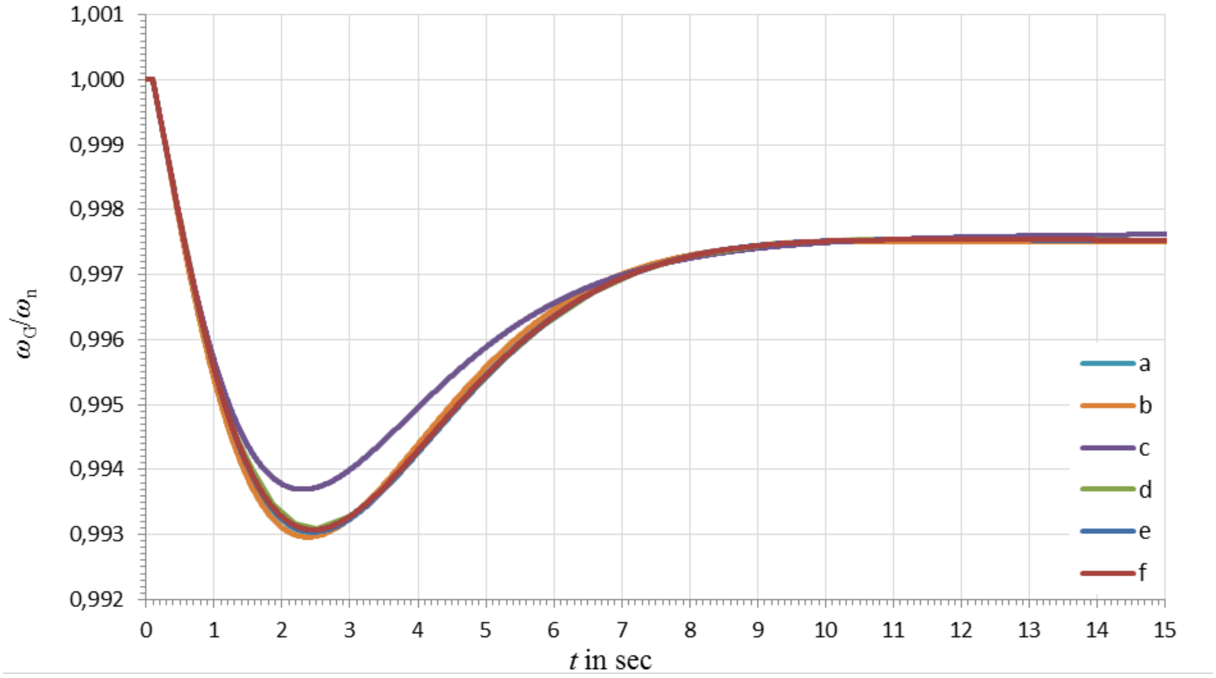

FIG. 5-6: RESPONSE OF MACHINE SPEED IN TEST CASE 2

5.3 TEST CASE 3

The following diagrams show the comparison of the results for the terminal voltage U_{NGEN}, excitation voltage E_{FD}, active power P_{G} of the synchronous machine, reactive power of the synchronous machine Q_{G}, machine speed ω_{G} and the PSS output signal VOTHSG.

