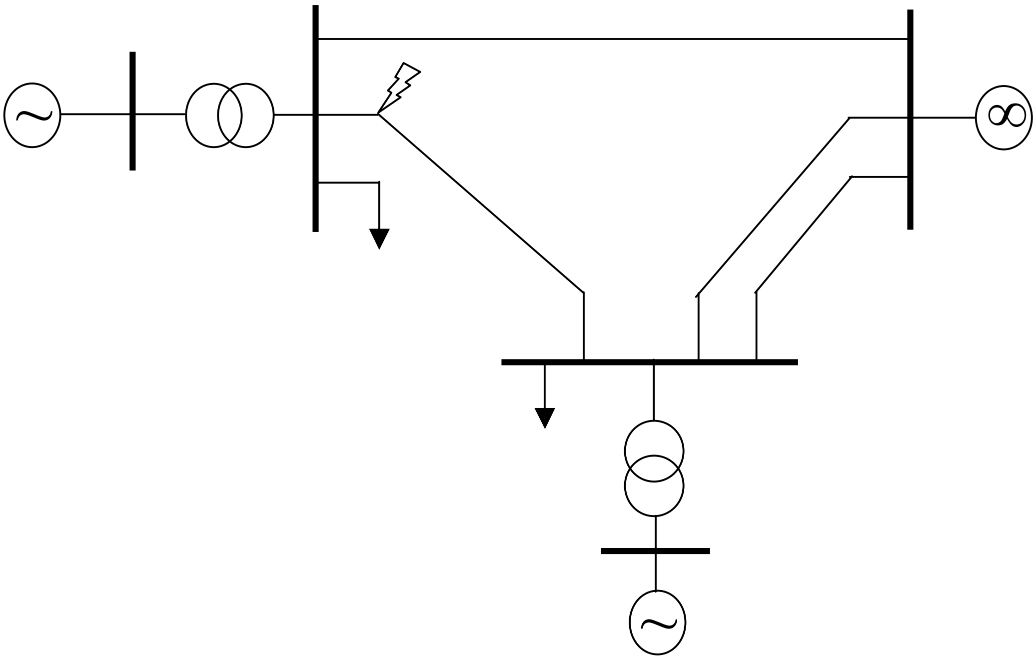
Grainger's Five Bus System



Five bus system used to demonstrate the
power system simulation software SIMPOW®

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"Power System Analysis", John J. Grainger & William D. Stevenson, Jr., page 729. Example 16.9 - Five Bus System[1]

A 60-Hz, 230-kV transmission system has two generators of finite inertia and an infinite production at bus 3. A solid three-phase fault occurs on line 4-5 near bus 4, see figure 1.

In the example, the swing curves for the two synchronous machines, $\delta(t)$, are shown for two values of fault clearing time; 0.225 and 0.050 s. For 0.225 s the system does not return to steady state (synchronism).

Also equal-area figures for one of the synchronous machines can be found at the last page of the example.

