39 Bus New England System

DIgSILENT *PowerFactory*[*]

Abstract

The 39 Bus New England System is a simplified model of the high voltage transmission system in the northeast of the U.S.A. (New England area). It was presented for the first time in 1970 and has since been often used for scientific research and publications. This paper describes the *PowerFactory* model of the 39 Bus New England System and its parameters as provided by *DIgSILENT*. Results of the steady-state power flow are given and plots generated from time-domain stability simulations are shown as examples.

1 General Description

The 39 Bus New England System consists of 39 buses (nodes), 10 generators, 19 loads, 34 lines and 12 transformers. Figure 1 shows the single line diagram. It is a simplified model of the transmission system in the New England area in the northeast of the U.S.A.

The nominal frequency of the New England transmission system is 60 Hz and the mains voltage level is 345 kV (nominal voltage). For nodes at a different voltage level, the following nominal voltages have been assumed for the *PowerFactory* model:

- Bus 12: 138 kV
- Bus 20: 230 kV
- Bus 30 – Bus 38: 16.5 kV

2 Model Parameters

Data have been taken from [1] and have been completed with data taken from [5, 6] for the *PowerFactory* model of the 38 Bus New England System. Additional data not available in [1, 5, 6] have been assumed by *DIgSILENT* (e.g. nominal voltages). The model only contains data for a balanced network representation (positive sequence).

It is stated in [1] that the data are taken from [2]. With respect to network data, [2] refers to [3, 4], which are the original data sources for the 39 Bus New England System.

2.1 Model Parameters for Steady-State Power Flow Calculation

The following subsections describe the network data used for the load flow calculation.

2.1.1 Loads

The loads are not voltage-dependent, but have constant active and reactive power demand. Please note that this is achieved by disabling the load option "Consider Voltage Dependency of Loads" in the *PowerFactory* load flow calculation command. Load data (active power P and reactive power Q) have been taken from [1] and are listed in Table 1.

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2.1.2 Generators

Generator "G 01" represents the interconnection to the rest of the transmission system (U.S. and Canadian) and is therefore directly connected at the 345 kV level. All other generators are connected via transformers.

Generator "G 02" is the slack element of the network model, therefore voltage magnitude and voltage angle are given (0.982 p.u., 0.0 degrees). For the other generators, active power dispatch and controlled voltage magnitude at their terminals are given. The data have been taken from [1] and are listed in Table 2.

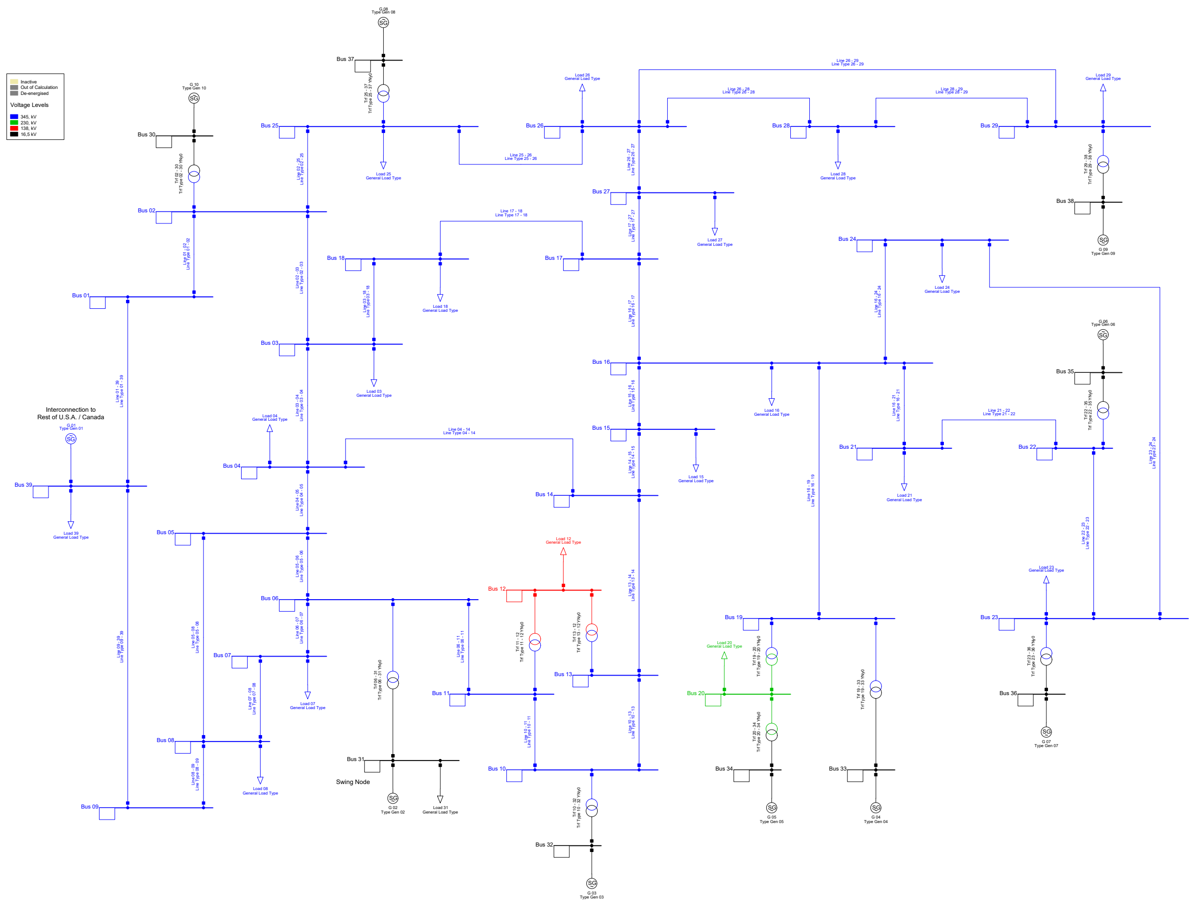

Figure 1: Single line diagram of the 39 Bus New England System

2.1.3 Transmission Lines

Line data are given in per unit (p.u.) based on 100 MVA as represented in Table 3, without information about the line length [1]. For the *PowerFactory* model input data are required in Ω/km and μF/km, respectively. Line data have been recalculated for the network model with a nominal voltage of 345 kV and a nominal frequency of 60 Hz. As no line length is provided in [1], the length of each line in the *PowerFactory* model has been estimated using the assumption that the reactance per length is 0.3 Ω/km. Line data used in the *PowerFactory* model are shown in Table 4. The rated current of each line is not known and is therefore assumed to be 1 kA.

2.1.4 Transformers

Transformer data are given in per unit (p.u.) as represented in Table 5 based on 100 MVA [1]. For the *PowerFactory* model realistic ratings have been assumed in accordance with generator ratings (see Section 2.2.2) and the parameters recalculated based on these ratings. Transformer parameters of the *PowerFactory* model are given in Table 6. In addition, tap changers are modelled in order to achieve the transformer taps as given in Table 5. Transformer "Trf 20 - 34" is represented by 2 parallel transformers with a rated power of 300 MVA each.

The vector group of all transformers has been assumed to be YNy0, in order to obtain results of the bus voltage angles which are consistent with results given in the literature, for example as in [7]. More realistic transformer vector groups (YNd) are available in alternative transformer types, which can be used by activating the Variation “YNd Transformers”.

2.2 Model Parameters for Stability Analysis

For stability analysis (time-domain simulation and eigenvalue analysis) additional parameters are required to represent the dynamic behaviour of the elements. These additional parameters are described in the following subsections.

2.2.1 Loads

For stability analyses loads are considered to have a voltage dependency according to Equation (1) and (2) within the voltage range 0.8 . . . 1.2 p.u. In the example of the 39 Bus System, the parameter kpu is set to 1 (constant current behaviour for active power) and kqu to 2 (constant impedance behaviour for reactive power). Frequency dependency and dynamic (time-dependent) load behaviour was neglected, but could be taken into account by changing the parameters of the load type [9].

$$P = P_{\mathrm{Ldf}} \cdot \left(\frac{U}{U_{\mathrm{Ldf}}}\right)^{kpu} \tag{1}$$

$$Q = Q_{\mathrm{Ldf}} \cdot \left(\frac{U}{U_{\mathrm{Ldf}}}\right)^{kqu} \tag{2}$$

2.2.2 Generators

Parameters for the synchronous generators according to [1] with additional subtransient parameters according to [6] are given in Table 7. The power ratings of the generators have been adapted in order to achieve realistic inertia time constants and to allow the power dispatch within reasonable governor limits. The parameters used in the *PowerFactory* model are listed in Table 8.