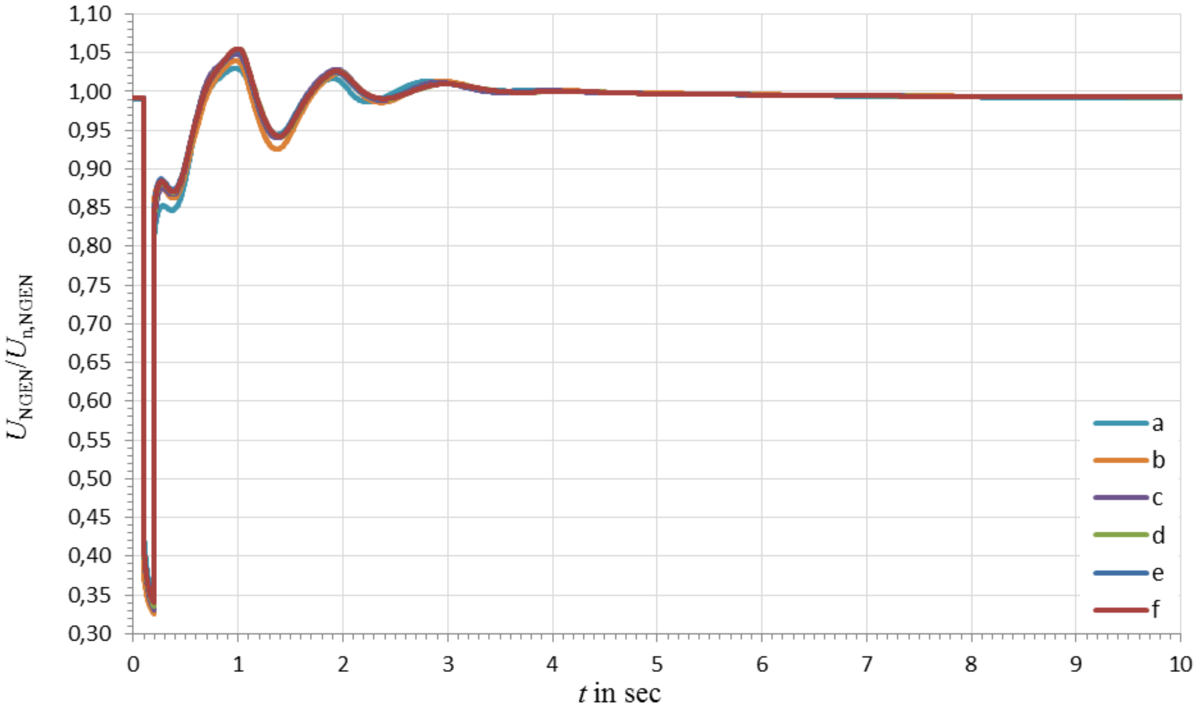

FIG. 5-7: RESPONSE OF TERMINAL VOLTAGE OF THE MACHINE IN TEST CASE 3

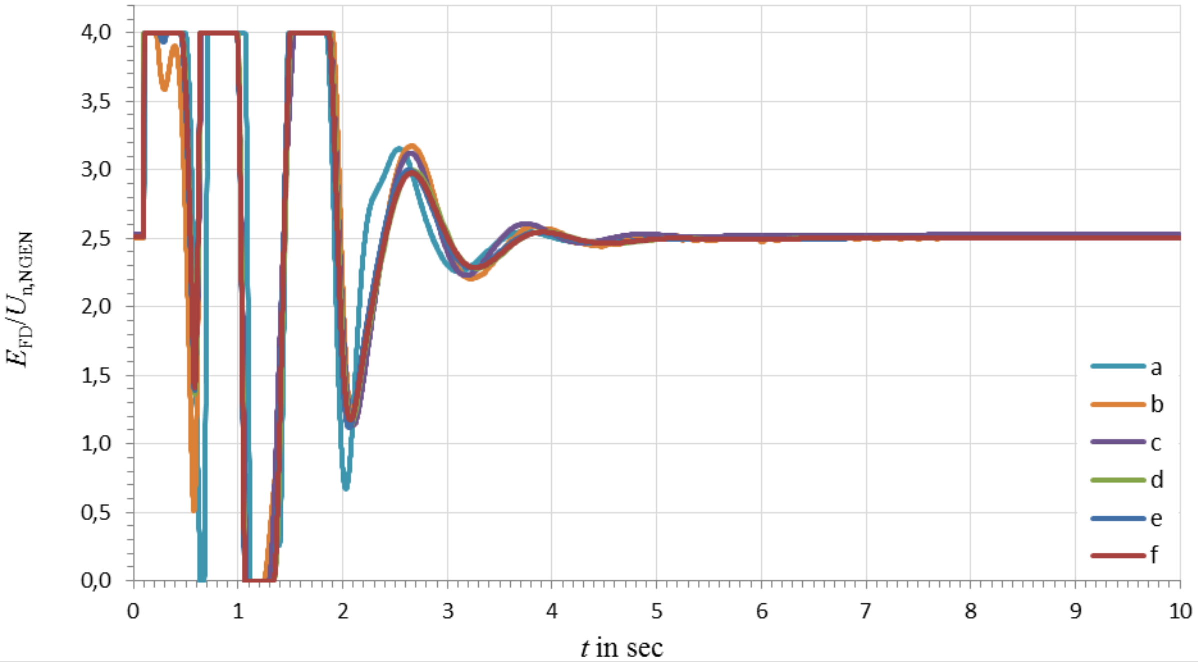

FIG. 5-8: RESPONSE OF EXCITATION VOLTAGE