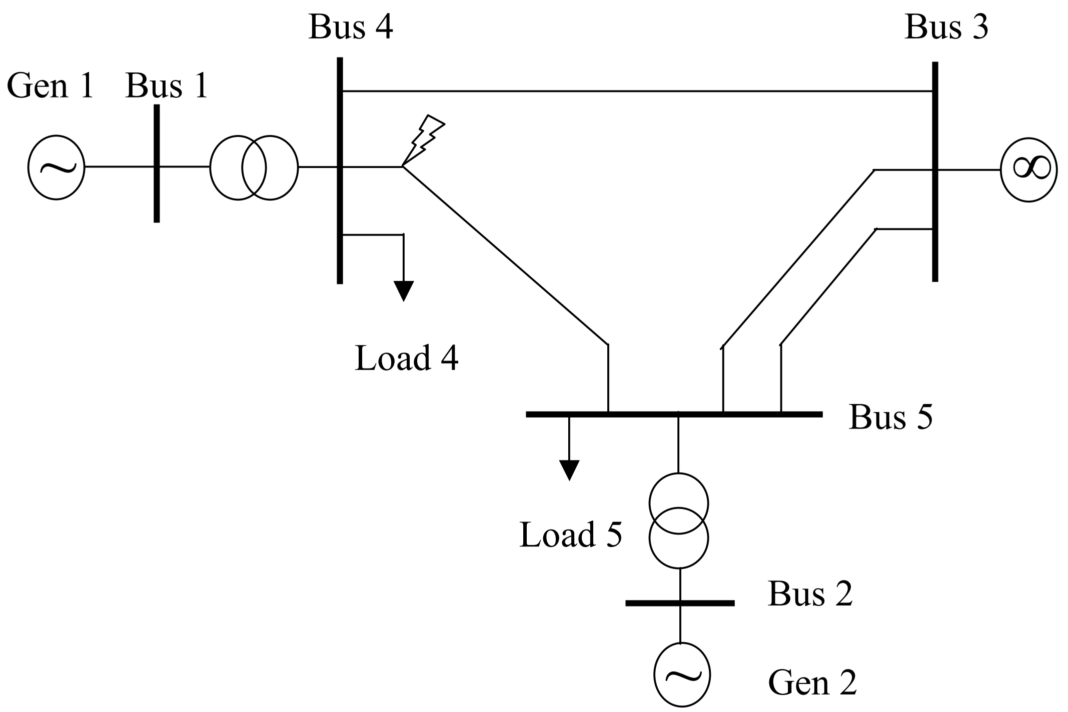

Figure 1. Single-line diagram of the Five Bus System.

Line and transformer data are given in table 1.

Table 1. Line and transformer data [$]

Bus to bus	Series Z	Shunt Y
Transformer 1 – 4	0 + j0.022	
Transformer 2 – 5	0 + j0.040	
Line 3 – 4	0.007 + j0.040	0 + j0.082

[1] McGraw-Hill Inc. ISBN: 0070612935, 1994.

Line 3 – 5, #1	0.008 + j0.047	0 + j0.098
Line 3 – 5, #2	0.008 + j0.047	0 + j0.098
Line 4 – 5	0.018 + j0.110	0 + j0.226

$ All values in per unit on 230-kV, 100-MVA base.

In the power flow, loads are modeled with constant power character and the generations at bus 1 and 2 are modeled as PQ-nodes. Bus 3 is a slack bus. Table 2 shows the power-flow settings of productions and loads for the system. Values in brackets are power-flow results from the textbook. Corresponding results from the Simpow calculation can be found in table 3.

Table 2. Power-flow settings of productions and loads $

Bus	Voltage	Generation, P + jQ	Load, P + jQ
1	(1.030 ∠ 8.88°)	3.5 + j0.712	
2	(1.020 ∠ 6.38°)	1.85 + j0.298	
3	1.000 ∠ 0°		
4	(1.018 ∠ 4.68°)		1.00 + j0.44
5	(1.011 ∠ 2.27°)		0.50 + j0.16

$ All values in per unit on 230-kV, 100-MVA base.

Power flow

The corresponding results from the power flow calculated in Simpow are shown in table 3.

Table 3. Power-flow results from Simpow $

Bus	Voltage	Generation, P + jQ	Load, P + jQ
1	**1.030 ∠ 8.90°**	3.5 + j0.712	
2	**1.020 ∠ 6.39°**	1.85 + j0.298	
3	1.000 ∠ 0°		
4	**1.018 ∠ 4.68°**		1.00 + j0.44
5	**1.011 ∠ 2.27°**		0.50 + j0.16

$ All values in per unit on 230-kV, 100-MVA base.

As can be seen, the voltages calculated with Simpow are the same as calculated in the textbook, see table 2. The calculated voltages are written in bold in table 3.

Dynamic simulation

In the dynamic simulation, both the fault and the line between bus 4 and 5 are disconnected at the same time.

The synchronous machines are modeled as constant voltages behind a transient reactance and without any exciter, governor or turbine, i.e. the synchronous machines are modeled as classical models.