2.2.3 Automatic Voltage Regulators

Automatic voltage regulators (AVRs) used for the synchronous generators in the 39 Bus New England System are rotating excitation systems of IEEE Type 1 according to [1]. The data are given in Table 9.

The feedback block for modelling the saturation (depending on the excitation voltage E_{f}) uses a transfer function according to Equations (3) – (7) [1].

$$y = E_{\mathrm{f}} \cdot A \cdot \exp\left(B \cdot E_{\mathrm{f}}\right) \tag{3}$$

$$A = \frac{C_2}{\exp(B \cdot EX_2)} \tag{4}$$

$$B = \frac{\ln(C_2/C_1)}{EX_2 - EX_1} \tag{5}$$

$$EX_1 = 0.75 \cdot EX_2 \tag{6}$$

$$EX_2 = \frac{V_{\mathrm{Rmax}}}{K_{\mathrm{E}} + C_2} \tag{7}$$

In the *PowerFactory* model of the AVR, the corresponding parameters are: E_{f} = uerrs, EX_1 = E1, EX_2 = E2, C_1 = Se1, C_2 = Se2, V_{Rmax} = Vrmax, K_{E} = Ke .

Unit No. 1, which represents the connection of the New England System to the rest of the U.S. and Canadian grid, is modelled with a constant excitation [1]. There is therefore no AVR connected to Generator “G 01”.

2.2.4 Power System Stabilisers

Power System Stabilisers (PSSs) are modelled according to [7]. However, the PSS settings given by [7] are not suitable for stabilising the generator units in the *PowerFactory* model, because a different AVR type and different AVR settings are used by [7] in comparison to those used in [1]. No PSS data are given in [1], which is the basis of the *PowerFactory* model. Hence, the *PowerFactory* model data of the PSSs are entered according to [7], but the PSSs are disabled. [1]

Unit No. 1 does not have a PSS in the *PowerFactory* model, as according to [1] it does not have an AVR.

[1] Please note that the PSS input signal in *PowerFactory* is the rotating speed in p.u., whereas [7] uses the angular frequency (deviation) in rad/s. Therefore the values of the gain K of the PSSs provided by [7] have been multiplied by a factor of $(2 \cdot \pi \cdot f_{\mathrm{n}}) = (2 \cdot \pi \cdot 60\,\mathrm{Hz})$ to input the values of the gain Kpss in *PowerFactory*.

2.2.5 Governors

Governors (GOVs) are considered as IEEE Type G1 (steam turbine) for Units No. 2 – 9, and IEEE Type G3 (hydro turbine) for Unit No. 10.

2.3 Parameters for EMT Model

Based on the CIGRE Technical Brochure 736 [8], a modified IEEE 39-bus benchmark for EMT type simulations is availabe and was implemented in *PowerFactory*.

The new benchmark is based on the original 39 BUS NEW ENGLAND SYSTEM from section 2. However, the EMT version of the IEEE 39 benchmark incorporates some significant modelling changes with regard section 2. These include:

- **Transmission lines** based on geometric models including frequency dependent and distributed line parameters
- **Transformer models** including winding connection, rated MVA, nonlinear saturation characteristics and winding parameters
- **Generator models** including the electrical and mechanical data of machines and control schemes including exciter, governor, and power system stabiliser (PSS)

Details about the models and changes with regard to the original IEEE 39 system are found in [8]. The *PowerFactory* model of the EMT benchmark is documented in Figure 2.

Due to significant changes in the modelling parameters, steady state and dynamic results will differ from the original case that are described above.

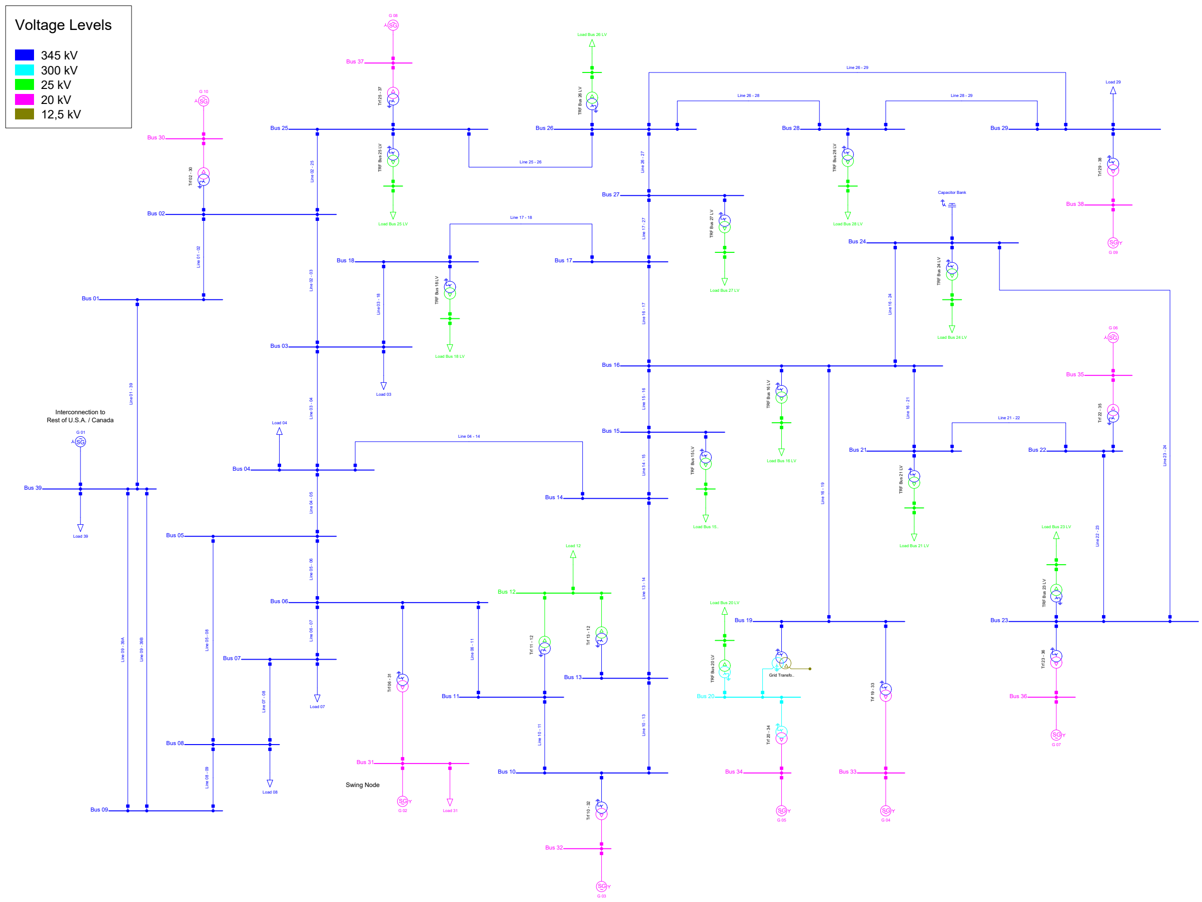

Figure 2: Single line diagram of the CIGRE IEEE 39 EMT Benchmark Model

3 Results

The *PowerFactory* project “39 Bus New England System” contains eight study cases, of which one displays the steady-state power flow results in bar diagrams, while the others are configured for stability analysis.

3.1 Results for Steady-State Power Flow

The steady-state power flow is examined by executing a load flow calculation ( ). The Study Case “Power Flow” contains pre-defined bar diagrams which display the results for busbar voltages (magnitudes and angles, see Figure 4 and 5). and power injection of generators (active and reactive power, see Figure 3).

