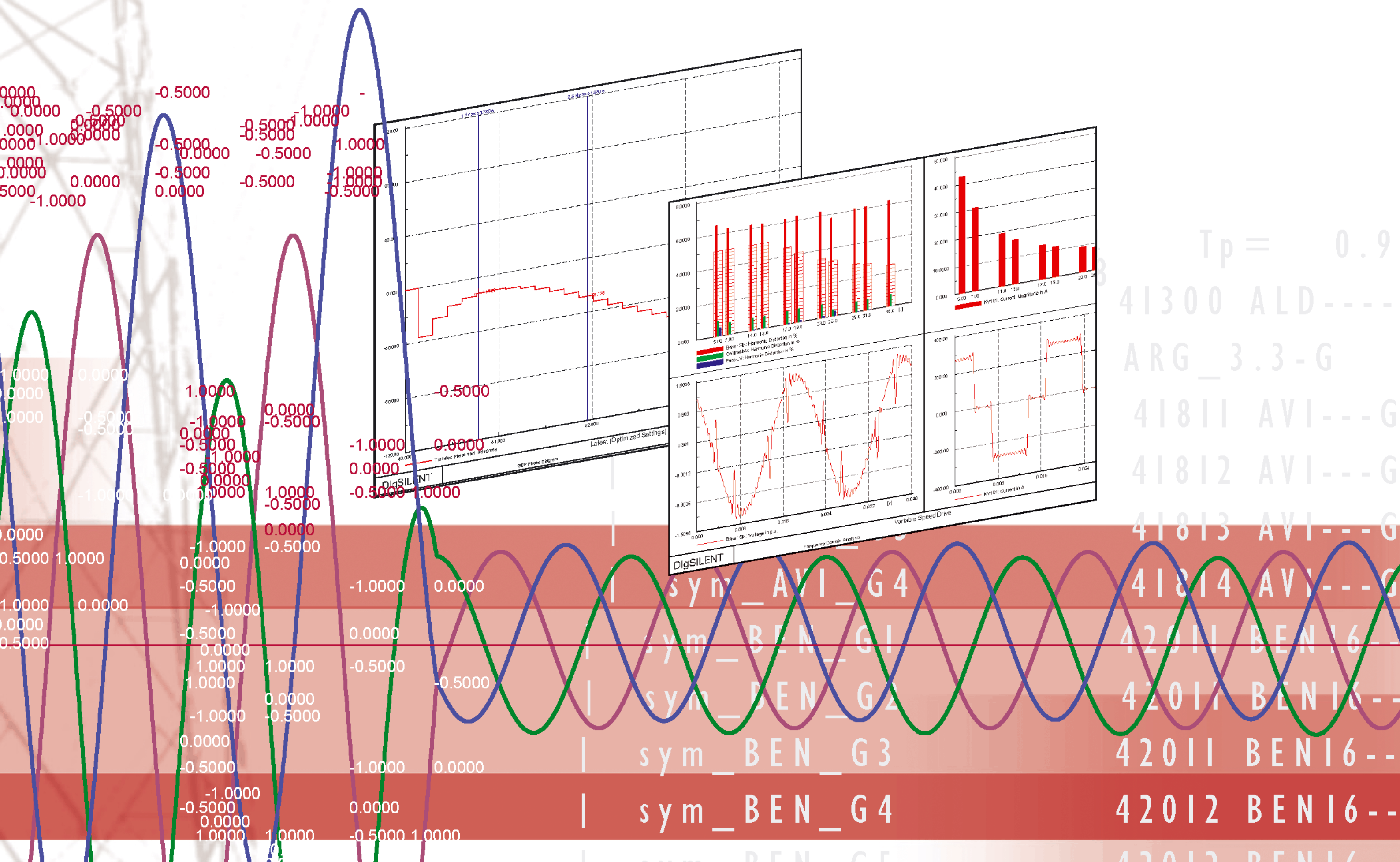
Application Report Jan-2017

Compatibility Issues in Time Domain Simulations with DIgSILENT PowerFactory and SIEMENS PSS/E

Part I - Large Grids with Type 1 Generators

Prepared for

DIgSILENT PowerFactory Users



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1 Modelling and Simulation Performance Aspects

1.1 Introduction

The heterogeneous power system software landscape, especially in the transmission sector, is demanding for application guidelines when exchanging data between utilities and their software applications. This is especially the case for high-level software independent network data definitions such as CIM / CGMES that are intended to support data exchange between various software packages and their applications easily and reliably.

Although software packages such as SIEMENS/Netomac or GE/PSLF are used by European TSOs in few cases, this paper makes recommendations exclusively for exchanging data between DIgSILENT PowerFactory and SIEMENS PSS/E, the software packages most commonly used in the transmission sector.

Power system software packages differ in various aspects such as modelling flexibility, integrated applications and functions, non-redundant handling of large sets of data, efficiency in scenario definitions, time domain simulation performance, applied simulation algorithms and their numerical stability characteristics as well as model precision handling.

This paper provides guidelines to DIgSILENT PowerFactory users when importing PSS/E originated data and models and when comparing time domain simulation cases under compatibility and simulation performance aspects.

Part I of this paper entitled "Compatibility Issues in Time Domain Simulation with DIgSILENT PowerFactory and SIEMENS PSS/E" is exclusively dealing with synchronous generation (generator type 1). Part II, issued later, will cover modelling and simulation compatibility issues of power systems with mixed type 1 and type 2 generation.

1.2 Benchmark Cases

1.2.1 Case Definitions

For providing advice when importing PSS/E data, preparing cases, adopting models and running simulations, a representative model of the European power system has been used. The system model is characterised by the following key data of a node & branch model:

No. of AC buses:	21,500	
No. of lines/cables:	18,300	
No. of transformers:	9,100	(2- and 3-winding transformers)
No. of loads:	11,300	
No. of type 1 generators:	1,150	

As the original case does not include any type 2 generation (inverter based generation), all "Part I" considerations are based on a case which is identical for calculations performed with PSS/E as well as PowerFactory.

It is further to be noted that the user should in general verify that the available PSS/E and PowerFactory databases are compatible insofar as there are no residual loads modelled in form of “Static Generators”, as these cannot be modelled in PSS/E.

1.2.1.1 Load Flow Solution

Generation infeeds are modelled as PV and PQ-buses. In order to guarantee that the load flow is solved within the synchronous generator capability, the option “consider reactive power limits” for synchronous generators is applied. A single slack bus has been defined which is located in the area “NL”. The loads are treated as fixed PQ-loads not being voltage dependent. All transformer tap positions as well as shunt switching statuses are kept fixed, not controlled automatically by the load flow execution.

Key parameters of the PowerFactory load flow summary are as follows:

Total system load:	293,349 MW
Total generation:	300,779 MW

The slack bus generator produces 1,823 MW / 74.5 MVAr at 0.9976 p.u. voltage. The load flow computed by PSS/E results in 1,836 MW / 77.3 MVAr which constitutes an active power mismatch of $4.3*10^{-3}$ [%] referred to the total generation. This mismatch of 13 MW is exclusively caused by the different treatment of the transformer no-load losses[1].

1.2.1.2 Stability Model Setup

Grid data including dynamic model data are available in round-trip-capable definitions for PSS/E v33/v34 (raw- and dyr-files) as well as for PowerFactory 2016 and 2017. The dyr-file holds the generator data and AVR/PSS-data as well as the governor data. Load definitions and models for renewable generation are not included in the dyr-file as PSS/E does not support consistently defined standard models for wind turbines and PV-parks (IEC, WECC, CIM/CGEMS, etc.). Consequently, respective models will be added step by step as required for the case definition utilizing appropriate available models (to be included in part II of this report).

The operational situation is characterised by high loaded generators with large load angle deviations across the European system resulting in stable but partially quite low damped oscillations. Internal rotor angles range from -55.2° (pumped storage) to +89.8°. The maximum rotor angles are -135.4° and +97.5° respectively. The 0.0° swing bus is located in “NL”.

Some bus voltages slightly exceed the common operational range of ±5%. Almost all generators are equipped with AVR/PSS and turbine governor with adequate settings. Pumped storage devices are only equipped with adequately tuned AVR and PSS. All initial conditions are calculated without exceeding any limits (for all derivatives $d\underline{x}/dt = 0.0$ is valid).

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[1] *In general, PowerFactory transformer models are based on T-equivalents whereas PSS/E uses π-equivalents. The T-equivalent model is the more suitable representation, allowing model compatibility with other integrated PowerFactory functions such as EMT-modelling with saturation.*

Contingency scenarios are defined as follows:

1. Scenario I: Simulation of the trip of a large generation unit loaded with some 1050 MW located in the centre of Spain.
2. Scenario II: Application of a three phase fault at the 400 kV level with a fault duration of 150ms. For the fault location, a bus located again in the centre of Spain has been selected.

The simulation is always started at t=0.0s. The above defined events for scenario I and II are applied at t=1.0s. The simulation time selected and respective computation time reported is always 60s. In both scenario cases, due to the very highly loaded system, a steady state situation is not yet reached after the 60s simulation time, thereby constituting a relevant case for the comparison of the models and algorithms as well as the simulation performance.

1.2.2 Simulation Solution Parameter Settings

1.2.2.1 PowerFactory Simulation Settings

Although DIgSILENT PowerFactory provides an adaptive step-length integration algorithm, only settings for the fixed step length procedure are used when comparing PSS/E and PowerFactory performance characteristics. Simulation cases with adaptive step-length are reported separately. The simulation error (errsm) is set to 10 kVA if not reported differently. The solution options "Fast convergence check", "Fast computation of outputs" and "Fast independent solution of network and dynamic models" as well as "reinitialise algebraic equations after interruption" are enabled. An integration step size of 10ms is selected for a high precision solution as suggested for the ENTSO-E system. In a number of cases, an integration step size 25ms is used. All models are using non-A-stable flag settings (flag disabled). Exceptions are discussed in the relevant sections below.

1.2.2.2 PSS/E Simulation Settings

PSS/E simulation settings are mainly based on default values with a number of case-specific modifications.

Compared with PowerFactory, where the integration step-size determines the precision of the simulation results without having an impact on the algorithmic stability, the numerical stability of PSS/E's simulation algorithm is strongly dependent on the integration step-size. To ensure that, for example, observed generator oscillations are inherent to the power system model and not caused by too large integration step-sizes, the user should reduce the step size until the damping of oscillation respective transients become independent of the integration step-size. The step size selected for the PSS/E-simulations has been determined using the above described mechanism. In most cases integration steps of below 5ms are required.

Other settings of the "Dynamic Solution Parameters" are as follows:

Network solution:	Iterations = 200, Acceleration = 0.998, Tolerance = 0.0001
Simulation parameters:	DELT = varying (see considerations above), Freq. filter = 0.015
Island frequency:	Acceleration = 1.0, Tolerance = 0.0005
Delta threshold:	Intermediate = 0.05, Island freq. = 0.11667

Output streams (definition of result variables) are specified according to case requirements.

1.2.3 Model Considerations

When comparing simulation runs generated by the PowerFactory software with those produced by PSS/E, results should be identical. This is observed between other software such as PowerFactory and SIEMENS/ Netomac). However, when comparing PowerFactory and PSS/E, the following aspects have to be taken into account:

1. The synchronous generator models of PSS/E and PowerFactory are slightly different. Although both packages offer a number of typical generators model levels adequate for various applications, the most comprehensive model differs in the way the equivalent circuit diagrams are implemented. The main effect of such difference is observed in the damping of generator oscillations and also to a small extent in the oscillation period. The reason for those differences originates in the method PowerFactory uses to transform the equivalent circuit diagram (being based on reactances) back to the equivalent circuit diagram composed of inductivities and flux couplings thus avoiding the necessary simplification required to derive to the reactance representation. It is understood that the DIgSILENT PowerFactory approach is more suitable and more precise.

2. Synchronous generators equations are largely dependent on the rotational speed. This is of course obvious for induced voltages. However, in most cases classical synchronous generator models assume that the rotor speed is close to nominal (= 1.0), resulting in a set of circuit diagram equations which are independent of the frequency. PowerFactory and PSS/E offer different options for considering those speed effects. However, when setting NETFRQ=0 (PSS/E) and selecting "Effect of speed variation = neglected" (PowerFactory), frequency dependency is treated similarly in both programs and simulated speed deviations are identical, as the calculation of the electrical torque is independent of speed whilst for the mechanical torque the correct relation between mechanical power and mechanical torque is maintained.

3. PSS/E requires the assumption that xd" = xq". Such an assumption and simplification is a fundamental requirement for the solution algorithm implemented in PSS/E, where bus voltages are eliminated by using the sub-transient generator voltages behind the sub-transient reactance instead. The paramount advantage of such approach is the non-iterative, fast solution for linear grid models (e.g. constant impedance loads). However, for any grid model substantially deviating from the linear case, such advantage is lost and iterative solutions are again required.

4. Other models such as AVRs, power system stabilisers (PSS) and governors must be considered fully compatible between PowerFactory and PSS/E. Should any discrepancy be observed, typical reasons are different interpretations of block diagrams with regard to limiters and other nonlinear devices, which are quite often not described to the level of detail required to avoid dual interpretation.

The above aspects are further taken into account and analysed in the following sections.