OF MACHINE IN TEST CASE 3

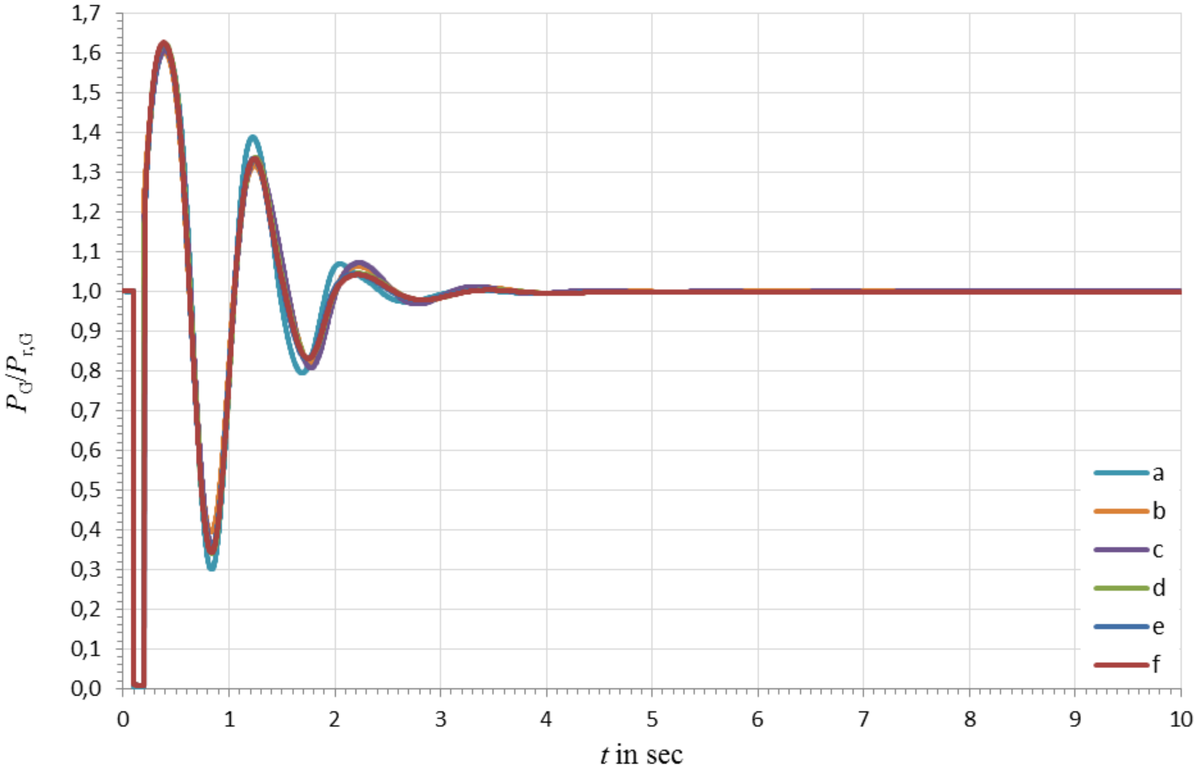

FIG. 5-9: RESPONSE OF MACHINE ACTIVE POWER IN TEST CASE 3

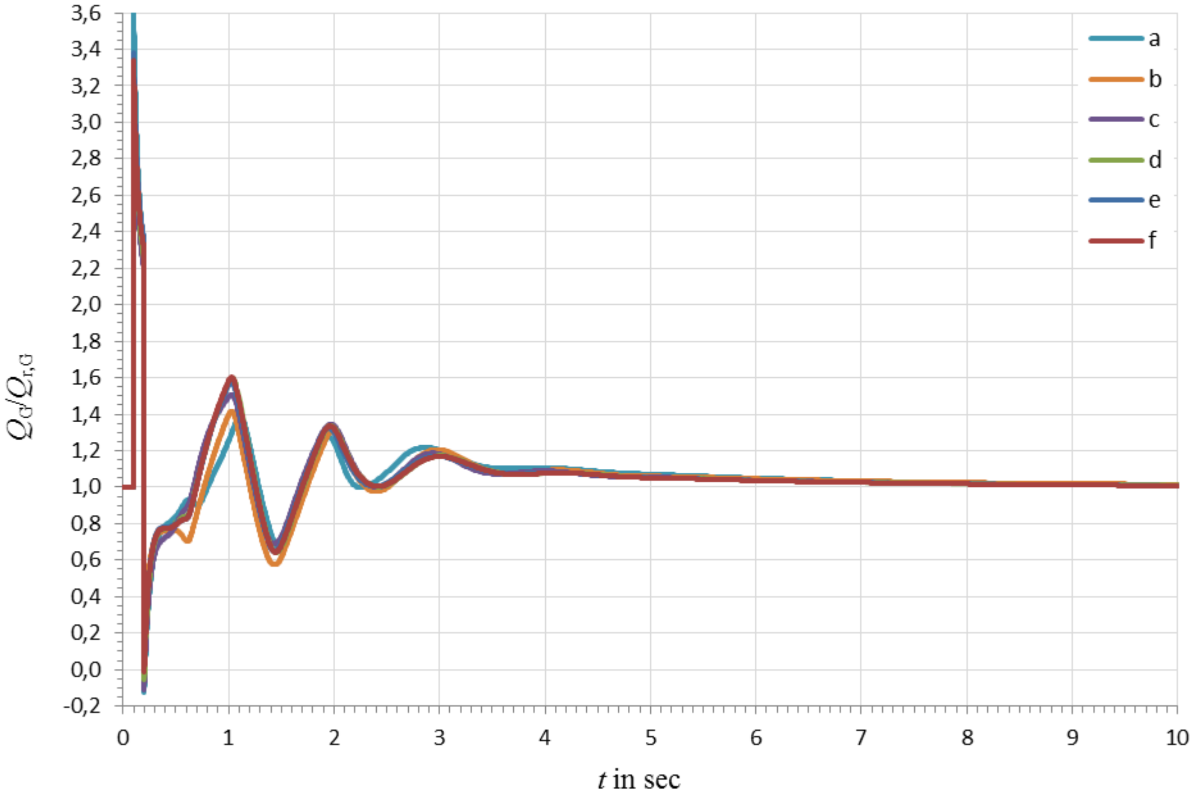