The results of the *PowerFactory* load flow calculation are also given in Appendix B. Comparison with results provided by [7] shows very close matching. The voltage magnitudes and angles match exactly for all buses with the accuracy given in [7], as shown in Table 10. Results for the active and reactive power injection by generators show small differences for two generators, as given in Table 11. However, the grid summary gives a small mismatch of total generation compared with the sum of total load and grid losses (Eq. (8)) for the results provided by [7], while *PowerFactory*’s results do not exhibit such a mismatch, see Table 12.

$$\text{Mismatch} = \text{Generation} - (\text{Load} + \text{Losses}) \tag{8}$$

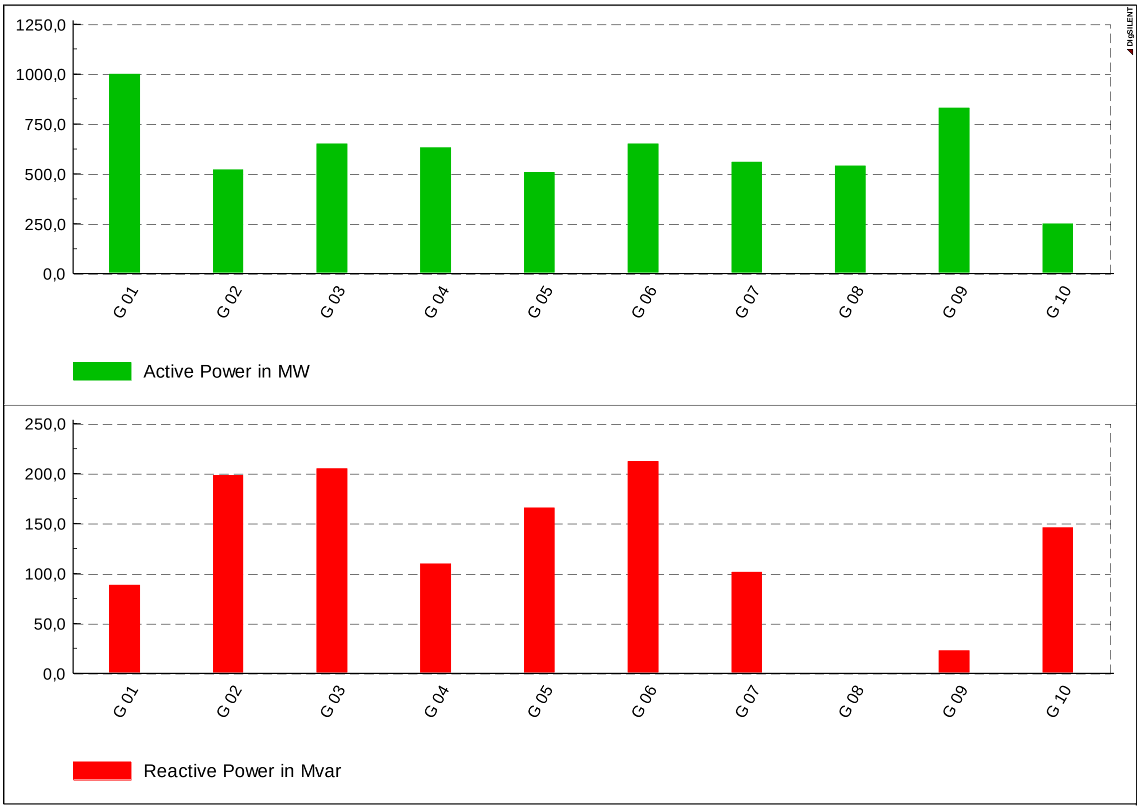

Figure 3: Active and reactive power of generators

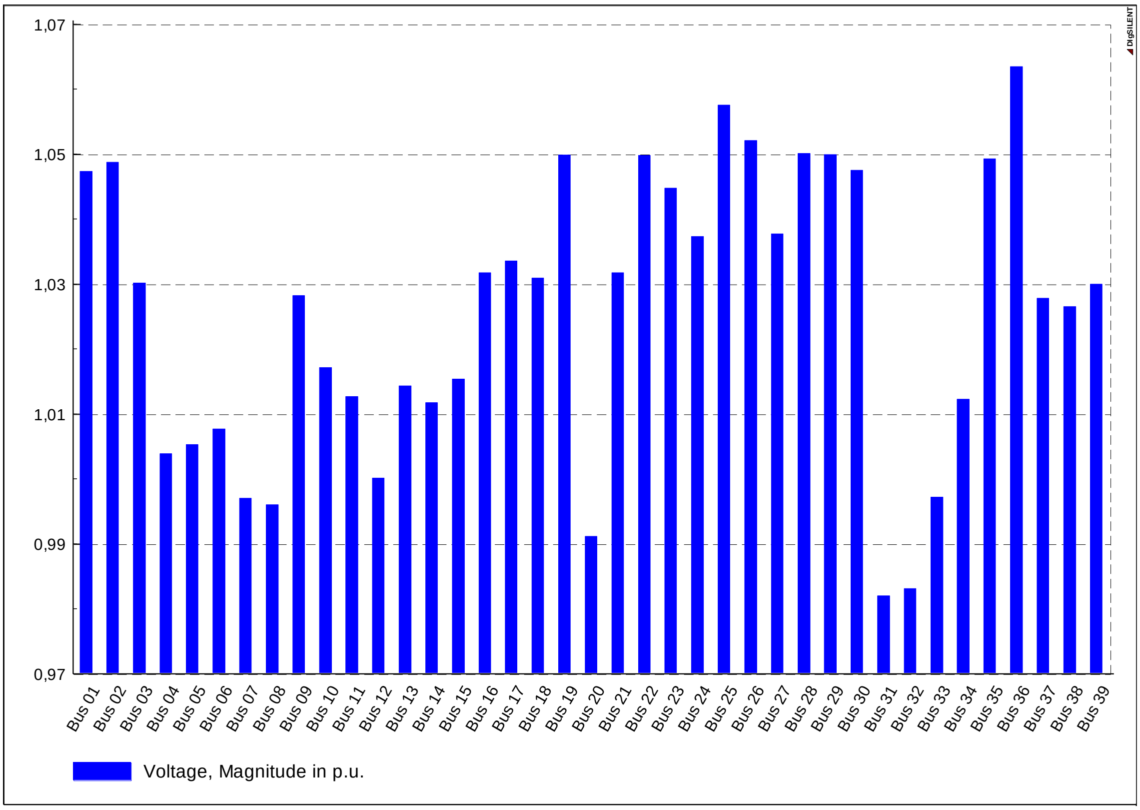

Figure 4: Voltage magnitudes

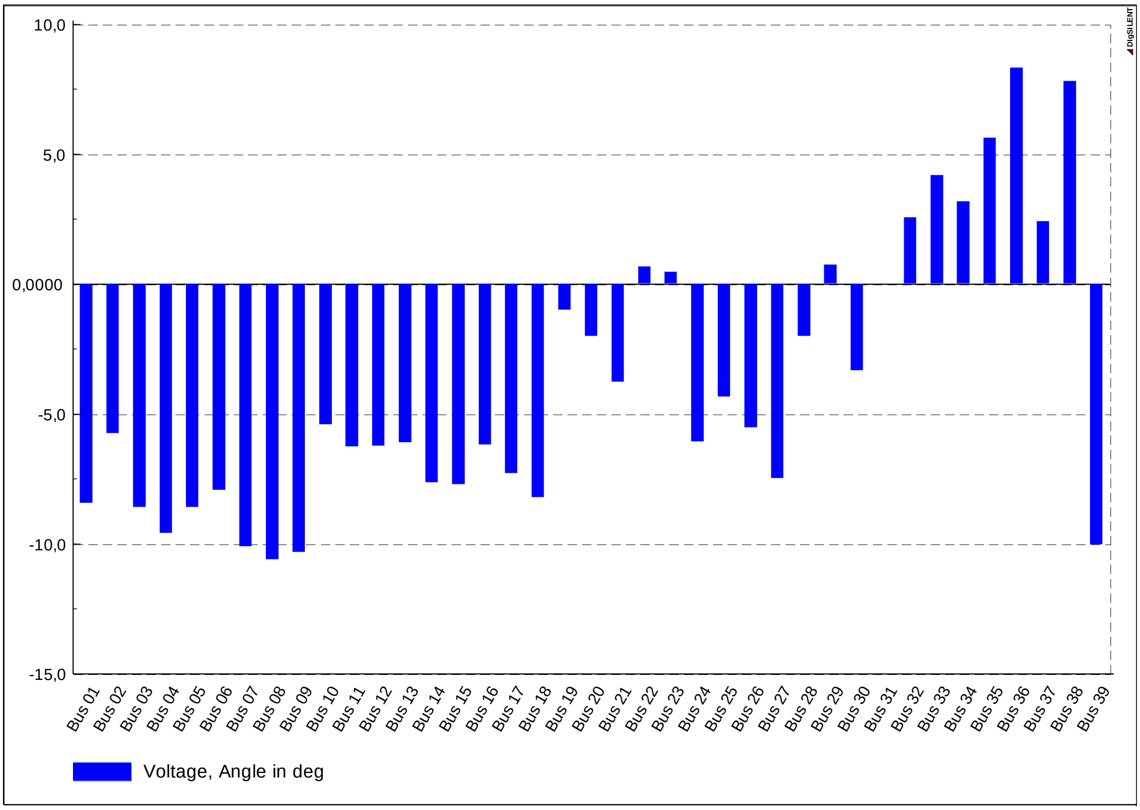

Figure 5: Voltage angles

3.2 Results for Stability Simulation

There are six pre-defined study cases for time-domain stability analysis and one study case for small signal eigenvalue analysis.