1.3 Definition of Study Cases

Inter-operability between DIgSILENT PowerFactory and SIEMENS/PSS/E is verified for a number of cases. All of them are based on the benchmark grid definitions as detailed in Section 1.2.1. The different cases analysed are summarised in the table 1.1 below.

Table 1.1: Summary of PowerFactory / PSS/E inter-operability Study Cases

Model Type	Grid Model	Description
1	Z-Load, no renewable generation	Standard model with constant Z-loads; no inverter-based renewable generation
2	General load, no renewable generation	Standard model with voltage- and frequency-dependent loads; no inverter-based renewable generation

Table 1.2: Summary of PowerFactory / PSS/E inter-operability Test Cases

Test No.	Grid Model	Scenario	Description / Comment
1	Type 1	I	**PowerFactory:** Integration step-size sensitivity analysis
2	Type 1	II	**PowerFactory:** Integration step-size sensitivity analysis
3	Type 1	II	**PowerFactory:** Determination of CFCT with varying step-sizes
4	Type 1	I	**PSS/E:** Numerical stability with 7.5ms and 10ms integration steps
5	Type 1	I	**PSS/E:** Integration step-size sensitivity analysis
6	Type 1	II	**PSS/E:** Integration step-size sensitivity analysis
7	Type 1	II	**PSS/E:** Determination of CFCT with varying step-sizes
8	Type 1	I	**PowerFactory & PSS/E**: Lower precision simulation
9	Type 1	I	**PSS/E:** Variation of acceleration parameter setting
10	Type 2	I	**PSS/E:** Integration step-size sensitivity analysis (1, 2.5 and 5ms)
11	Type 2	I	**PSS/E:** Integration step-size sensitivity analysis (1 and 2.5ms)
12	Type 2	I	**PowerFactory:** Integration step-size sensitivity analysis (1, 10, 20ms)
13	Type 2	II	**PSS/E:** Integration step-size sensitivity analysis (1, 2.5 and 5ms)
14	Type 2	II	**PowerFactory:** Integration step-size sensitivity analysis (1, 10, 20ms)

2 Simulation Studies

2.1 Case 1: Z-Load, no Renewable Generation

This initial case is predominantly used to benchmark key grid characteristics as determined by PowerFactory versus PSS/E regarding generator oscillation, AVR and primary response as well as critical fault clearing time (CFCT). The main focus for this initial case is the determination of an adequate integration step size for the PSS/E software to enable the comparison and reproduce PowerFactory results.

2.1.1 Determination of a suitable PowerFactory Integration Step-Size

Although the recommendation and tradition of most European TSOs is the usage of an integration step-size of 10ms, a first sensitivity study is performed with PowerFactory varying the integration step-size between 1ms and 20ms including the cases: 1ms, 5ms, 10ms, 15ms and 20ms.

2.1.1.1 Test 1: Scenario I, Unit trip loaded with 1050 MW

The first series of simulation runs is performed by tripping unit "ES_1" located in the centre of Spain.

Fig. 1.1a: Test 1- PowerFactory integration step-size of 1, 5, 10, 15 and 20ms (trip of 1050 MW unit)

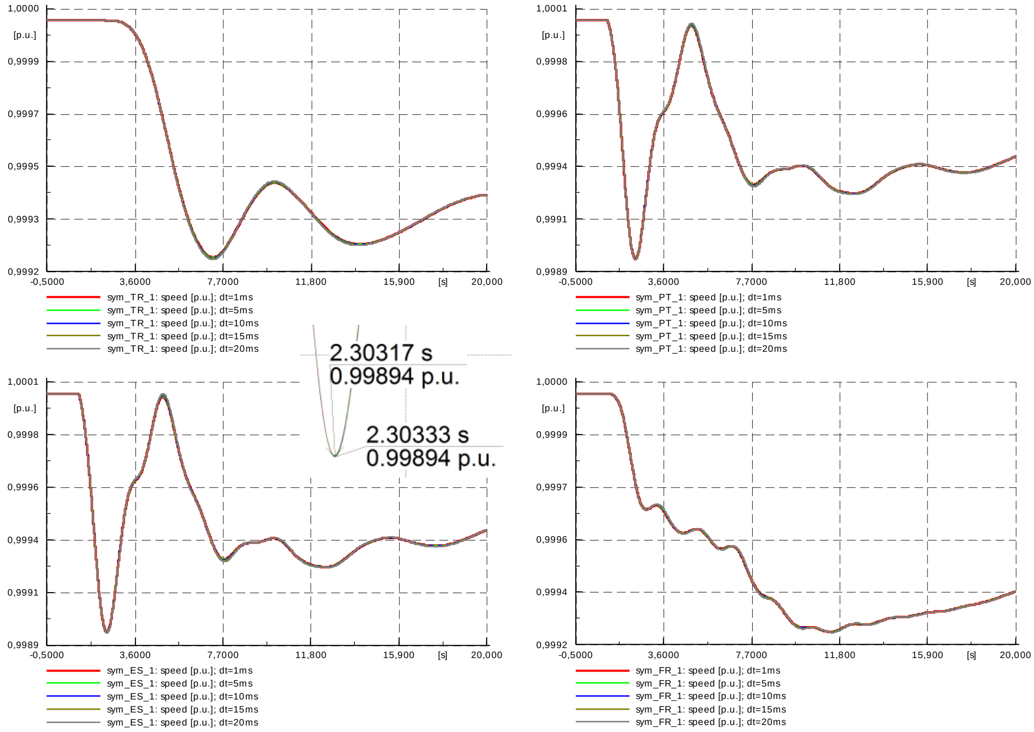
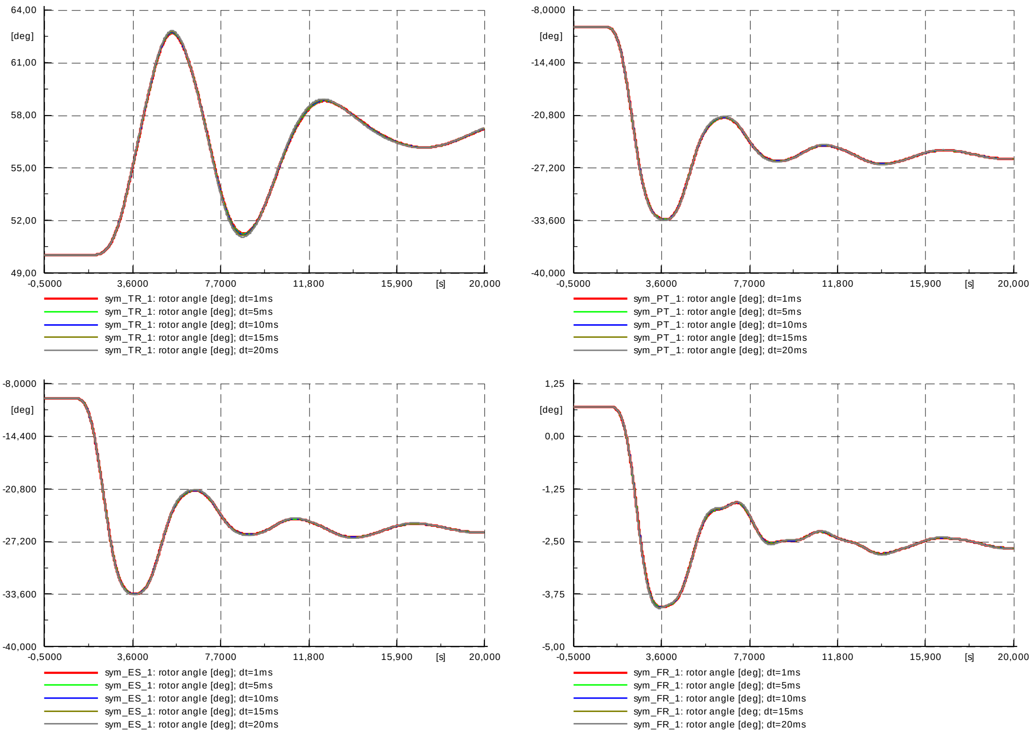


Fig. 1.1b: Test 1- <u>PowerFactory</u> integration step-size of 1, 5, 10, 15 and 20ms (trip of 1050 MW unit)



From the visual analysis of the simulation curves (see Fig. 1.1a) it is to be noted that in the case of a relatively small disturbance (scenario I), no relevant difference in the bus frequency respective rotor speeds can be observed when varying the integration step-size between 1ms and 20ms.

A similar observation is made for the rotor angles displayed in Fig 1.1b, showing the same generation units selected across Europe. Due to the relatively small fault, the transient rotor angle deviations do not exceed 15° in any grid location. No noticeable difference can be observed for the simulation results presented for the varying step-sizes.

2.1.1.2 Test 2: Scenario II, 3-phase fault at the 400 kV side of unit transformer "ES_1"

A slightly different situation is expected for scenario II, which is defined by a 3-phase fault with a fault duration of 150 ms. The fault location selected is the HV-side (400kV) of the unit step-up transformer of generator "ES_1" loaded with 1050 MW corresponding to approx. 83.2 % of nominal power.

The bus voltages as well as rotor angle are displayed in Fig. 1.2a. and Fig. 1.2b respectively. Corresponding bus voltages are shown in Fig. 1.2c, where the time scale is limited to 1.5s so as to see more easily the transient voltage sag during the 150ms fault duration.

Although the deviations between simulation results are slightly higher (but still very minor), the main issue when calculating faults would be the differences in the critical fault clearing time (CFCT). This aspect is analysed in the following section.

Fig. 1.2a/b: Test 2- PowerFactory integration step-size of 1, 5, 10, 15 and 20ms (3 phase fault)

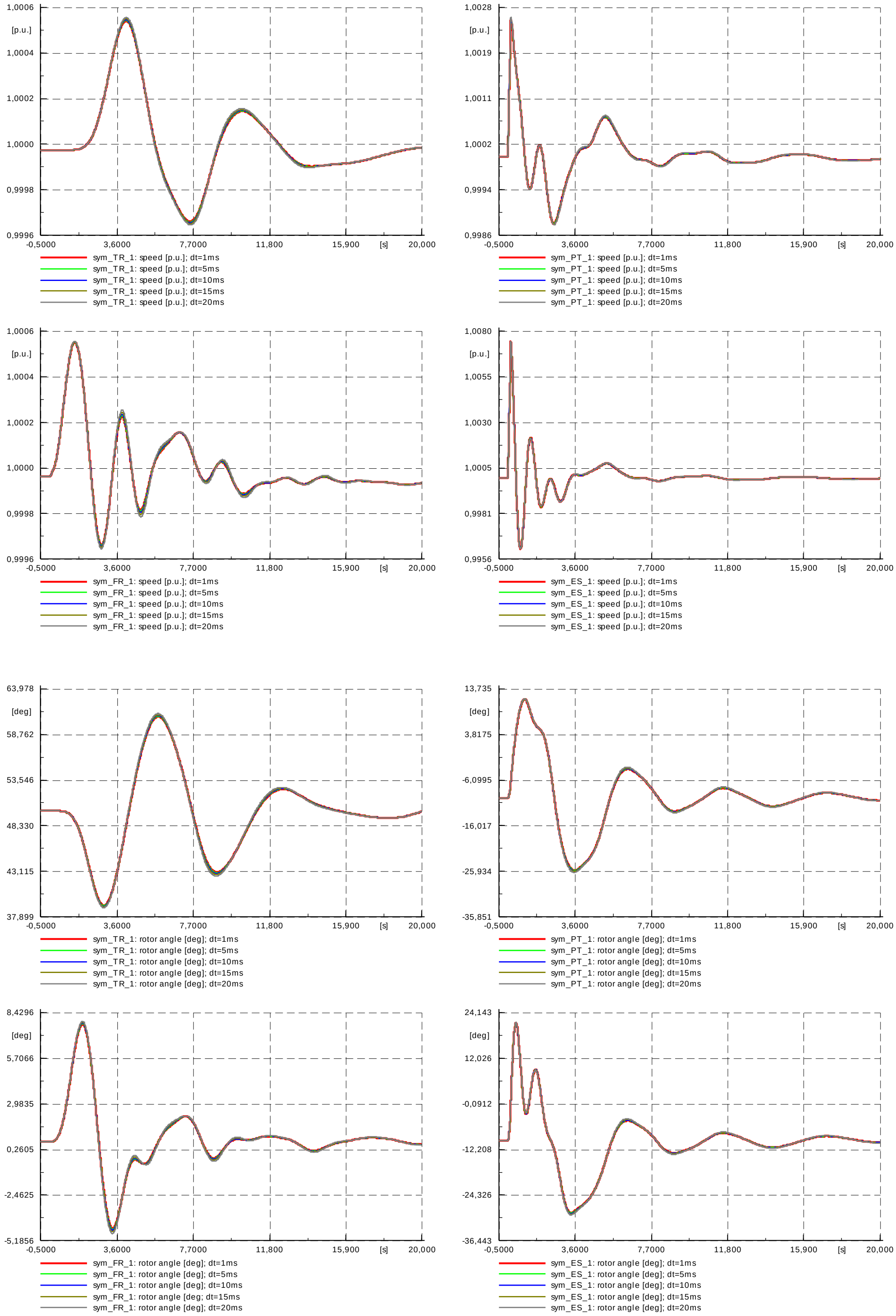
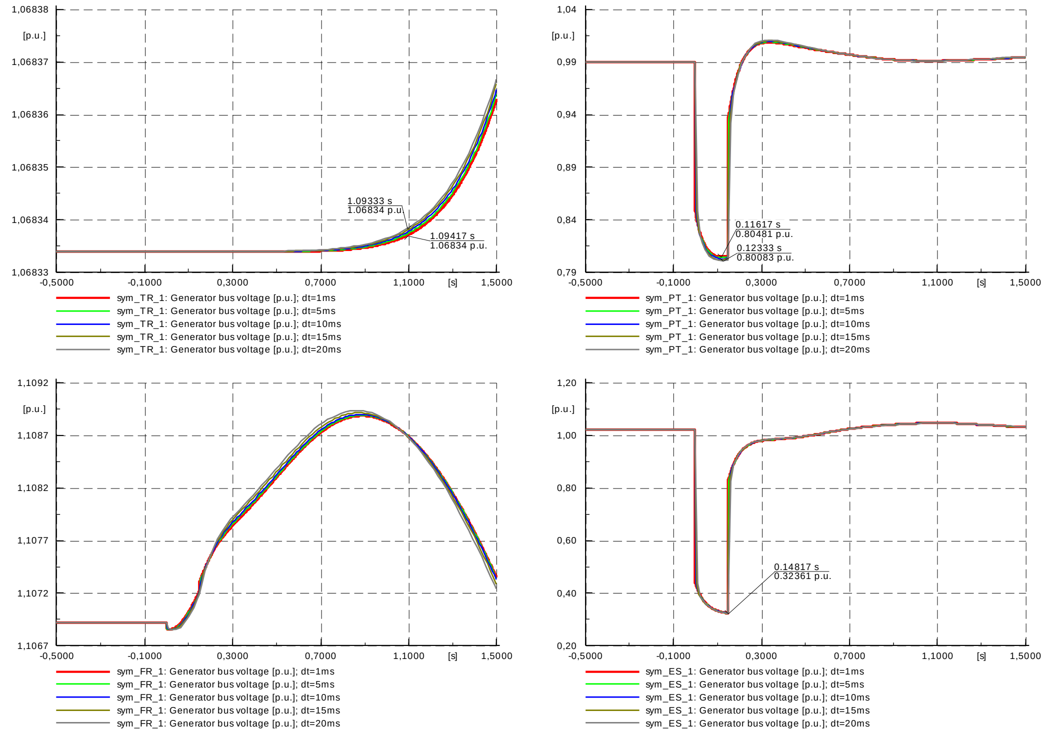