FIG. 5-10: RESPONSE OF MACHINE REACTIVE POWER IN TEST CASE 3

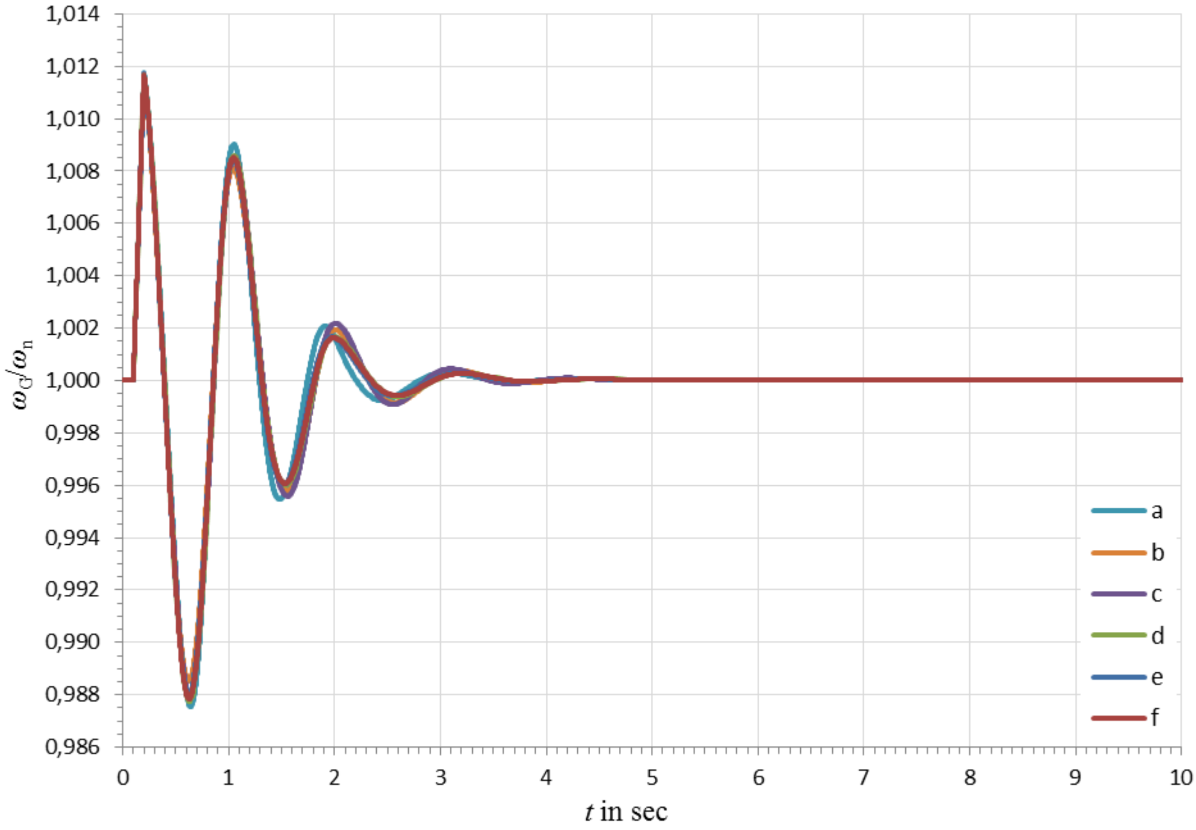

FIG. 5-11: RESPONSE OF MACHINE SPEED IN TEST CASE 3

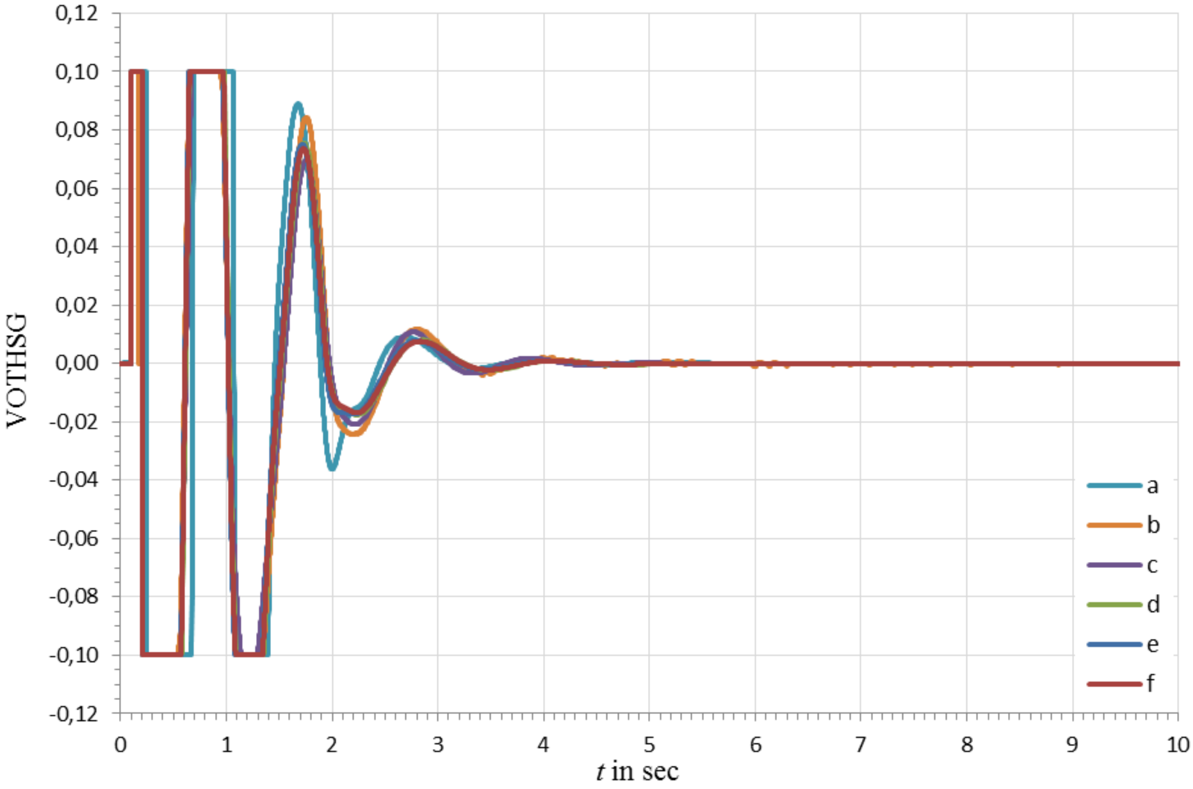

FIG. 5-12: RESPONSE OF PSS OUTPUT SIGNAL IN TEST CASE 3

For further analysis the active and reactive power P_{GRIDL} and Q_{GRIDL} of the constant impedance load GRIDL are shown in Fig. 5-13 and Fig. 5-14.