3.2.1 Time-Domain Simulation

To run time-domain simulations in *PowerFactory* the RMS/EMT Simulation toolbar should be selected as shown in Figure 6.

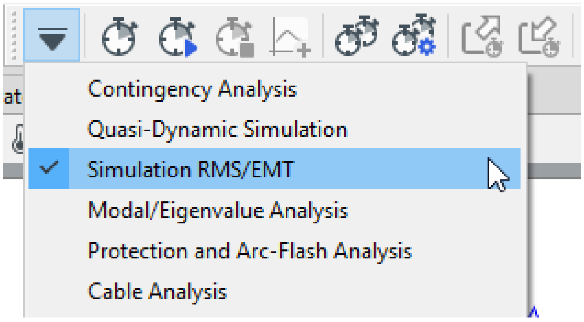

Figure 6: Selection of the RMS/EMT Simulation toolbar

A simulation has to be initialized first. The required dialogue is accessible via the button *Calculate Initial Conditions* ( ). For the study cases described in the following subsections, all settings are already correctly configured. By pressing **Execute** the simulation is initialized. The simulation can then be started by pressing the *Start Simulation* button ( ) and executing the command. The results are visible after the simulation has finished.

The following pre-defined study cases for time-domain simulation are available:

- **Simulation Fault Bus 16 Stable:** A short-circuit at Bus 16 (located in the middle of the grid) is simulated and cleared after 180 ms. Transient stability is ensured for all generators.
- **Simulation Fault Bus 16 Unstable:** A short-circuit at Bus 16 (located in the middle of the grid) is simulated and cleared after 200 ms. Transient instability occurs.
- **Simulation Fault Bus 31 Stable:** A short-circuit at Bus 31 (terminal of Generator “G 02”) is simulated and cleared after 210 ms. Transient stability is ensured for all generators.
- **Simulation Fault Bus 31 Unstable:** A short-circuit at Bus 31 (terminal of Generator “G 02”) is simulated and cleared after 230 ms. Transient instability occurs for Generator “G 02”.
- **Simulation Fault Line 2-3 Stable:** A short-circuit at the beginning of “Line 02 - 03” is simulated and cleared after 230 ms by switching off the faulted line. Transient stability is ensured for all generators. Figure 8 shows the speed of the synchronous generators.
- **Simulation Fault Line 2-3 Unstable:** A short-circuit at the beginning of “Line 02 - 03” is simulated and cleared after 250 ms by switching off the faulted line. The speed of the generators is shown in Figure 9. Generator “G 09” becomes unstable (transient instability).

3.2.2 Modal Analysis

To run a small signal analysis (Eigenvalue or Modal Analysis), in *PowerFactory* the Modal Analysis toolbar has to be selected as shown in Figure 7.

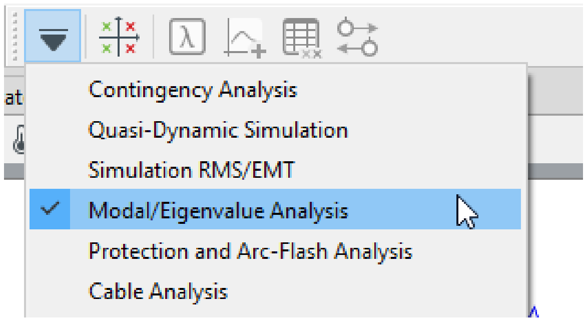

Figure 7: Selection of the Modal Analysis toolbar

The equation system has to be initialized (button *Calculate Initial Conditions* ( )), before the calculation of the eigenvalues can be executed by pressing the button *Modal Analysis* ( ). The study case “Small Signal Analysis (Eigenvalues)” contains an eigenvalue plot which displays the results (see Figure 10 for results without Power System Stabilisers). It is possible to add further diagrams for depicting the controllability, observability, and participation of each eigenvalue.

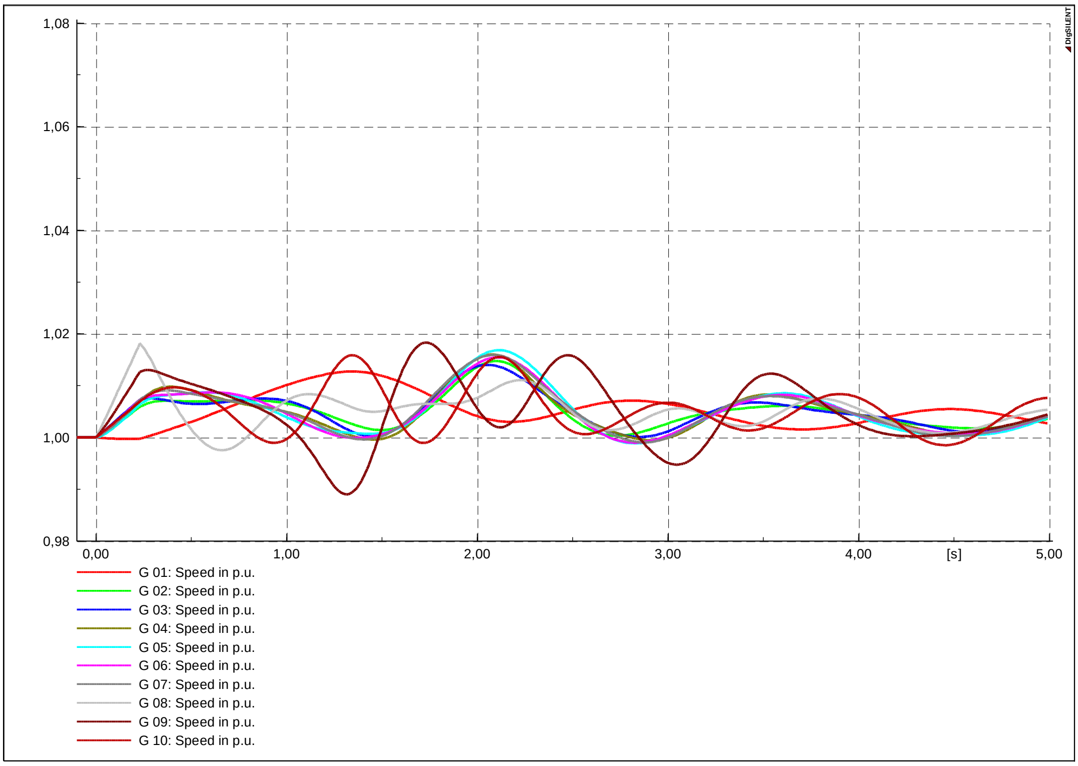

Figure 8: Speed of generators in the case of a fault on “Line 02 - 03”, cleared by switching off the line after 230 ms