Fig. 1.2c: Test 2- PowerFactory integration step-size of 1, 5, 10, 15 and 20ms (3 phase fault)



It can be further observed that the deviations of variables (rotor speeds, rotor angles as well as bus voltages) differ for the integration step sizes applied in inverse proportion to the electrical distance from the fault. In other words, the smallest differences in the monitored variables are for the ones closest to the fault location.

2.1.1.3 Test 3: Scenario II - Determination of Critical Fault Clearing Times (CFCT)

A further series of simulations has been performed to determine the CFCT for 3-phase faults as per Section 2.1.1.2. The CFCT-resolution of the various runs executed for the integration step sizes analysed is 1ms[2].

Table 2: Test 3 - Summary of CFCTs for varying simulation step-sizes (PowerFactory)

Integration Step size	1 ms	5 ms	10 ms	15 ms	20 ms
CFCT (close-end fault)	414 ms	414 ms	414 ms	414 ms	415 ms
CFCT (remote fault)	893 ms	890 ms	886 ms	883 ms	882 ms
CFCT (remote fault)[3]	893 ms	894 ms	894 ms	905 ms	907 ms

The CFCTs determined for a close-end fault and remote fault are summarised in Table 2. In case of a close-end fault, the CFCT determined with PowerFactory are basically identical for all integration step-sizes. For a remote fault, CFCTs are practically identical for step-sizes ranging from 1ms to 10ms when disabling the option "Fast

[2] *The resolution of 1ms has no practical meaning as fault clearing takes place always at current zero-crossing.*

[3] *The option "Fast independent solution of network and dynamic models" is disabled.*

independent solution of network and dynamic models". However, when activating such option, the mismatch to the exact solution does not exceed 1%.

2.1.1.4 PowerFactory Integration Step-Size Analysis – Summary

PowerFactory simulation results differ only slightly when applying the integration settings as discussed in Section 2.1.1 where the step-size has been varied between 1ms and 20ms. From these results it can be concluded that taking performance into account, the most appropriate PowerFactory integration step-size can be identified to be in the range of 10-15ms. If not otherwise noted, in the following sections, all PowerFactory simulations will be based on an integration step-size of 10ms.

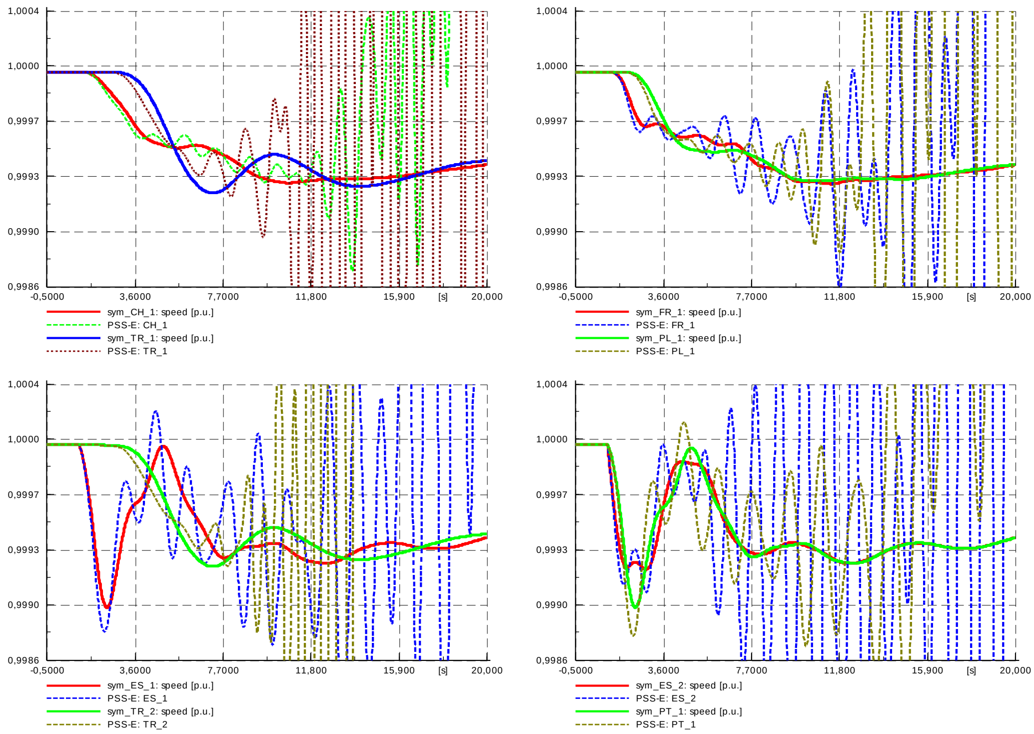
2.1.2 Determination of a suitable PSS/E Integration Step-Sizes

In the following sections a integration step-size screening is performed for PSS/E covering same contingencies (scenario I and II) as well as the determination of the critical fault clearing time at the same grid location as analysed for PowerFactory (tests 1-3).

2.1.2.1 Test 4: Scenario I - Comparing PSS/E and PowerFactory for step-sizes of 10ms and 7.5ms

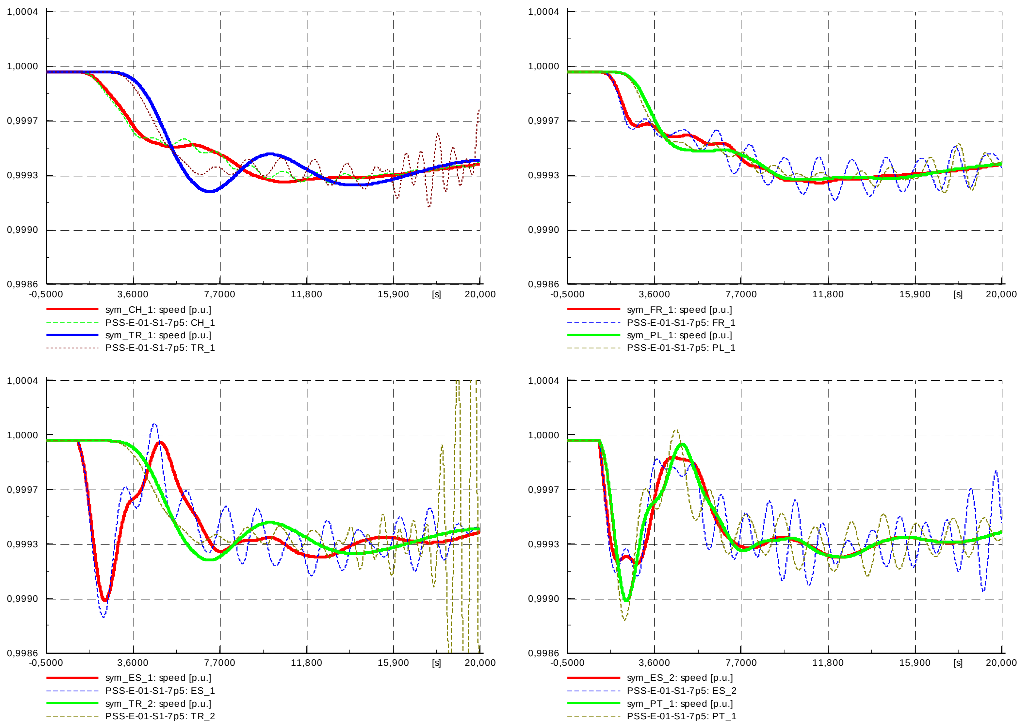
The PSS/E step-size screening is reported in this section for applied step-sizes of 7.5ms and 10ms. From Fig. 2.1a it can be concluded that PSS/E does not provide stable and useful simulation results when applying an integration step-size of 10ms, which is seen as the optimal step-size for PowerFactory (PSS/E results are shown as dashed lines. The PowerFactory simulation results on the basis of a 10ms integration step-size are shown as bold lines).

Fig 2.1a: Test 4 - PSS/E integration step-size of 10ms (trip of 1050 MW unit)



As further demonstrated in Fig. 2.1b, even a reduced integration step-size of 7.5ms still shows numerical oscillations with a clearly visible instability after some 17 seconds. Consequently, integration step-sizes of 7.5ms and 10ms are excluded from further PSS/E test runs.

Fig 2.1b: Test 4 - PSS/E integration step-size of 7.5ms (trip of 1050 MW unit)



2.1.2.2 Test 5: Scenario I, Unit trip loaded with 1050 MW

In the following sections, a series of PSS/E runs will be executed, verifying further the impact and sensitivity of the integration step-size on the simulation results, aiming for a final determination of a suitable PSS/E step-size to generate PowerFactory-precision compatible simulation results.

Fig. 2.2a to 2.2c show the Test 5-PSS/E simulation results applying simulation step-sizes of 5ms, 2.5ms, 1.0ms and 0.5ms where the following observations can be made on basis of the analysis of generator speed and rotor angle:

1. The simulation case with a step-size of 5ms is stable. However, local generator oscillations characteristics are greatly affected in some areas of the grid. In particular, the oscillation damping is unacceptable.

2. When reducing the integration step-size further down to 0.5ms, the PSS/E solution converges quite precisely to the PowerFactory solution achieved with a step-size of 10ms.

However, from Fig. 2.2a and 2.2b it cannot be concluded whether or not an integration step-size of 0.5ms is the most appropriate integration step-size.