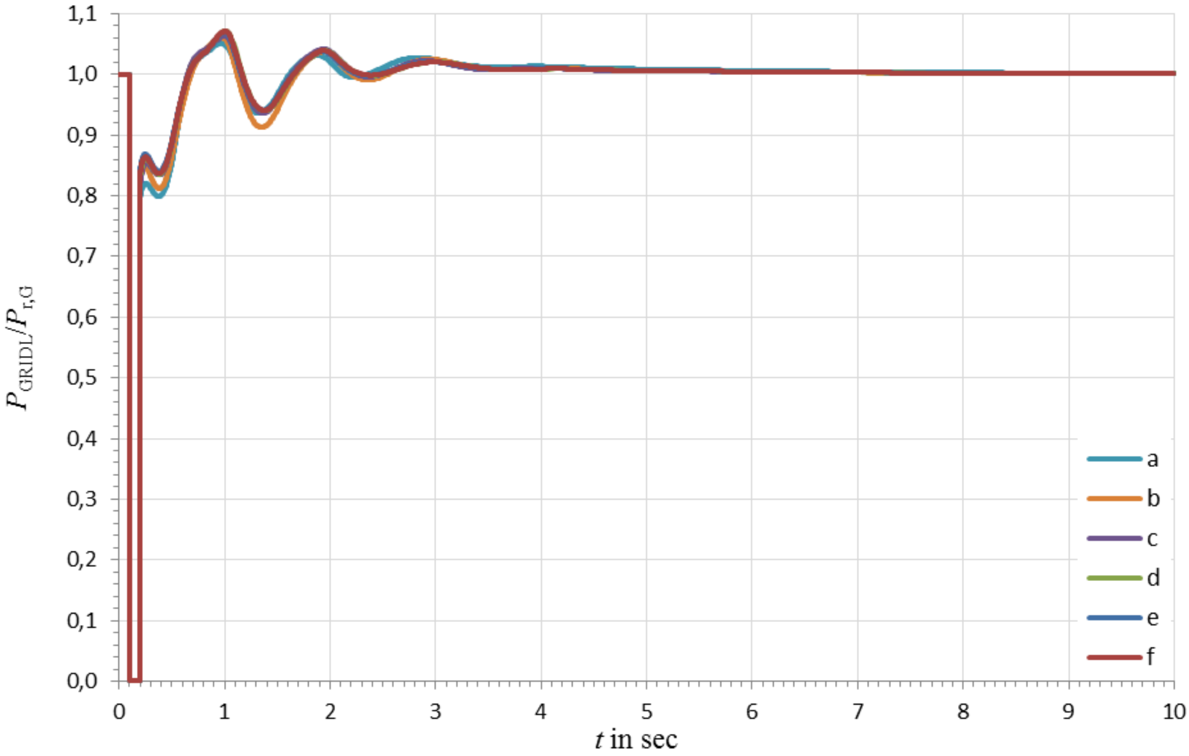

FIG. 5-13: RESPONSE OF LOAD ACTIVE POWER IN TEST CASE 3

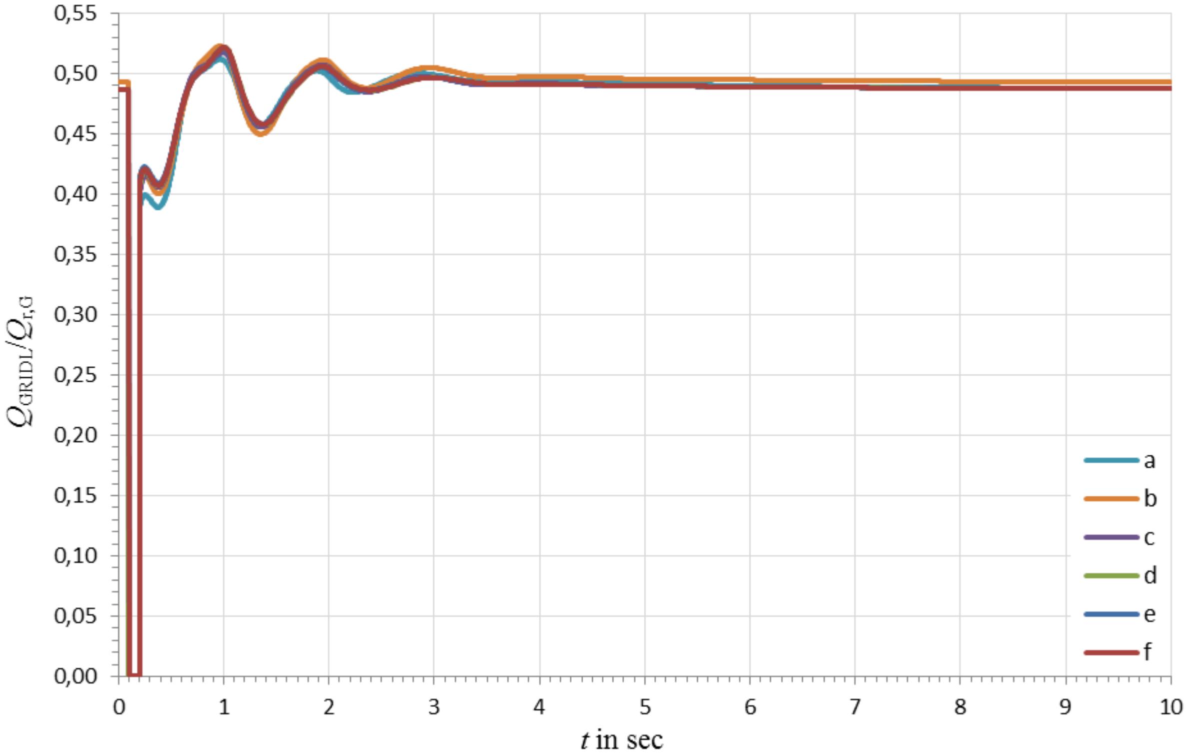

FIG. 5-14: RESPONSE OF LOAD REACTIVE POWER IN TEST CASE 3

6 CONCLUSION

This documentation records results of the initial step in the process of developing a common, simulation tool independent dynamic model of the Continental European synchronous power system. A simple test circuit with a synchronous machine with control devices connected to an infinite source was defined. A stationary load flow case and three test cases for time domain were performed with each simulation tool in order to receive a comparison of the performance of the standard models for synchronous machine and control.

The results show a good accordance between the simulation tools with some small deviations due to different model implementations. Most of the identified deviations are neglectable for the purpose of dynamic modelling of the Continental European synchronous power system and the objective of proper frequency response. The level of conformity is considered to be sufficient to proceed to the next stage of the project.