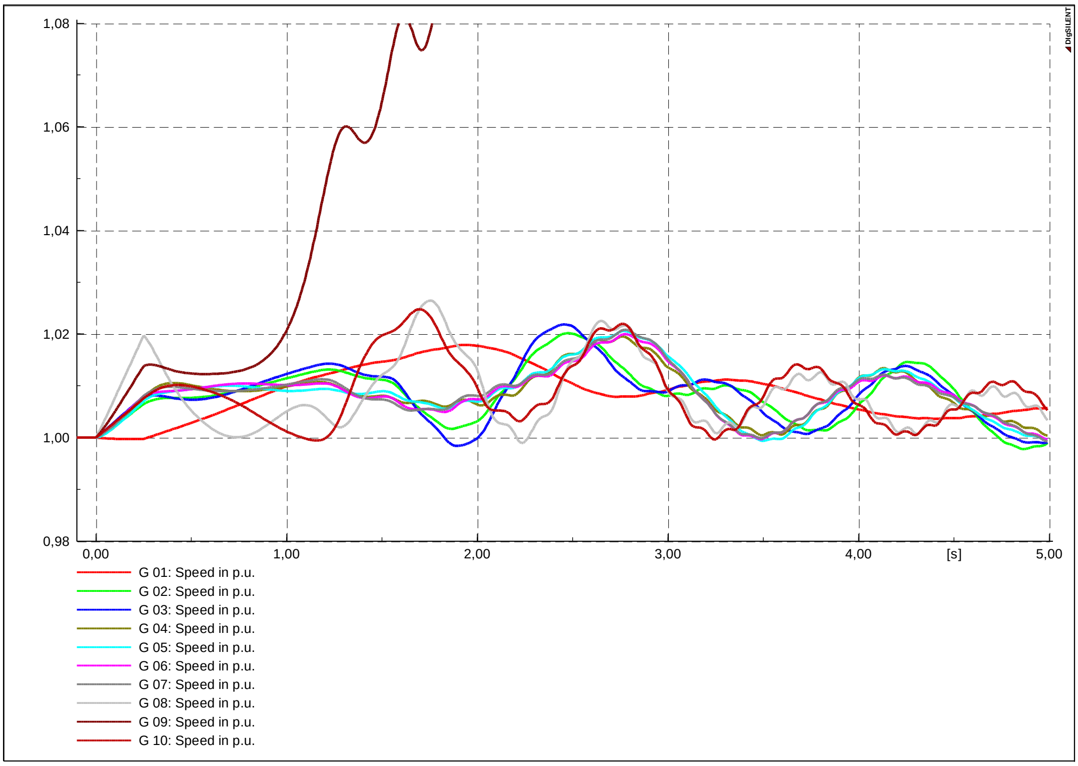

Figure 9: Speed of generators in the case of a fault on “Line 02 - 03”, cleared by switching off the line after 250 ms

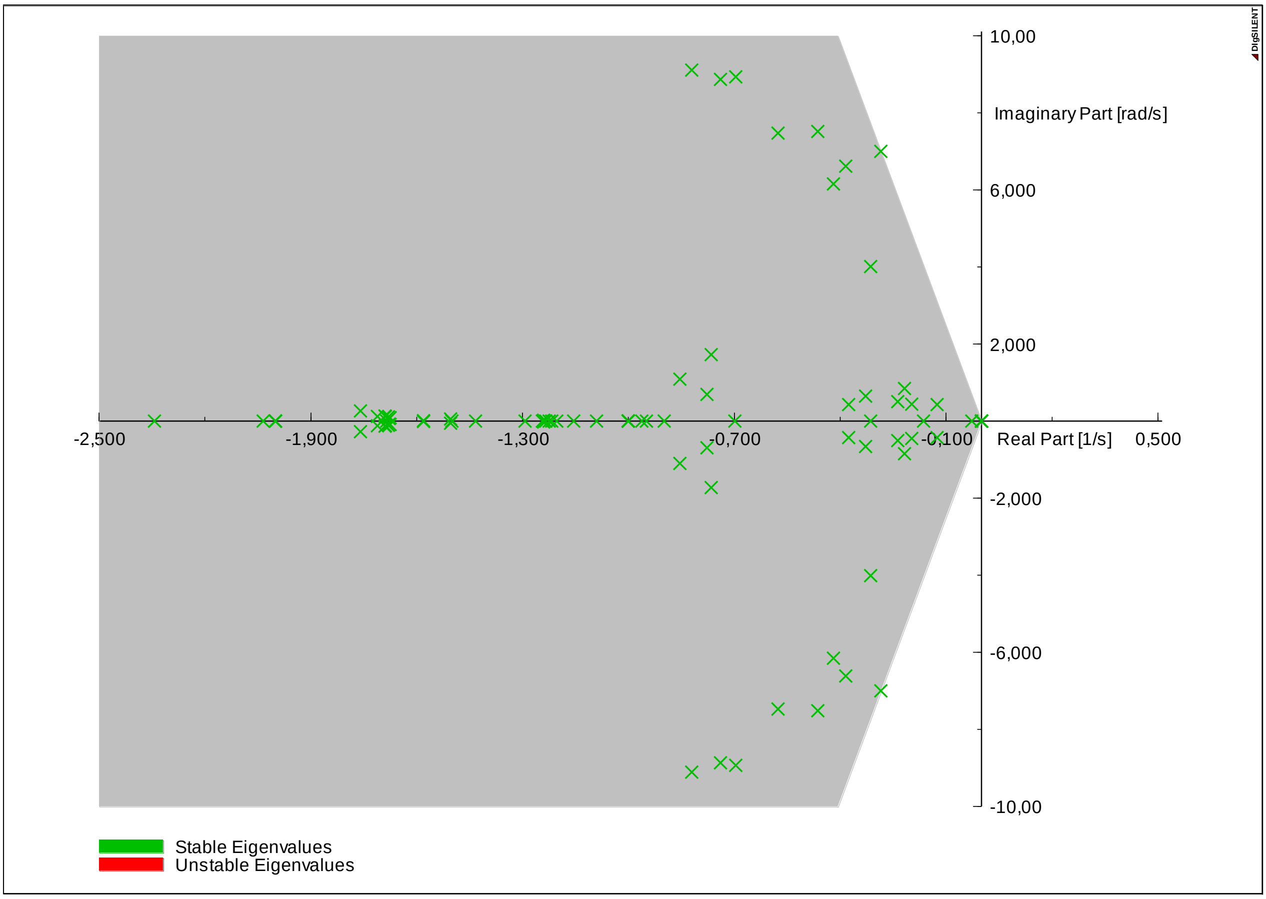

Figure 10: Eigenvalues of the 39 Bus System without Power System Stabilisers

3.3 Results for EMT Simulation

The transient response of the network model to a phase-to-phase fault is investigated in this section.

The simulation sequence is as follows:

- $t = 0\,ms$:
  Start of simulation
- $t = 200\,ms$:
  Phase-to-phase fault on phases *A* and *B* at terminal Bus 03
- $t = 300\,ms$:
  Fault clearing by isolating terminal Bus 03 (opening of corresponding circuit breakers)
- $t = 20\,s$:
  End of simulation

Figure 11 shows the simulation results presenting the angular frequency of the synchronous machine at terminal Bus30 in p.u. and output real and reactive power of the generator. As a consequence of the fault, the voltage in the system drops and results in a surplus of active power generation. This leads a increase in the angular velocity of the turbine. After fault clearing, the voltage recovers and the systems oscillates back into a stable operating condition.

The fault current at the terminals Bus 03 is shown in Figure 12. fault current initially has a peak of nearly 20 kA and decays to approximately 15 kA when the fault is cleared.

The overall system behaviour is stable. According to the simulation results, the system maintains stability, and the frequency returns to (a new) steady-state after about 20 s.