Fig 2.2a: Test 5 - PSS/E integration step-size of 0.5, 1, 2.5 and 5ms (trip of 1050 MW unit)

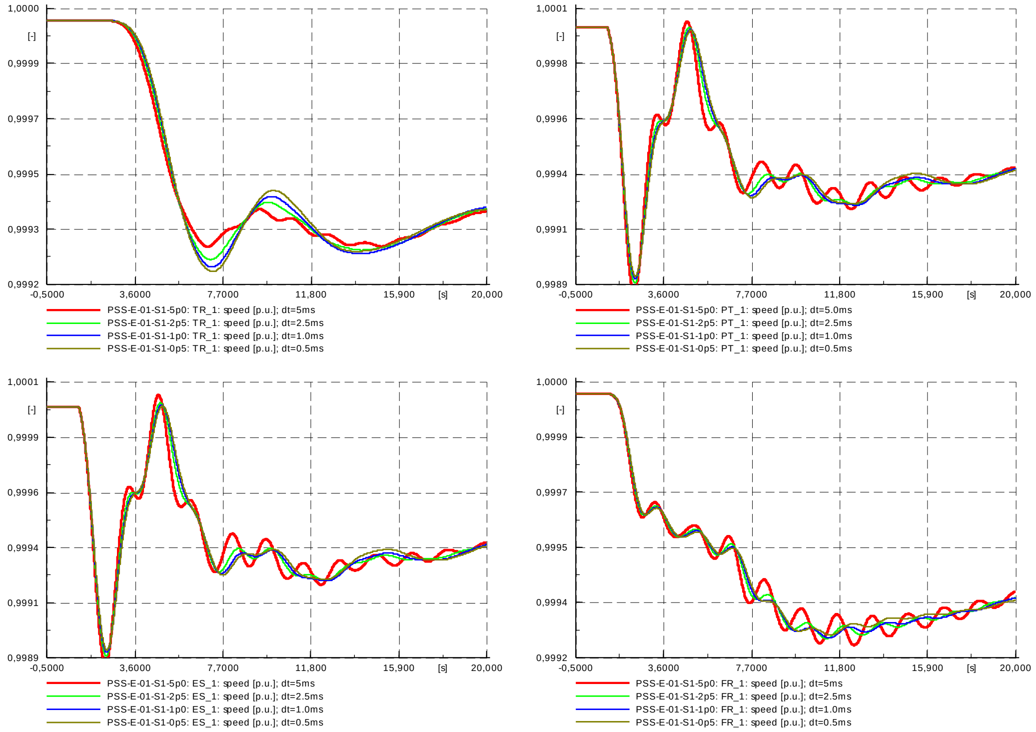


Fig 2.2b Test 5: PSS/E integration step-size of 0.5, 1, 2.5 and 5ms (trip of 1050 MW unit)

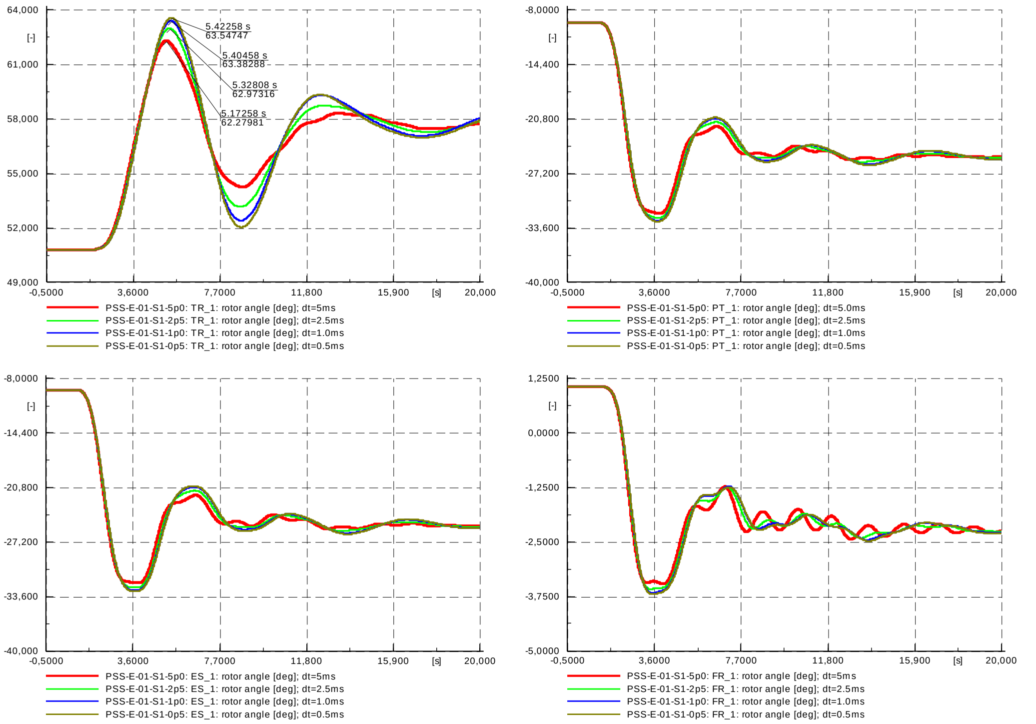


Fig. 2.2c therefore shows a further case applying a step-size of 0.1ms along with a longer observation time with a total duration of 60s. The following observations can be summarised:

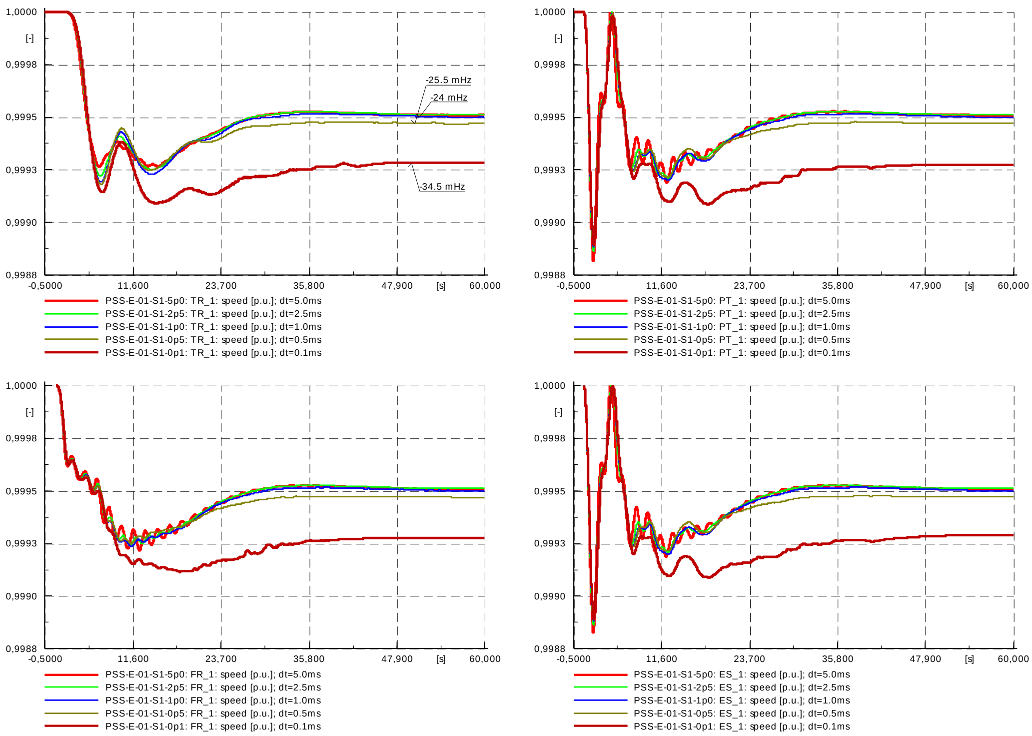
1. Applying PSS/E integration step-sizes below 1ms will change the steady state result of the simulation substantially or even drastically (this must not be the case as the grid model includes closed-loop control for voltage and frequency).

2. The steady state result of the 0.5ms step-size case already deviates by 6.25% from the larger step-size cases (1ms, 2.5 and 5ms).

3. The steady state result of the 0.1ms step-size case deviates drastically from the larger step-size cases, by some 43.8%.

From the above observations it can be concluded that simulation results based on a step-size below 1ms increasingly lose precision and validity, possibly due to numerical accumulation errors or other reasons which are not transparent to the users.

Fig. 2.2c: Test 5 - PSS/E integration step size of 0,1ms (trip of 1050 MW)



2.1.1.2 Test 6: Scenario II, 3-phase fault at the 400 kV side of unit transformer "ES_1"

Test 6 simulations are based on scenario II, which is defined by a 3-phase fault with a fault duration of 150 ms. The fault location selected is the HV-side (400kV) of the unit step-up transformer of generator "ES_1" loaded with 1050 MW corresponding to approx. 83.2 % of nominal power.

Fig 2.3a/b: Test 6 - <u>PSS/E</u> integration step-size of 0.5, 1, 2.5 and 5ms (3phase fault)

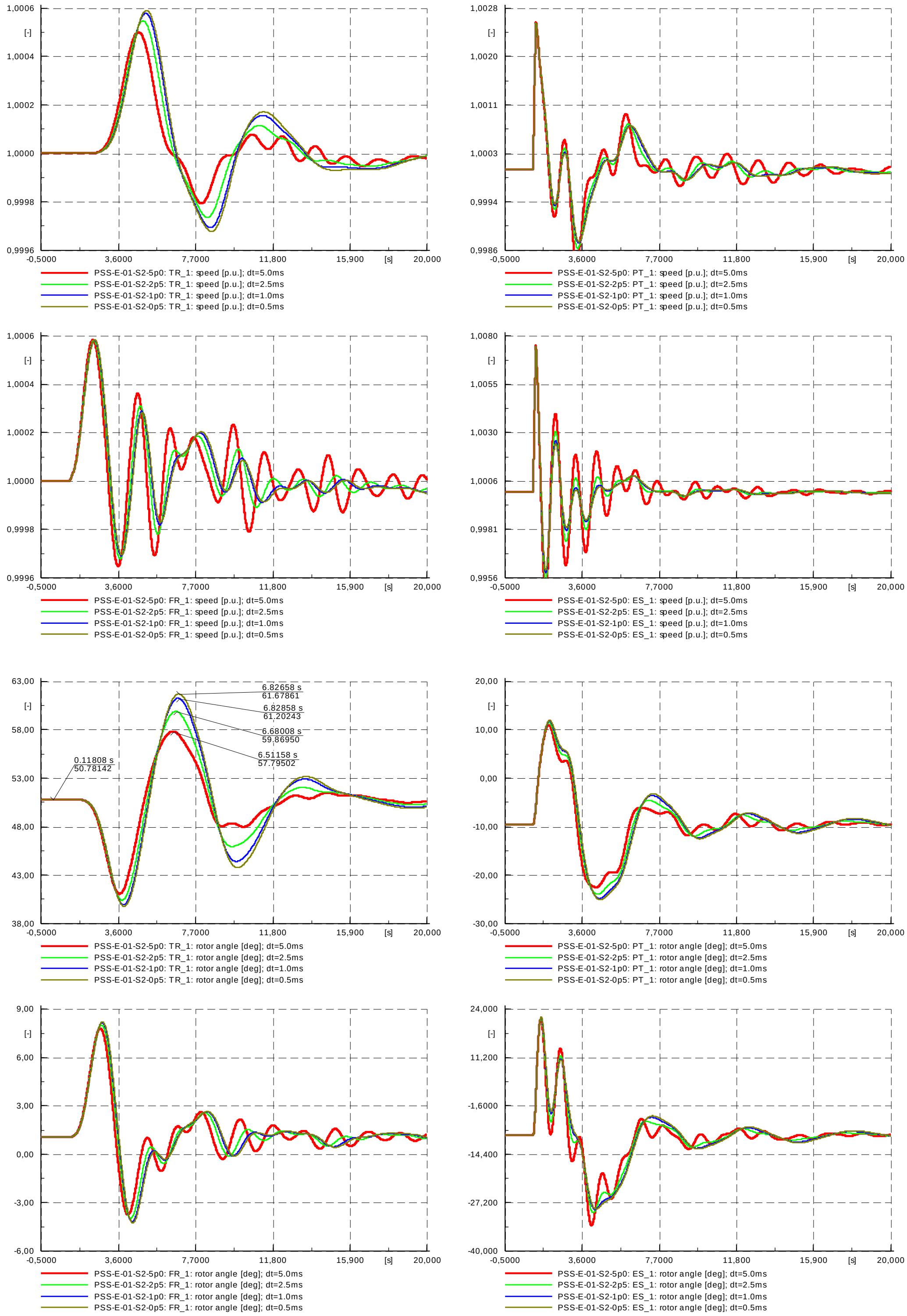
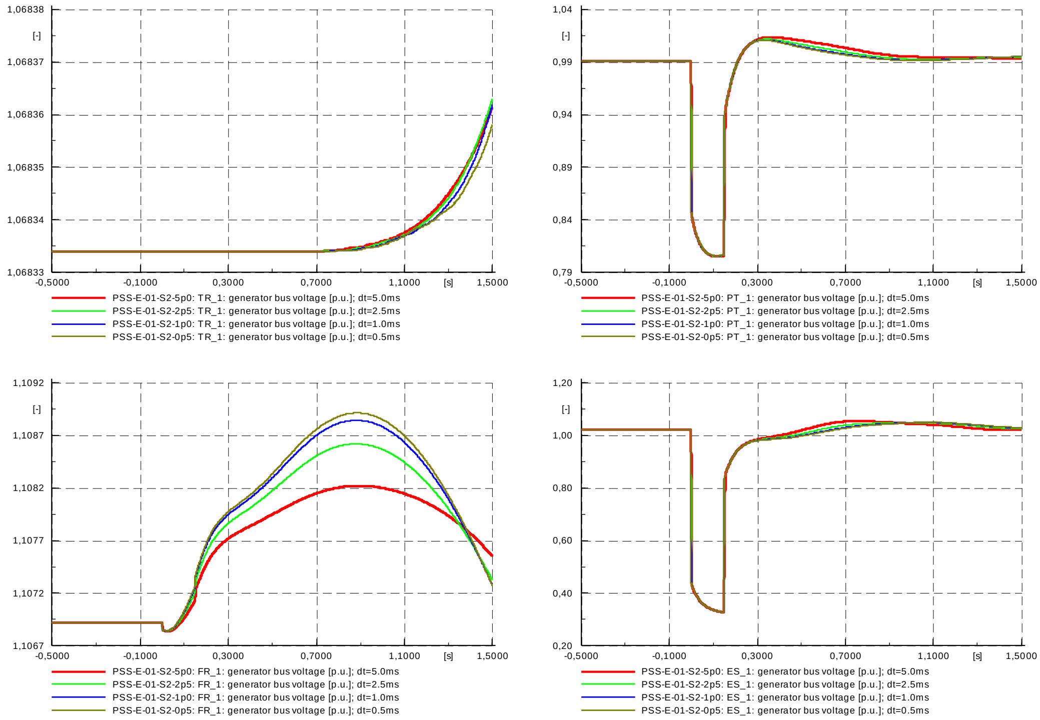


Fig 2.3c: Test 6 - <u>PSS/E</u> integration step-size of 0.5, 1, 2.5 and 5ms (3phase fault)



Generation unit rotor speeds as well as rotor angles are displayed in Fig. 2.3a and Fig. 2.3b respectively. Corresponding bus voltages which are shown in Fig. 2.3c are documented in the zoomed time frame of 1.5s so as to see more easily the transient voltage sag during the 150ms fault duration. As the key dynamic patterns of the grid under investigation are relatively slow, the deviations between simulation results of varying step-size are relatively small in areas of the grid area close to the fault (e.g. bus "PT_1" and "ES_1") and again remarkably high for areas further away from the fault location (e.g. bus "FR_1").

2.1.2.3 Test 7: Scenario II - Determination of Critical Fault Clearing Times (CFCT)

As for PowerFactory, a further series of simulations has been performed to determine the CFCT for 3-phase faults. The CFCT-resolution of the various runs executed for the integration step sizes analysed is again 1ms.

The CFCTs determined are summarized in Table 3 making again reference to a close-end fault as well as a remote 3-phase fault. In all cases, integration step-sizes below 5.0ms provide practically identical results. However, it should be noted that in case of the remote fault (longer fault duration) the PSS/E results differ from the PowerFactory results by some 2%.

Table 3: Test 7 - Summary of CFCTs for varying simulation step-sizes (PSS/E)

Integration Step size	0.5 ms	1.0 ms	2.5 ms	5.0 ms	10 ms
CFCT (close-end fault)	416 ms	416 ms	415 ms	415 ms	410 ms
CFCT (remote fault)	876 ms	876 ms	877 ms	875 ms	870 ms

2.1.3 The most adequate Integration step-sizes for PowerFactory and PSS/E

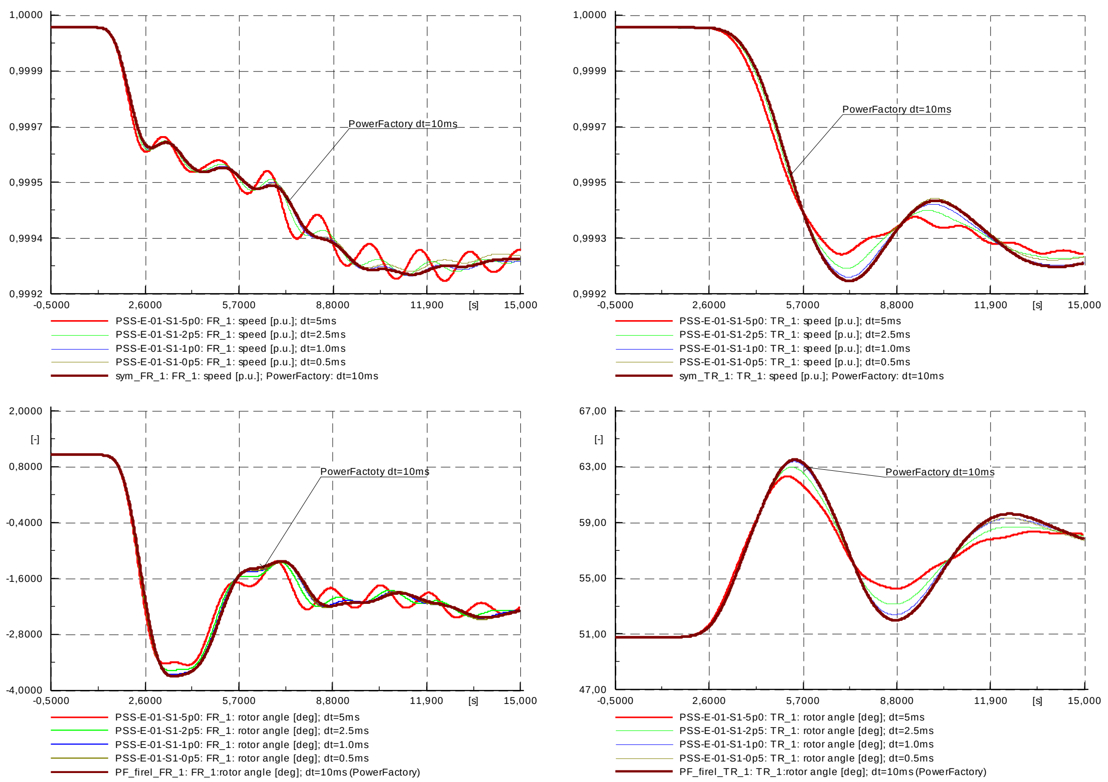
Based on the various simulation screenings performed with PowerFactory and PSS/E, the most suitable step size for simulating the European test system with **PSS/E**, complying with the simulation precision of PowerFactory, has been identified to be **1.0ms**. Step-sizes above 1ms present substantial deformations of solution trajectories, impacting mode frequencies and to a large extent mode damping. The user may of course select slightly higher integration step-sizes when determining the first-swing stability where the integration step-size less decisive. However, in all other cases such as grid damping analysis (e.g. PSS tuning), frequency stability, primary- and secondary control issues, etc. an integration step-size of 1ms should not be exceeded.

When using **PowerFactory**, the selection of the most adequate step-size is less critical, as the simulation screening has shown extremely compatible results for step-sizes varying between 1ms and 20ms (using fixed step-sizes). From the experience of European users, a fixed step-length of **10ms** has been found most suitable.

Summary: *The simulation runs executed demonstrate impressively that PSS/E simulation results obtained with an integration step-size of 1ms are comparable to simulation results obtained with PowerFactory on basis of an integration step-size of 10ms.*

Results obtained with PSS/E on basis of step-sizes <u>above</u> 1ms or <u>below</u> 1ms diverge from this most accurate solution. The convergence of simulation results for PowerFactory (dt=10ms) and PSS/E (dt=1ms) is clearly demonstrated in Fig. 2.4.

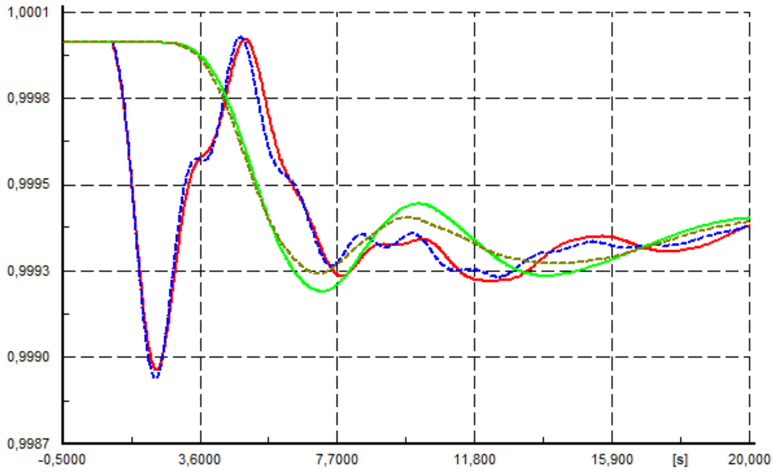
Fig. 2.4: Test 1: <u>PowerFactory</u> and <u>PSS/E</u> performance comparison (trip of 1050 MW)



2.1.4 Test 8: Verification of a Precision reduced Integration Step-Size

Taking into account that not all simulation runs need to be of highest precision, especially in the initial phase of a study project when models and data are being setup and tested, simulation step-sizes of 2.5ms for PSS/E and 25ms for PowerFactory could be an acceptable compromise between performance and precision as demonstrated in the simulation case below (Fig. 2.5 / Test 8).

Fig. 2.5: Test 8 - PSS/E step size of 2.5ms and 25ms for PowerFactory (trip of 1050 MW)



Simulation with more relaxed precision requirements on basis of 2.5ms step-sizes for PSS/E and 25ms step-sizes for Power-Factory showing generator speed signals at two representative grid locations (bold lines = PowerFactory, dashed lines = PSS/E).

2.1.5 Test 9: Sensitivity check for the PSS/E “Acceleration” Parameter Setting

The PSS/E Network solution parameter “Acceleration” is set by default close to one (0.998). However, some literature proposes different integration control settings. For example, [Procedure for PSS/E model validation, Hydro-Québec TransÉnergie, April 2014] and some other authors suggest a value of 0.5.

In order to verify the impact of the setting of the acceleration parameter, a further test (Test 9) has been executed, comparing PSS/E runs with different integration step sizes and different acceleration parameter settings.

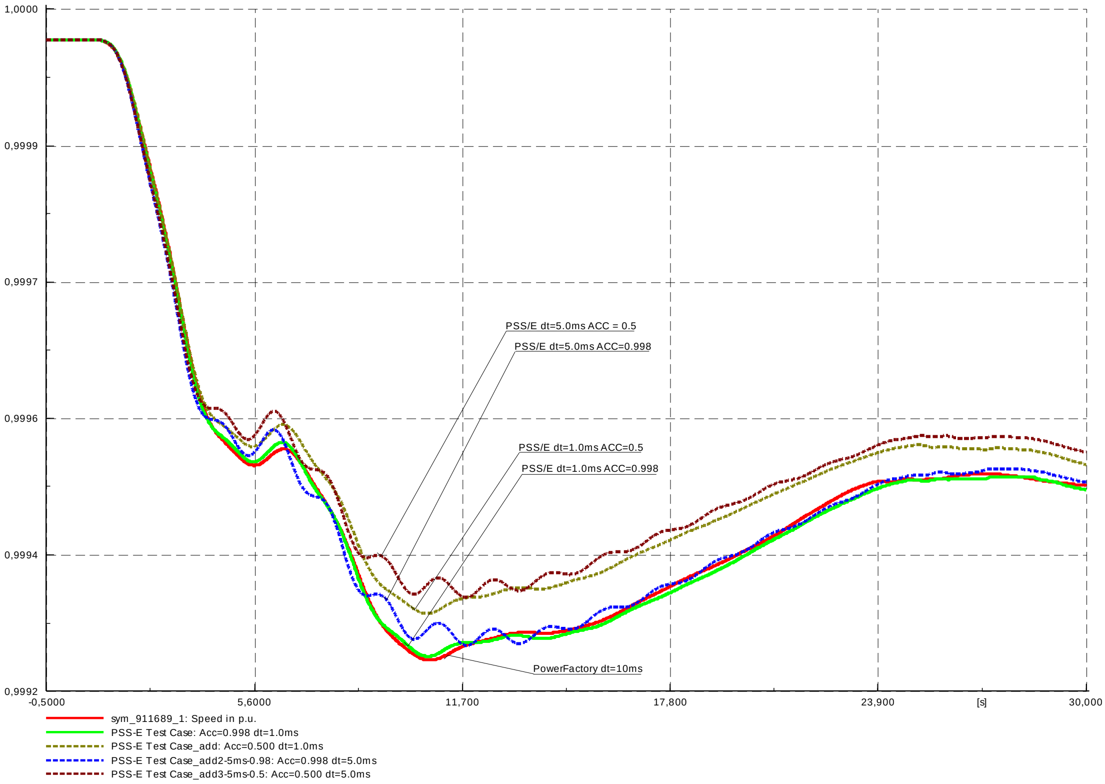
A number of relevant combinations of PSS/E step-size and acceleration parameter settings (see table 4) have been analysed and documented in Fig. 2.6. Again, a corresponding simulation run performed with PowerFactory on basis of a 10ms integration step-size is shown for comparison purposes.

Table 4: Variation of PSS/E integration step-size and ACCELERATION parameter

Integration step-size	1.0 ms	1.0 ms	5.0 ms	5.0 ms
ACCELERATION parameter	0.5	0.998	0.5	0.998

From Fig. 2.6, it can be clearly observed that setting the acceleration parameter to 0.5 will drastically distort the simulation result by introducing a clearly visible offset on the displayed variable “rotor speed”. It is further observed that at the same time the characteristics of the numeric oscillations, clearly visible for the simulation cases with an integration step-size of 5.0ms, are not improved at all.

Fig. 2.6: Test 9 - <u>PSS/E</u> integration step size of 2.5ms and 25ms for PowerFactory (trip of 1050 MW)



Result: for achieving a good compliance with DIgSILENT PowerFactory, it is suggested to keep the PSS/E default settings of the parameter "Network solution acceleration = 0.998" unchanged.