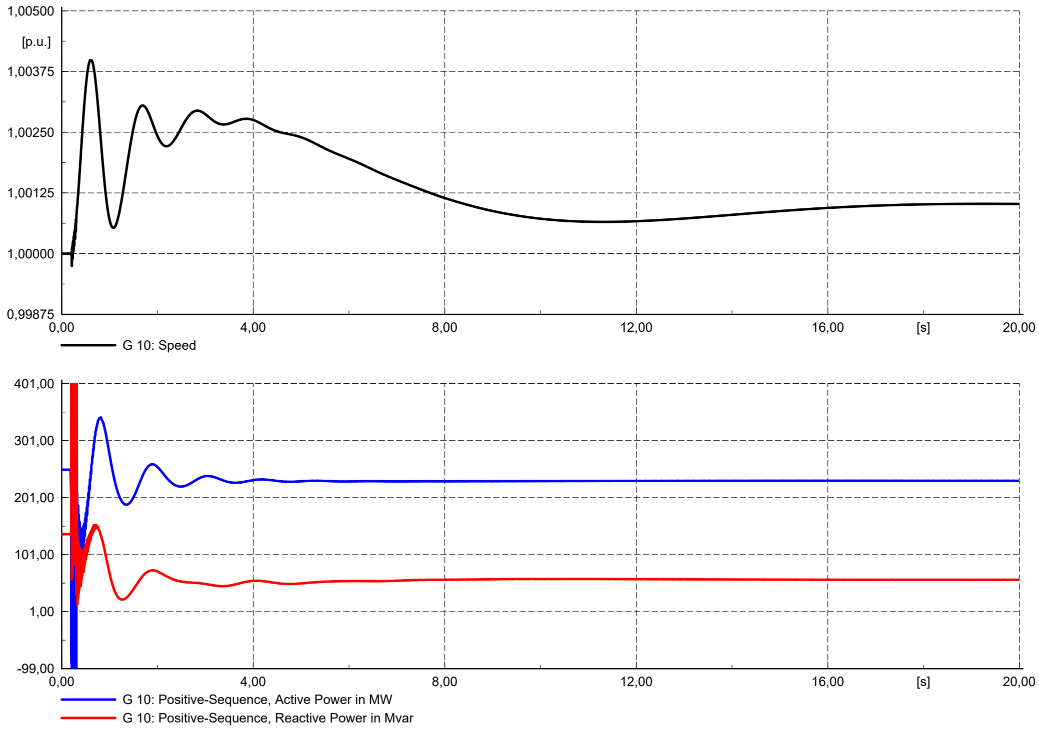

Figure 11: Response of the syncrhonous machine to a phase-to-phase fault

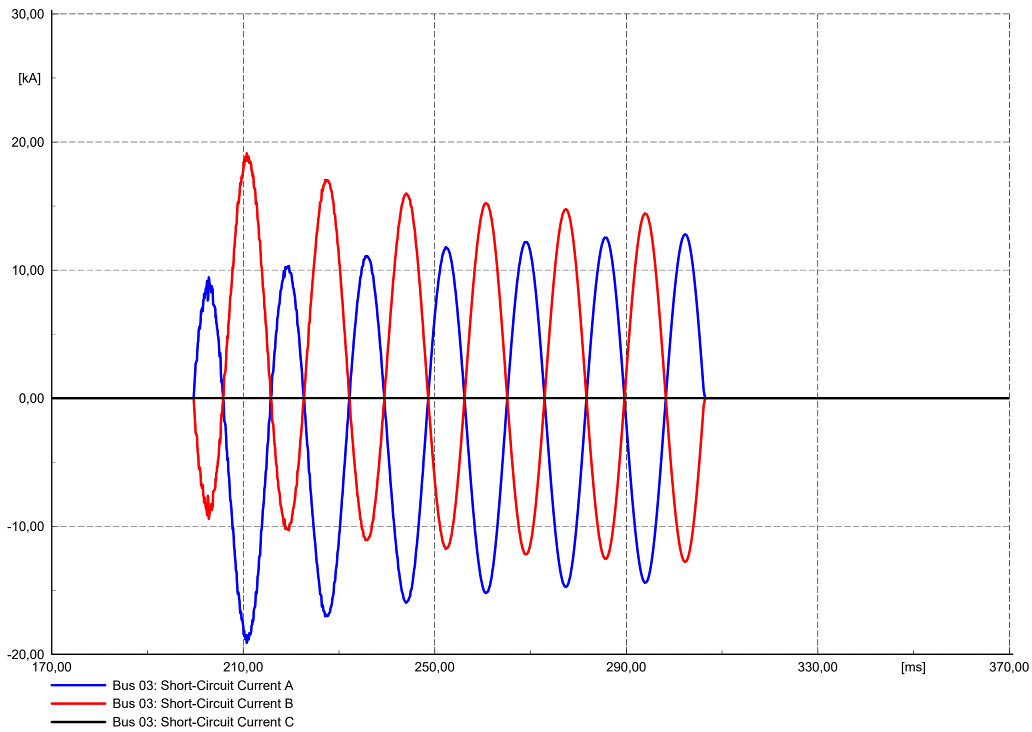

Figure 12: Fault current during the transient in phase A, B and C

References

[1] M. A. Pai: "Energy Function Analysis for Power System Stability", Kluwer Academic Publishers, Boston/Dordrecht/London, 1989, ISBN: 0-7923-9035-0, ISBN-13: 978-1-4612-8903-6

[2] T. Athay, R. Podmore, S. Virmani: "A practical method for direct analysis of transient stability", IEEE Trans. on Power Apparatus and Systems, Vol. PAS-98, No. 2, March/April 1979, pp. 573-584

[3] T. Athay, R. Podmore, S. Virmani: "Transient Energy Stability Analysis", Engineering Foundation Conference - System Engineering for Power, Henniker, New Hampshire, August 21-26, 1977

[4] G. W. Bills et al.: "On-Line Stability Analysis Study", RP90-1 Report for the Edison Electric Institute, October 12, 1970

[5] Website of the IEEE PES PSDPC SCS, Task Force on Benchmark Systems for Stability Controls, Power System Test Cases: http://www.sel.eesc.usp.br/ieee/index.htm

[6] Website of the IEEE PES PSDPC SCS, Task Force on Benchmark Systems for Stability Controls: "IEEE 10 Generator 39 Bus System", http://www.sel.eesc.usp.br/ieee/IEEE39/main.htm (downloaded in March 2014)

[7] Website of the IEEE PES PSDPC SCS, Task Force on Benchmark Systems for Stability Controls: "39 bus system Base Case" and PDF-document "39bus.out" (39bus.pdf), http://www.sel.eesc.usp.br/ieee/IEEE39/base.htm (downloaded in May 2014)

[8] CIGRE TB736: "Power System Test Cases for EMT-Type Simulation Studies", Working Group C4.503, August 2018

[9] DIgSILENT *PowerFactory* 2017: Technical Reference Documentation - General Load, Gomaringen, Germany, 2016

A Tables with Input Data

Table 1: Load demand

Load	Bus	P in MW	Q in Mvar
Load 03	Bus 03	322.0	2.4
Load 04	Bus 04	500.0	184.0
Load 07	Bus 07	233.8	84.0
Load 08	Bus 08	522.0	176.0
Load 12	Bus 12	7.5	88.0
Load 15	Bus 15	320.0	153.0
Load 16	Bus 16	329.0	32.3
Load 18	Bus 18	158.0	30.0
Load 20	Bus 20	628.0	103.0
Load 21	Bus 21	274.0	115.0
Load 23	Bus 23	247.5	84.6
Load 24	Bus 24	308.6	-92.2
Load 25	Bus 25	224.0	47.2
Load 26	Bus 26	139.0	17.0
Load 27	Bus 27	281.0	75.5
Load 28	Bus 28	206.0	27.6
Load 29	Bus 29	283.5	26.9
Load 31	Bus 31	9.2	4.6
Load 39	Bus 39	1104.0	250.0

Table 2: Generator dispatch

Generator	Bus	Bus Type	P in MW	V in p.u.
G 01	Bus 39	PV	1000.0	1.0300
G 02	Bus 31	Slack	N.A.	0.9820
G 03	Bus 32	PV	650.0	0.9831
G 04	Bus 33	PV	632.0	0.9972
G 05	Bus 34	PV	508.0	1.0123
G 06	Bus 35	PV	650.0	1.0493
G 07	Bus 36	PV	560.0	1.0635
G 08	Bus 37	PV	540.0	1.0278
G 09	Bus 38	PV	830.0	1.0265
G 10	Bus 30	PV	250.0	1.0475

Table 3: Data of lines given in [1] based on 100 MVA and 60 Hz

From Bus	To Bus	R in p.u.	X in p.u.	B in p.u.
1	2	0.0035	0.0411	0.6987
1	39	0.0010	0.0250	0.7500
2	3	0.0013	0.0151	0.2572
2	25	0.0070	0.0086	0.1460
3	4	0.0013	0.0213	0.2214
3	18	0.0011	0.0133	0.2138
4	5	0.0008	0.0128	0.1342
4	14	0.0008	0.0129	0.1382
5	6	0.0002	0.0026	0.0434
5	8	0.0008	0.0112	0.1476
6	7	0.0006	0.0092	0.1130
6	11	0.0007	0.0082	0.1389
7	8	0.0004	0.0046	0.0780
8	9	0.0023	0.0363	0.3804
9	39	0.0010	0.0250	1.2000
10	11	0.0004	0.0043	0.0729
10	13	0.0004	0.0043	0.0729
13	14	0.0009	0.0101	0.1723
14	15	0.0018	0.0217	0.3660
15	16	0.0009	0.0094	0.1710
16	17	0.0007	0.0089	0.1342
16	19	0.0016	0.0195	0.3040
16	21	0.0008	0.0135	0.2548
16	24	0.0003	0.0059	0.0680
17	18	0.0007	0.0082	0.1319
17	27	0.0013	0.0173	0.3216
21	22	0.0008	0.0140	0.2565
22	23	0.0006	0.0096	0.1846
23	24	0.0022	0.0350	0.3610
25	26	0.0032	0.0323	0.5130
26	27	0.0014	0.0147	0.2396
26	28	0.0043	0.0474	0.7802
26	29	0.0057	0.0625	1.0290
28	29	0.0014	0.0151	0.2490

Table 4: Data of lines in the *PowerFactory* model (345 kV, 60 Hz)