2.2 Case 2: General Load, no Renewable Generation

This second case is identical to case 1 reported under Section 2.1 except for the load characteristic definitions where more realistic parameters are now applied. Compared to the initial test case where constant impedance loads have been used, the load model now considers a static frequency dependency as well as a non-Z load with a specific voltage dependency for active and reactive power. The selected parameters are as follows (see also appropriate PowerFactory Technical Reference for the general load model, IEELAL- model in case of PSS/E):

Frequency dependence:	kpf = 1 % / %
Voltage dependence of P:	aP / bP / cP = 1 / 0 / 0; e_aP = 1.25
Voltage dependence of Q:	aQ / bQ / cQ = 1 / 0 / 0; e_aQ = 0.95
All time constants are set to:	0.0s

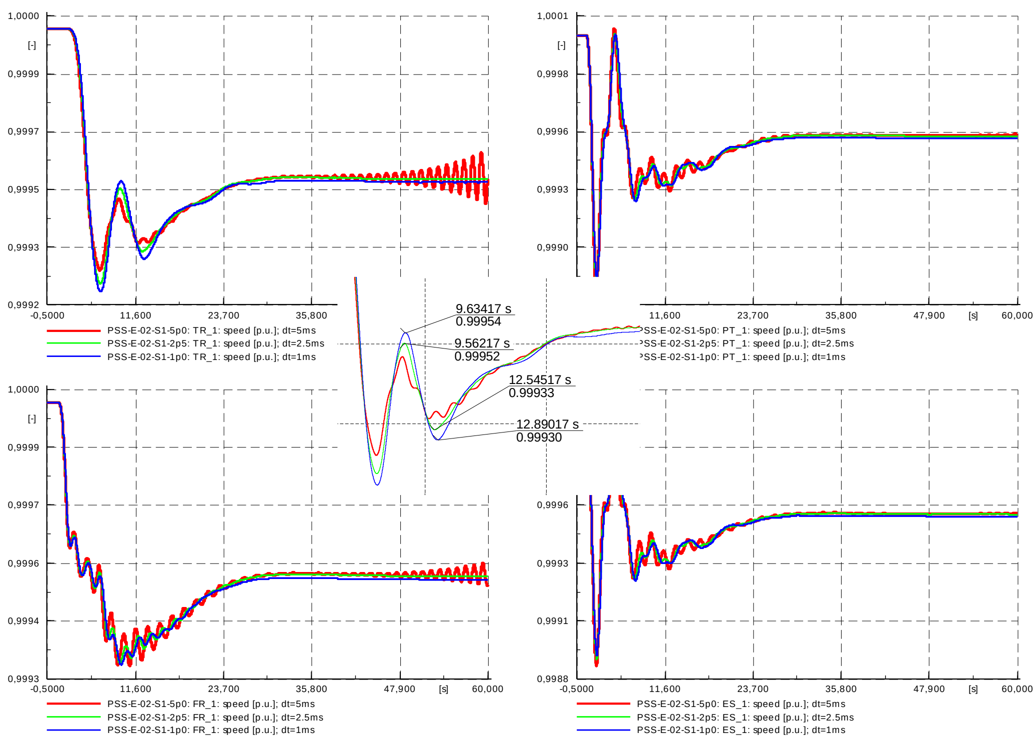
2.2.1 Verification of suitable integration step-size

In the following sections, a number of runs are executed aiming to verify the integration step-size as determined to be adequate for the scenarios based on the Z-load but now applying the generic, non-Z load.

2.2.1.1 Test 10: Scenario I, Unit trip loaded with 1050 MW (PSS/E verification)

A first simulation test (test 10) is executed with PSS/E varying the integration step-size in the range of 1.0ms to 5.0ms. This range has been identified to produce numerically stable results for case 1 (Z-load), see Section 2.1.3.

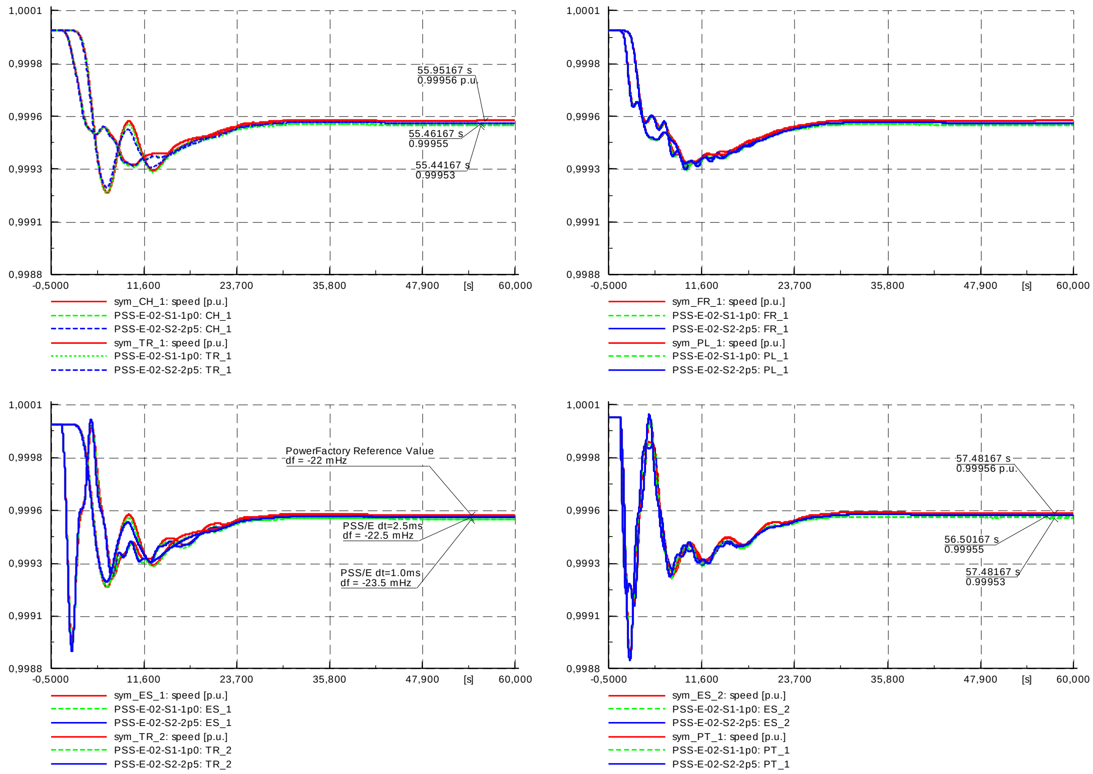
Fig. 2.7: Test 10 - PSS/E integration step size of 1, 2.5 and 5ms (trip of 1050 MW).



Now, as demonstrated in Fig. 2.7, the 5.0ms integration step-size results in unstable numerical oscillations. Those oscillations are not present when applying integration step-sizes of 1.0ms and 2.5ms. Consequently, in the following PSS/E performance tests, only step-sizes with 1.0ms and 2.5ms are applied and further analysed. As already observed for case 1, there are again notable differences visible in the transient response when comparing simulations with 1.0ms and 2.5ms integration step sizes.

A further observation can be made for the steady state deviation of the system frequency. Compared with PowerFactory simulation results, the PSS/E steady state deviation varies depending on the integration step-size. In the below Fig. 2.8 (test 11), a deviation of 0.5mHz is observed for the case with a step-size of 2.5ms, corresponding to an error of 2.3%. When applying a step-size of 1.0ms, the steady deviation increases to 1.5mHz, corresponding to an error of 6.8%.

Fig. 2.8: Test 11 - PSS/E integration step size of 1 and 2.5ms. PowerFactory 10ms (trip of 1050 MW)



2.2.1.2 Test 12: Scenario I, Unit trip loaded with 1050 MW (PowerFactory verification)

The robustness of PowerFactory simulation results are documented in Fig. 2.9a, varying the integration step-size from 1.0ms to 10ms and 20ms. In all cases numerical stability is guaranteed. For the applied integration step-sizes, simulation results can be considered to have no relevant deviations. It is further observed that the steady state solution is always identical and therefore independent of the integration step-size. This is also expected from the theoretical point of view as the steady state speed deviation / system frequency depends exclusively on the prime mover droop settings, the AVR droop settings as well as on the frequency- and voltage dependency of the grid loads.

Fig. 2.9b shows the steady state result of PSS/E and PowerFactory for the applied integration step-sizes in more detail.

Fig. 2.9a: Test 12 - <u>PowerFactory</u> integration step size of 1, 10 and 20ms (trip of 1050 MW)

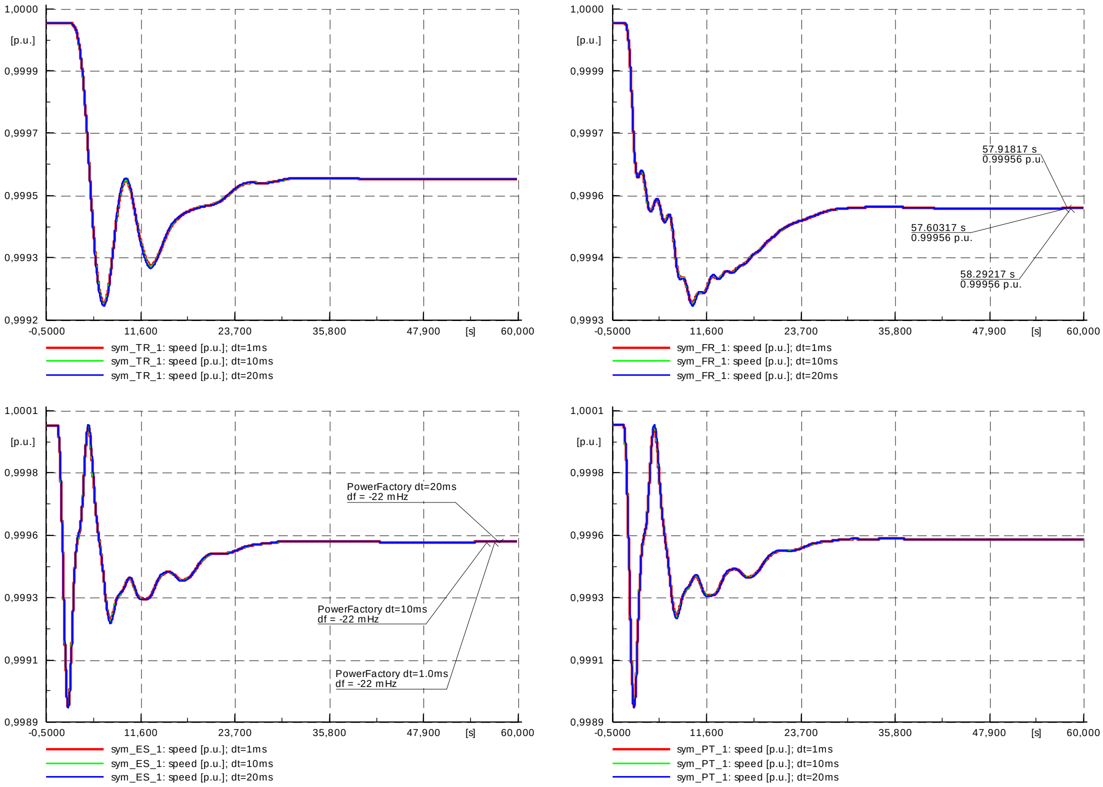
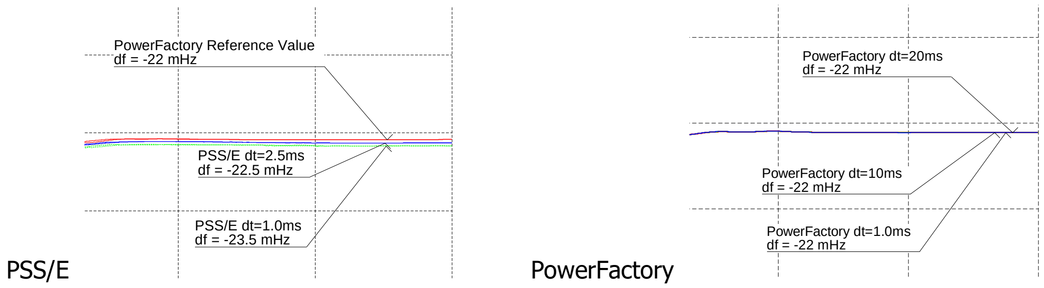


Fig. 2.9b: Test 12 - <u>PSS/E</u> and <u>PowerFactory</u> comparison (zoom into Fig. 2.8a)



2.2.1.3 Test 13: Scenario II, 3-phase fault at the 400 kV side of the unit transformer "ES_1"

It is expected that the critical fault clearing times (CFCT) and the simulation characteristics will not change substantially when comparing the study case defined as "tests 2 & 3 (PowerFactory)" and "tests 6 & 7 (PSS/E)" which are based on the Z-load model with this "test 13 (PSS/E)" and "test 12 (PowerFactory)" applying a more generic load type with defined static voltage- and frequency dependency.

However, for the sake of completeness respective simulation runs are documented in this section. Fig. 2.10a/b show the PSSE/S simulations of a 3phase fault with a duration of 150ms (test 13). Due to the Z-load behaviour during low voltage conditions, there is not much difference observed from the simulations documented for "Test 6". It is again observed that the transient grid response during the initial some hundreds of milliseconds differ only slightly depending on the applied integration step-sizes of 1, 2.5 and 5.0ms. It could therefore be expected that the first swing stability (CFCT) will be basically identical for all step-sizes.

Simulation results (Test 14) obtained with PowerFactory applying integration step-sizes of 1, 10 and 20ms are shown in Fig. 2.11. As already demonstrated for the case "Test 2" there are no noticeable differences observed, leaving the user full flexibility in selecting the integration step-size according to specific application aspects (e.g. fast DSA applications).