Line	From Bus	To Bus	Length in km	R' in Ω/km	X' in Ω/km	C' in μF/km
Line 01 - 02	Bus 01	Bus 02	163.06425	0.02554745	0.300	0.0095491
Line 01 - 39	Bus 01	Bus 39	99.18750	0.01200000	0.300	0.0168514
Line 02 - 03	Bus 02	Bus 03	59.90925	0.02582781	0.300	0.0095677
Line 02 - 25	Bus 02	Bus 25	34.12050	0.24418605	0.300	0.0095360
Line 03 - 04	Bus 03	Bus 04	84.50775	0.01830986	0.300	0.0058386
Line 03 - 18	Bus 03	Bus 18	52.76775	0.02481203	0.300	0.0090296
Line 04 - 05	Bus 04	Bus 05	50.78400	0.01875000	0.300	0.0058892
Line 04 - 14	Bus 04	Bus 14	51.18075	0.01860465	0.300	0.0060177
Line 05 - 06	Bus 05	Bus 06	10.31550	0.02307692	0.300	0.0093763
Line 05 - 08	Bus 05	Bus 08	44.43600	0.02142857	0.300	0.0074026
Line 06 - 07	Bus 06	Bus 07	36.50100	0.01956522	0.300	0.0068993
Line 06 - 11	Bus 06	Bus 11	32.53350	0.02560976	0.300	0.0095149
Line 07 - 08	Bus 07	Bus 08	18.25050	0.02608696	0.300	0.0095247
Line 08 - 09	Bus 08	Bus 09	144.02025	0.01900826	0.300	0.0058864
Line 09 - 39	Bus 09	Bus 39	99.18750	0.01200000	0.300	0.0269622
Line 10 - 11	Bus 10	Bus 11	17.06025	0.02790698	0.300	0.0095230
Line 10 - 13	Bus 10	Bus 13	17.06025	0.02790698	0.300	0.0095230
Line 13 - 14	Bus 13	Bus 14	40.07175	0.02673267	0.300	0.0095825
Line 14 - 15	Bus 14	Bus 15	86.09475	0.02488479	0.300	0.0094740
Line 15 - 16	Bus 15	Bus 16	37.29450	0.02872340	0.300	0.0102184
Line 16 - 17	Bus 16	Bus 17	35.31075	0.02359551	0.300	0.0084699
Line 16 - 19	Bus 16	Bus 19	77.36625	0.02461538	0.300	0.0087569
Line 16 - 21	Bus 16	Bus 21	53.56125	0.01777778	0.300	0.0106018
Line 16 - 24	Bus 16	Bus 24	23.40825	0.01525424	0.300	0.0064740
Line 17 - 18	Bus 17	Bus 18	32.53350	0.02560976	0.300	0.0090353
Line 17 - 27	Bus 17	Bus 27	68.63775	0.02254335	0.300	0.0104420
Line 21 - 22	Bus 21	Bus 22	55.54500	0.01714286	0.300	0.0102914
Line 22 - 23	Bus 22	Bus 23	38.08800	0.01875000	0.300	0.0108013
Line 23 - 24	Bus 23	Bus 24	138.86250	0.01885714	0.300	0.0057937
Line 25 - 26	Bus 25	Bus 26	128.15025	0.02972136	0.300	0.0089213
Line 26 - 27	Bus 26	Bus 27	58.32225	0.02857143	0.300	0.0091555
Line 26 - 28	Bus 26	Bus 28	188.05950	0.02721519	0.300	0.0092457
Line 26 - 29	Bus 26	Bus 29	247.96875	0.02736000	0.300	0.0092480
Line 28 - 29	Bus 28	Bus 29	59.90925	0.02781457	0.300	0.0092627

Table 5: Data of transformers given in [1] based on 100 MVA

From Bus	To Bus	R in p.u.	X in p.u.	Transformer Tap Magnitude in p.u.	Transformer Tap Angle in deg
12	11	0.0016	0.0435	1.0060	0.00
12	13	0.0016	0.0435	1.0060	0.00
6	31	0.0000	0.0250	1.0700	0.00
10	32	0.0000	0.0200	1.0700	0.00
19	33	0.0007	0.0142	1.0700	0.00
20	34	0.0009	0.0180	1.0090	0.00
22	35	0.0000	0.0143	1.0250	0.00
23	36	0.0005	0.0272	1.0000	0.00
25	37	0.0006	0.0232	1.0250	0.00
2	30	0.0000	0.0181	1.0250	0.00
29	38	0.0008	0.0156	1.0250	0.00
19	20	0.0007	0.0138	1.0600	0.00

Table 6: Data of transformers in the *PowerFactory* model (in addition transformer taps according to Table 5)

Trans-former	From Bus	To Bus	Sr in MVA	Ur HV in kV	Ur LV in kV	R in p.u.	X in p.u.	Z in p.u.	uk in %	ukr in %
Trf 12 - 11	Bus 12	Bus 11	300	345.0	138.0	0.0048	0.1305	0.1306	13.05882	0.480000
Trf 12 - 13	Bus 12	Bus 13	300	345.0	138.0	0.0048	0.1305	0.1306	13.05882	0.480000
Trf 06 - 31	Bus 06	Bus 31	700	345.0	16.5	0.0000	0.1750	0.1750	17.50000	0.000000
Trf 10 - 32	Bus 10	Bus 32	800	345.0	16.5	0.0000	0.1600	0.1600	16.00000	0.000000
Trf 19 - 33	Bus 19	Bus 33	800	345.0	16.5	0.0056	0.1136	0.1137	11.37379	0.560000
Trf 20 - 34	Bus 20	Bus 34	2 x 300	230.0	16.5	0.0054	0.1080	0.1081	10.81349	0.540000
Trf 22 - 35	Bus 22	Bus 35	800	345.0	16.5	0.0000	0.1144	0.1144	11.44000	0.000000
Trf 23 - 36	Bus 23	Bus 36	700	345.0	16.5	0.0035	0.1904	0.1904	19.04322	0.350000
Trf 25 - 37	Bus 25	Bus 37	700	345.0	16.5	0.0042	0.1624	0.1625	6.24543	0.420000
Trf 02 - 30	Bus 02	Bus 30	1000	345.0	16.5	0.0000	0.1810	0.1810	18.10000	0.000000
Trf 29 - 38	Bus 29	Bus 38	1000	345.0	16.5	0.0080	0.1560	0.1562	15.62050	0.800000
Trf 19 - 20	Bus 19	Bus 20	1000	345.0	230.0	0.0070	0.1380	0.1382	13.81774	0.700000

Table 7: Data of generators given in [1, 6] based on 100 MVA (subtransient data taken from [6])

Unit No.	H in s	Ra in p.u.	x'd in p.u.	x'q in p.u.	xd in p.u.	xq in p.u.	T'd0 in s	T'q0 in s	xl in p.u.	x" in p.u.	T"d0 in s	T"q0 in s
1	500.0	0.0000	0.0060	0.0080	0.0200	0.0190	7.000	0.700	0.0030	0.0040	0.050	0.035
2	30.3	0.0000	0.0697	0.1700	0.2950	0.2820	6.560	1.500	0.0350	0.0500	0.050	0.035
3	35.8	0.0000	0.0531	0.0876	0.2495	0.2370	5.700	1.500	0.0304	0.0450	0.050	0.035
4	28.6	0.0000	0.0436	0.1660	0.2620	0.2580	5.690	1.500	0.0295	0.0350	0.050	0.035
5	26.0	0.0000	0.1320	0.1660	0.6700	0.6200	5.400	0.440	0.0540	0.0890	0.050	0.035
6	34.8	0.0000	0.0500	0.0814	0.2540	0.2410	7.300	0.400	0.0224	0.0400	0.050	0.035
7	26.4	0.0000	0.0490	0.1860	0.2950	0.2920	5.660	1.500	0.0322	0.0440	0.050	0.035
8	24.3	0.0000	0.0570	0.0911	0.2900	0.2800	6.700	0.410	0.0280	0.0450	0.050	0.035
9	34.5	0.0000	0.0570	0.0587	0.2106	0.2050	4.790	1.960	0.0298	0.0450	0.050	0.035
10	42.0	0.0000	0.0310	0.0500	0.1000	0.0690	10.200	0.000	0.0125	0.0250	0.050	0.035

Table 8: Data of generators in the *PowerFactory* model (x'' = x''d = x''q)