2.2.1.4 Verification of the Critical Fault Clearing Times (CFCT) for the General Load Model

A summary of critical fault clearing times determined on basis of varying step-sizes is included in table 5a (PowerFactory) and table 5b (PSS/E). Even with the precision relaxed option "Fast independent solution of network and dynamic models" enabled, PowerFactory shows a slightly more consistent solution when calculating the CFCTs for a 3phase fault close to the generator. In case of a remote fault, CFCTs vary by 6ms for PSS/E when applying step-sizes between 1ms and 10ms and 1ms[4] (respective 7ms) only for PowerFactory.

Table 5a: Test 12 - Summary of CFCTs for varying simulation step-sizes (PowerFactory)

Integration Step size	1 ms	5 ms	10 ms	15 ms	20 ms
CFCT (close-gen fault)	404 ms	404 ms	404 ms	404 ms	404 ms
CFCT (remote fault)	866 ms	862 ms	859 ms	856 ms	854 ms
CFCT (remote fault)[4]	866 ms	867 ms	867 ms	868 ms	869 ms

Table 5b: Test 13 - Summary of CFCTs for varying simulation step-sizes (PSS/E)

Integration Step size	0.5 ms	1.0 ms	2.5 ms	5 ms (*)	10 ms(*)
CFCT (close-gen fault)	403 ms	403 ms	402 ms	400 ms	400 ms
CFCT (remote fault)	826 ms	826 ms	825 ms	820 ms	820 ms

(*) Numerically unstable integration step-size

In case of the fault applied close to the generator, CFCTs determined by PowerFactory and PSS/E are basically identical. However, in case of the remote fault, CFCTs determined by PSS/E are some 5% lower than those determined with the high precision algorithms of PowerFactory.

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[4] *Simulation option "Fast independent solution of network and dynamic models" disabled*

Fig. 2.10a: Test 13 - <u>PSS/E</u> integration step size of 1, 2.5 and 5.0ms (3phase fault)

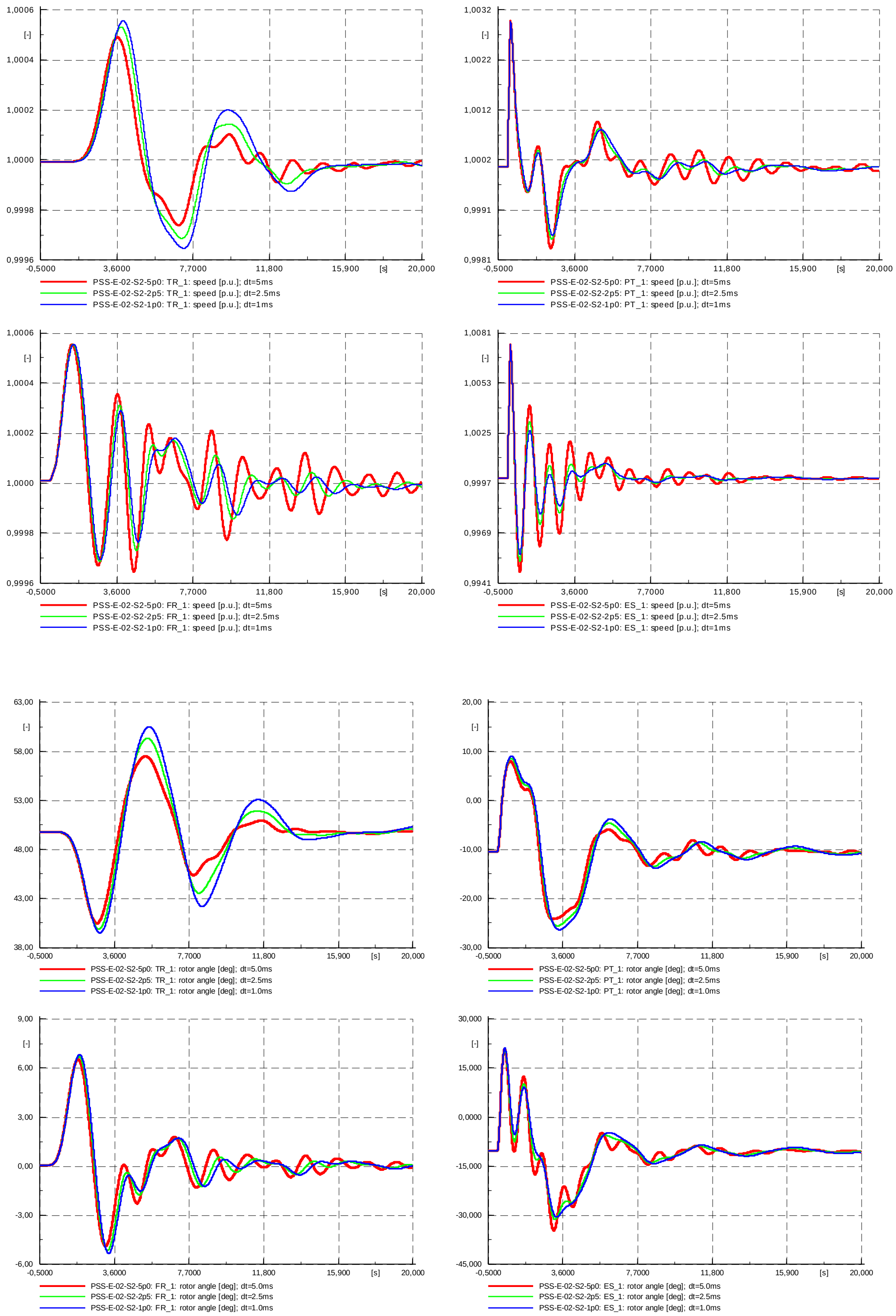


Fig. 2.10b: Test 13 - <u>PSS/E</u> integration step size of 1, 2.5 and 5.0ms (3phase fault)

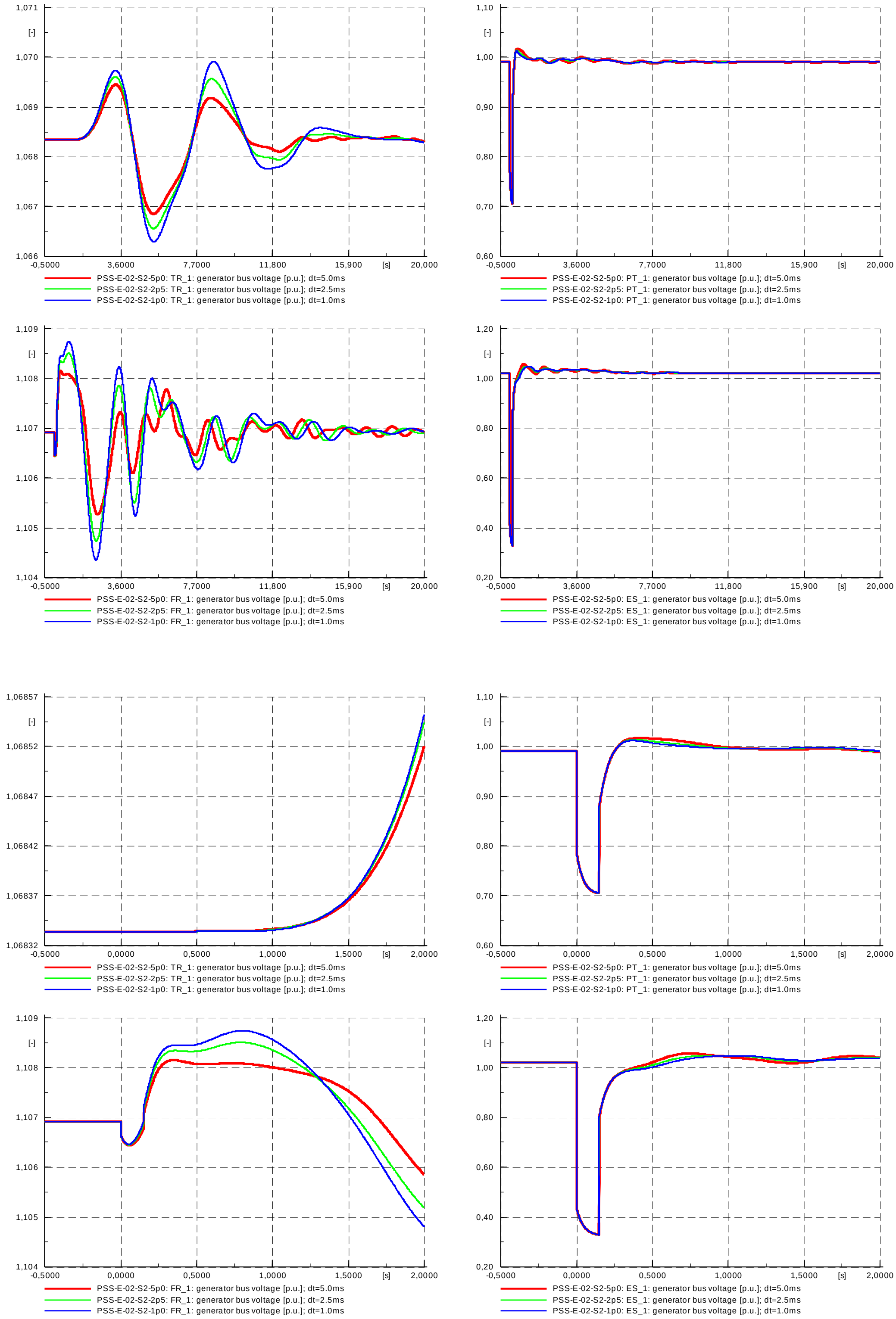


Fig. 2.11a: Test 14 - PowerFactory integration step size of 1, 10 and 20ms (3phase fault)