Unit No.	Sr in MVA	H in s	Ra in p.u.	x'd in p.u.	x'q in p.u.	xd in p.u.	xq in p.u.	T'd0 in s	T'q0 in s	xl in p.u.	x'' in p.u.	T''d0 in s	T''q0 in s
1	10000	5.000	0.0000	0.6000	0.8000	2.0000	1.9000	7.000	0.7000	0.3000	0.4000	0.050	0.035
2	700	4.329	0.0000	0.4879	1.1900	2.0650	1.9740	6.560	1.5000	0.2450	0.3500	0.050	0.035
3	800	4.475	0.0000	0.4248	0.7008	1.9960	1.8960	5.700	1.5000	0.2432	0.3600	0.050	0.035
4	800	3.575	0.0000	0.3488	1.3280	2.0960	2.0640	5.690	1.5000	0.2360	0.2800	0.050	0.035
5	300	4.333	0.0000	0.3960	0.4980	2.0100	1.8600	5.400	0.4400	0.1620	0.2670	0.050	0.035
6	800	4.350	0.0000	0.4000	0.6512	2.0320	1.9280	7.300	0.4000	0.1792	0.3200	0.050	0.035
7	700	3.771	0.0000	0.3430	1.3020	2.0650	2.0440	5.660	1.5000	0.2254	0.3080	0.050	0.035
8	700	3.471	0.0000	0.3990	0.6377	2.0300	1.9600	6.700	0.4100	0.1960	0.3150	0.050	0.035
9	1000	3.450	0.0000	0.5700	0.5870	2.1060	2.0500	4.790	1.9600	0.2980	0.4500	0.050	0.035
10[a]	1000	4.200	0.0000	0.3100	—	1.0000	0.6900	10.200	—	0.1250	0.2500	0.050	0.035

[a] Generator “G 10” is entered as machine with salient pole rotor type in *PowerFactory*, because T'q0 is given as 0.000, see Table 7. Therefore T'q0 and x'q do not apply for “G 10” in the *PowerFactory* example.

Table 9: Data of AVRs in the *PowerFactory* model, taken from [1]

Unit No.	Ka $= K_{\mathrm{A}}$	Ta $= T_{\mathrm{A}}$	Vrmin $= V_{\mathrm{Rmin}}$	Vrmax $= V_{\mathrm{Rmax}}$	Ke $= K_{\mathrm{E}}$	Te $= T_{\mathrm{E}}$	Kf $= K_{\mathrm{F}}$	Tf $= T_{\mathrm{F}}$	Se1 $= C_1$	Se2 $= C_2$	E1 $= EX_1$	E2 $= EX_2$
2	6.2	0.05	-1.0	1.0	-0.6330	0.405	0.0570	0.500	0.660	0.880	3.036437	4.048583
3	5.0	0.06	-1.0	1.0	-0.0198	0.500	0.0800	1.000	0.130	0.340	2.342286	3.123048
4	5.0	0.06	-1.0	1.0	-0.0525	0.500	0.0800	1.000	0.080	0.314	2.868069	3.824092
5	40.0	0.02	-10.0	10.0	1.0000	0.785	0.0300	1.000	0.070	0.910	3.926702	5.235602
6	5.0	0.02	-1.0	1.0	-0.0419	0.471	0.0754	1.246	0.064	0.251	3.586801	4.782401
7	40.0	0.02	-6.5	6.5	1.0000	0.730	0.0300	1.000	0.530	0.740	2.801724	3.735632
8	5.0	0.02	-1.0	1.0	-0.0470	0.528	0.0854	1.260	0.072	0.282	3.191489	4.255319
9	40.0	0.02	-10.5	10.5	1.0000	1.400	0.0300	1.000	0.620	0.850	4.256757	5.675676
10	5.0	0.06	-1.0	1.0	-0.0485	0.250	0.0400	1.000	0.080	0.260	3.546099	4.728132

B Tables with Results for Steady-State Power Flow

Table 10: Results for bus voltages

Bus Name	*PowerFactory* Results		Results provided by [7]		Differences	
	u, Magn. in p.u.	u, Angle in deg	u, Magn. in p.u.	u, Angle in deg	u, Magn. in p.u.	u, Angle in deg
Bus 01	1.0474	-8.44	1.0474	-8.44	0.0000	0.00
Bus 02	1.0487	-5.75	1.0487	-5.75	0.0000	0.00
Bus 03	1.0302	-8.60	1.0302	-8.60	0.0000	0.00
Bus 04	1.0039	-9.61	1.0039	-9.61	0.0000	0.00
Bus 05	1.0053	-8.61	1.0053	-8.61	0.0000	0.00
Bus 06	1.0077	-7.95	1.0077	-7.95	0.0000	0.00
Bus 07	0.9970	-10.12	0.9970	-10.12	0.0000	0.00
Bus 08	0.9960	-10.62	0.9960	-10.62	0.0000	0.00
Bus 09	1.0282	-10.32	1.0282	-10.32	0.0000	0.00
Bus 10	1.0172	-5.43	1.0172	-5.43	0.0000	0.00
Bus 11	1.0127	-6.28	1.0127	-6.28	0.0000	0.00
Bus 12	1.0002	-6.24	1.0002	-6.24	0.0000	0.00
Bus 13	1.0143	-6.10	1.0143	-6.10	0.0000	0.00
Bus 14	1.0117	-7.66	1.0117	-7.66	0.0000	0.00
Bus 15	1.0154	-7.74	1.0154	-7.74	0.0000	0.00
Bus 16	1.0318	-6.19	1.0318	-6.19	0.0000	0.00
Bus 17	1.0336	-7.30	1.0336	-7.30	0.0000	0.00
Bus 18	1.0309	-8.22	1.0309	-8.22	0.0000	0.00
Bus 19	1.0499	-1.02	1.0499	-1.02	0.0000	0.00
Bus 20	0.9912	-2.01	0.9912	-2.01	0.0000	0.00
Bus 21	1.0318	-3.78	1.0318	-3.78	0.0000	0.00
Bus 22	1.0498	0.67	1.0498	0.67	0.0000	0.00
Bus 23	1.0448	0.47	1.0448	0.47	0.0000	0.00
Bus 24	1.0373	-6.07	1.0373	-6.07	0.0000	0.00
Bus 25	1.0576	-4.36	1.0576	-4.36	0.0000	0.00
Bus 26	1.0521	-5.53	1.0521	-5.53	0.0000	0.00
Bus 27	1.0377	-7.50	1.0377	-7.50	0.0000	0.00
Bus 28	1.0501	-2.01	1.0501	-2.01	0.0000	0.00
Bus 29	1.0499	0.74	1.0499	0.74	0.0000	0.00
Bus 30	1.0475	-3.33	1.0475	-3.33	0.0000	0.00
Bus 31	0.9820	0.00	0.9820	0.00	0.0000	0.00
Bus 32	0.9831	2.57	0.9831	2.57	0.0000	0.00
Bus 33	0.9972	4.19	0.9972	4.19	0.0000	0.00
Bus 34	1.0123	3.17	1.0123	3.17	0.0000	0.00
Bus 35	1.0493	5.63	1.0493	5.63	0.0000	0.00
Bus 36	1.0635	8.32	1.0635	8.32	0.0000	0.00
Bus 37	1.0278	2.42	1.0278	2.42	0.0000	0.00
Bus 38	1.0265	7.81	1.0265	7.81	0.0000	0.00
Bus 39	1.0300	-10.05	1.0300	-10.05	0.0000	0.00

Table 11: Results for generators

Unit No.	*PowerFactory* Results P in MW	*PowerFactory* Results Q in Mvar	Results provided by [7] P in MW	Results provided by [7] Q in Mvar	Differences P in MW	Differences Q in Mvar
1	1000.00	88.28	1000.00	88.28	0.00	0.00
2	520.81	198.25	520.81	198.25	0.00	0.00
3	650.00	$205.1444 \approx 205.14$	650.00	205.15	0.00	-0.01
4	632.00	109.91	632.00	109.91	0.00	0.00
5	508.00	165.76	508.00	165.76	0.00	0.00
6	650.00	212.41	650.00	212.41	0.00	0.00
7	560.00	$101.1750 \approx 101.18$	560.00	101.17	0.00	+0.01
8	540.00	0.44	540.00	0.44	0.00	0.00
9	830.00	22.84	830.00	22.84	0.00	0.00
10	250.00	146.16	250.00	146.16	0.00	0.00
Sum	6140.81	1250.37	6140.81	1250.37	0.00	0.00

Table 12: Grid summary

	Generation		Load		Losses		Mismatch	
	P in MW	Q in Mvar	P in MW	Q in Mvar	P in MW	Q in Mvar	P in MW	Q in Mvar
***PowerFactory* Results**	6140.81	1250.37	6097.10	1408.90	43.71	-158.53	0.00	0.00
Results provided by [7]	6140.81	1250.37	6097.10	1408.90	43.71	-158.52	0.00	-0.01

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