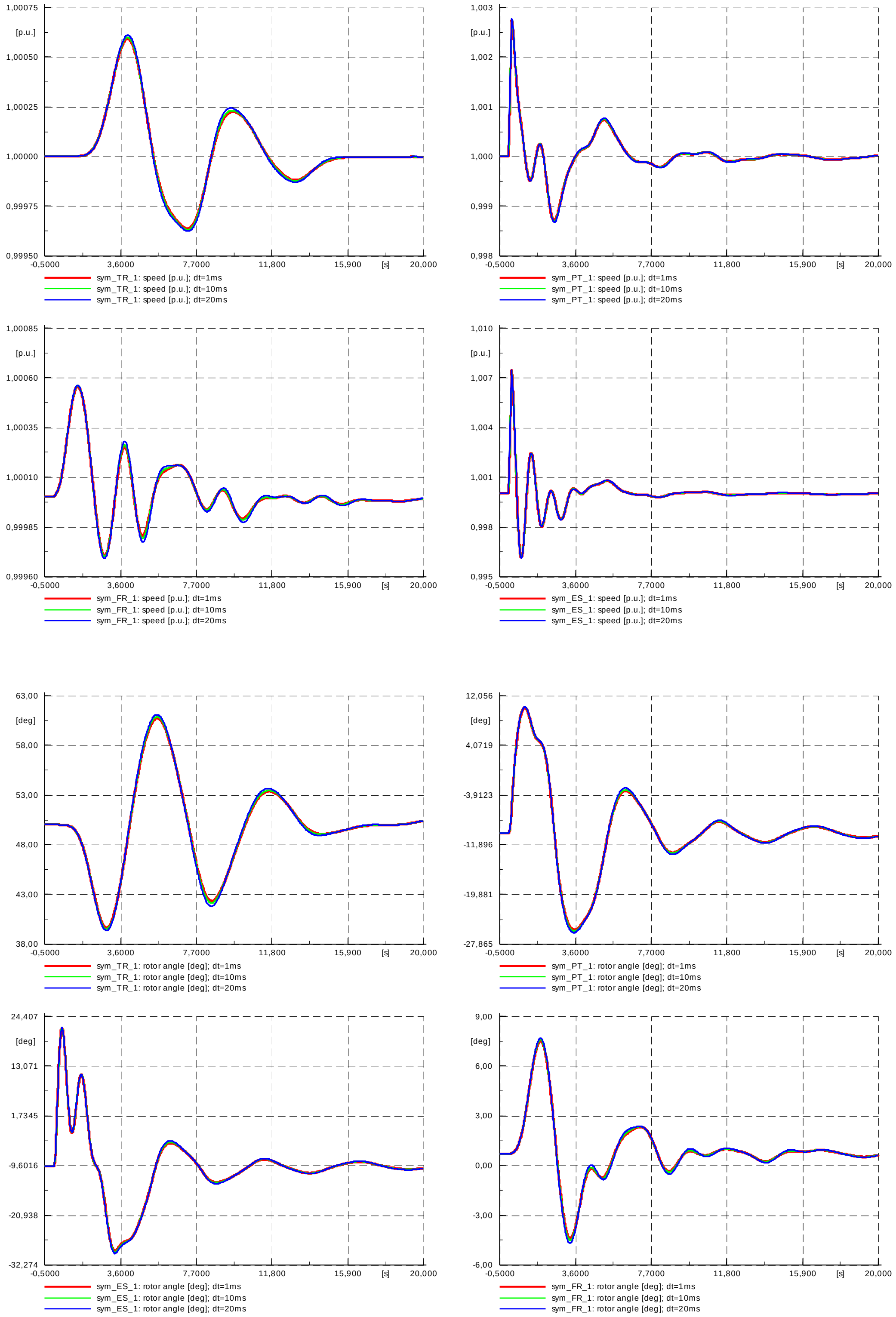
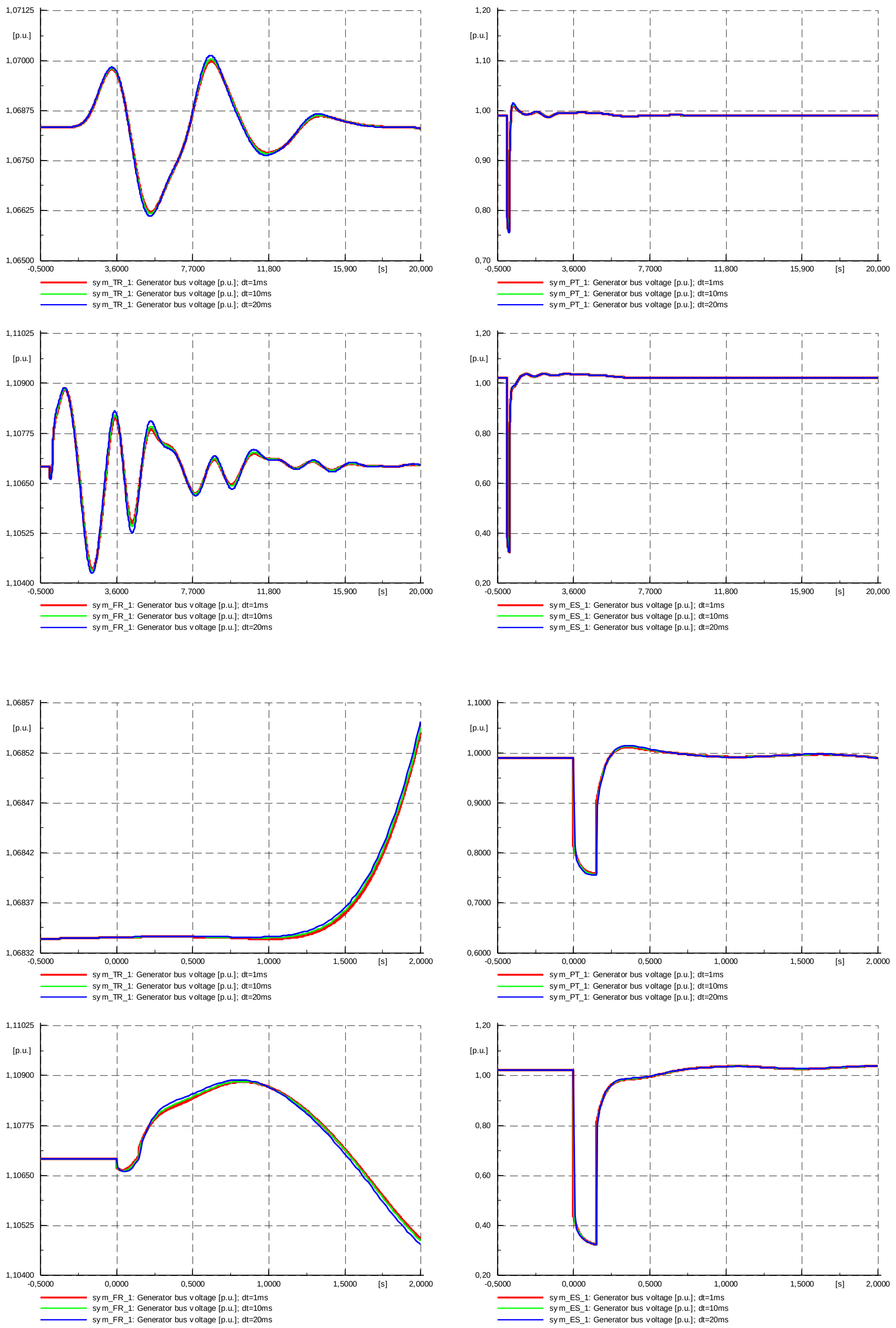


Fig. 2.11b: Test 14 - <u>PowerFactory</u> integration step size of 1, 10 and 20ms (3phase fault)



2.3 PSS/E and PowerFactory Simulation Performance

When executing the various runs reported in the above sections, the simulation times have all been recorded. The simulation run time recorded for "Test 5" with PSS/E on basis of an integration step-size of 1ms has been set to 100%. All other simulation cases, executed with PSS/E or PowerFactory make reference to this performance.

A run time above 100% indicates that a simulation is slower than the reference simulation. Similarly, a run time below 100% indicates a performance better than the defined benchmark case. The benchmark case "Test 5" requires **637s** for a simulation time of 60s. All shown load angles are calculated relative to the single slack bus (option: "Set relative machine angles (*) relative to machine = slack bus number")[5].

The software versions used are PSS/E v33 and v34 and PowerFactory 2017.

The simulation runs are executed on an Intel® Xeon® CPU X3450 with 2.67 GHz. The operating system used is MS Windows 7 / 64 bit. The system is equipped with 8.0 GB main memory thus guaranteeing that no memory swapping will take place that could adversely affect the performance. All runs are executed several times. Reported run times are average times as a variation of some ±5% have been observed due to stochastic operating system behaviour.

Table 6 summarises the PSS/E and PowerFactory simulation run times for the various cases and applied step-sizes.

Table 6: PSS/E and PowerFactory simulation run times normalized to PSS/E Test 5 ≡ 100%

Test	Grid Model	Event	PSS/E 1.0ms	PSS/E 2.5ms	PSS/E 5ms(1)	PF 5ms	PF 10ms	PF 25ms
1/5	Type 1	Trip 1050 MW (Spain)	100% (637s)	42% (268s)	22% (137s)	63% (404s)	**35%** (223s)	14% (92s)
2/6	Type 1	150ms 3ph short circuit (Spain)	**83%** (528s)	34% (216s)	18% (116s)	64% (410s)	**32%** (204s)	14% (89s)
12/10	Type 2	Trip 1050 MW (Spain)	**174%** (1108s)	84% (533s)	44% (282s)	214% (1362s)	**96%** (613s)	43% (271s)
13/14	Type 2	150ms 3ph short circuit (Spain)	**107%** (679s)	45% (285s)	42% (265s)	177% (1127s)	**85%** (543s)	38% (243s)

(1) – It is not advisable to apply the 5ms step-size due to numeric oscillations or even numerical instability.

[5] *It is to be noted that the PSS/E simulation run time differs substantially when calculating relative machine angles relative to the system average angle or the system weighted average angle instead of relative to a machine (the more intuitive case). Selecting the system average angle as reference will speed up the simulation run by a factor of up to approximately 1.45.*

3 Summary and Recommendations

This paper entitled "Compatibility Issues in Time Domain Simulations with DIgSILENT PowerFactory and SIEMENS®PSS/E ; Part I – Large Grids with Type 1 Generators" covers grid modelling and simulation compatibility aspects of grids with synchronous generation. The inclusion of inverter-based generation (type 2 generation such as wind and PV) will be covered in "Part II – Large Grids with Type 1 and Type 2 Generators" as well as consideration of PowerFactory's adaptive step-size algorithm and features which will be issued in a next step.

Aiming to provide compatibility guidelines when interchanging power system modelling data between DIgSILENT PowerFactory and SIEMENS ®PSS/E, a number of representative test runs have been executed on basis of a European grid model comprising some 21,500 buses and around 1,150 synchronous generators (type 1 generators). The load model applied covers the classical Z-load as well as a generic voltage- and frequency dependent load.

In the following sections the most important findings and recommendations to support a successful round-trip compatibility of PowerFactory and PSS/E are summarised.

3.1 PowerFactory - PSS/E Data and Model Conversion Aspects

The PowerFactory import of PSS/E data is available for *.raw, *.seq and *.dyn files. PSS/E version 33 and version 34 are fully supported for the grid model studied in this paper. The PowerFactory import of PSS/E single-line graphics is not provided. Should the user require a single line representation of grid sections, areas or even the complete grid, use of the PowerFactory feature "automatic generation of single line graphics" is recommended.

As an alternative to the import of PSS/E-specific files, the usage of CIM (CGMES) is a further option, especially when a complete data round-trip is required.

Regarding the compatibility of load flow results, the following aspects need to be taken into account:

1. PSS/E does not support the PowerFactory "static generator" which has been used in the applied grid model for representing generation units with a nominal power of 100 MW and below. Use of negative loads instead will also fail in PSS/E, as negative loads are not supported as PV-buses. To overcome this modelling limitation in PSS/E, all negative loads modelled as PV-buses have been converted into synchronous machines.

2. The load flow results as such are highly compatible. The only objects which cause slightly different results between PSS/E and PowerFactory are the 2- and 3-winding transformers with defined no-load losses. For overall modelling compatibility reasons (e.g. saturation modelling for EMT-transients analysis), PowerFactory transformer models are based on T-equivalents whilst PSS/E uses Π-equivalents. The mismatch between PowerFactory and PSS/E load flow results arising from the slightly different transformer models is around 13 MW, constituting a deviation of 0.004% related to the total system load of around 300,000 MW.

3.2 PowerFactory – PSS/E Stability Simulation Compatibility

A total of 14 simulation test scenarios have been executed with PowerFactory and PSS/E on the basis of an identical grid model of the European transmission system (ENTSO-E). Key simulation algorithm settings such as the integration control parameter "network solution tolerance (PSS/E)" and "maximum error for bus equations (PowerFactory)" have also been selected to be identical. Other parameters such as the integration step-size have been varied and investigated further.

The main findings are summarized as follows:

1. Full synchronous machine modelling compatibility between PowerFactory and PSS/E is achieved when setting the PSS/E parameter "NETFRQ=0" and when leaving all PowerFactory synchronous machine "torque coefficients" at zero ("Damping"-tab). Also, the effect of speed variation must be neglected ("Advanced"-tab). Other settings combinations with "NETFRQ=1" and PowerFactory improved model settings result in a modelling incompatibility.

2. Machine load angles are compatible between PowerFactory and PSS/E when calculating in PSS/E load machine angles relative to a machine with reference to the slack bus. The corresponding PowerFactory variable is: "c:firel".

3. **Simulation results obtained with PSS/E are highly sensitive to the simulation step-length**. Regardless of the load model applied, the step-size of 10ms, which is typically applied for simulating the European interconnected system (ENTSO-E), will result in an immediate numerical instability. Numerical stability is obtained for step-sizes of 5ms and below when using the Z-load model. However, when applying the general frequency and voltage dependent model a step size of 2.5ms or below is required for obtaining numeric stability with PSS/E.

4. **The suitable step-size for PSS/E has been determined to be 1ms.** In such a case, the PSS/E result is highly compatible to simulation results obtained with PowerFactory where step-sizes between 1ms and 25ms show basically identical solutions.

5. **Simulation results obtained with PowerFactory are not sensitive to the simulation step-length.** Results obtained with step-sizes varying between 1ms and 25ms are practically identical. **The most suitable PowerFactory fixed step-length integration step-size within the interval of 1-25ms has been determined to be 10ms**.

6. **When reducing the PSS/E integration step-size to 1ms, the simulation results will converge to those obtained with PowerFactory on basis of an integration step-size of 10ms.** PSS/E integration step-sizes below 1ms are not recommended as they show increased integration summation errors (increased steady state deviations).

7. **Choosing an inappropriately large PSS/E integration step size will result in mode shifts towards characteristics with lower damping and lower mode frequencies**. The mode shift will apply to lightly damped modes first.

8. **Larger step sizes of up to 25ms applied in PowerFactory will not change mode characteristics and will therefore not lead to undamped modes**. Applying the adaptive step-size algorithm will guarantee a defined integration error within varying step-sizes ranging from milliseconds to minutes.

9. When calculating first swing critical fault clearing times (CFCT) with a total simulation time below 1.0s, the simulation results (CFCT) obtained with PSS/E or PowerFactory are highly insensitive to the integration step-sizes (this statement is not generic and will depend on the local generator mode characteristics). CFCTs below 500ms obtained with PowerFactory and PSS/E are basically identical. Certain deviations between PSS/E and PowerFactory are observed for larger CFCTs (e.g. > 500ms).

10. **The PSS/E network solution parameter "Acceleration" should be set to the default value of 0.998**. Any setting deviating from the default value (e.g. 0.5 as suggested by some users) will result in an unacceptable offset of the steady value of variables such as the grid frequency. In such a case, PSS/E simulation results will no longer be compatible with those from PowerFactory.

11. **When using the general, frequency- and voltage dependent load model, PSS/E steady state results will show an incorrect offset in all variables.** The offset itself will also depend on the integration step-size. In such case, PSS/E and PowerFactory results will show respective discrepancies.

12. Any type of study executed with **PSS/E** including PSS-tuning, any control optimisation (AVR, prime mover, etc.), load-shedding analysis, etc. where the main simulation result is not determined within the initial second, will require integration step-sizes of **1ms**. When using **PowerFactory**, integration step-sizes can be selected to be **10ms** or above (maximum 25ms recommended when using fixed step-sizes, up to minutes when using adaptive step-sizes).