Table 4. Generator data [+]

Generator	SN (MVA)	UN (kV)	$X_d^{'}$ (p.u.)	H (MJ/MVA)
1	400	20	0.067	11.2
2	250	18	0.100	8.0

[+] Values in per unit on 20-kV, 100-MVA base.

It is more common to give generator data in p.u. of each machine's rating, therefore the table below shows generator data in p.u. of each machine base which is the input data in the Dynpow file of Simpow.

Table 5. Generator data in per unit of each machine base [@]

Generator	SN (MVA)	UN (kV)	$X_d^{'}$ (p.u.)	H (MJ/MVA)
1	400	20	0.268	2.80
2	250	18	0.308642	3.20

[@] Values in per unit on machine voltage (20 resp. 18 kV) and machine rated power (400 resp. 250 MVA).

Swing curves of the synchronous machines

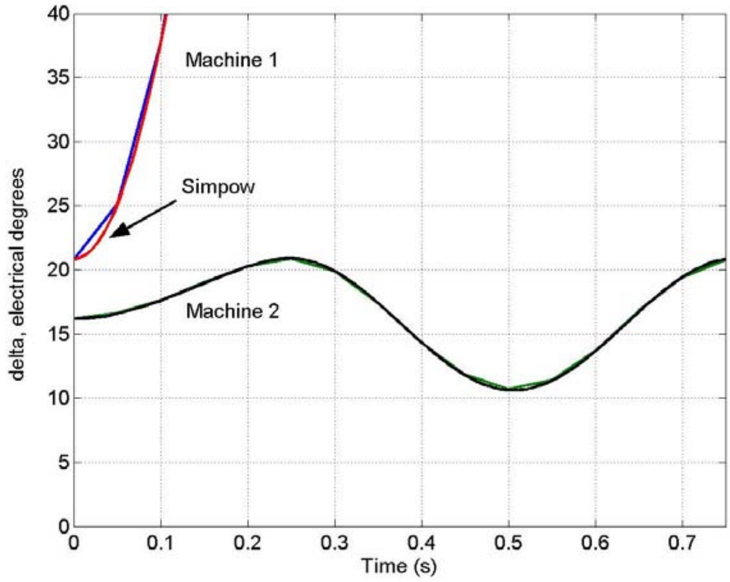

Figure 2. Swing curves for machines 1 and 2 when clearing the fault at 0.225 s. Results from both the textbook and Simpow are shown and there are no discrepancies between the textbook and Simpow except for the first 0.05 s where the reader can see that the results from the textbook are generated with a fixed time step of 0.05 s while Simpow uses a variable time step. See corresponding figure 16.15 in the textbook and table 6 below.

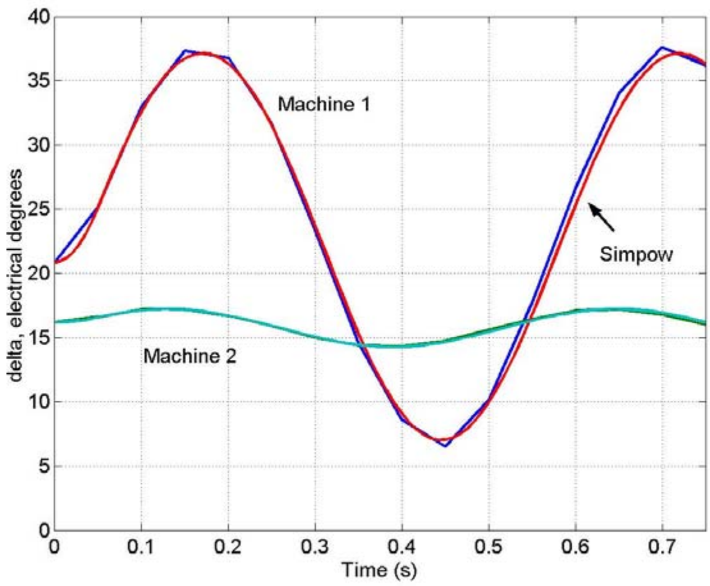

Figure 3. Swing curves for machines 1 and 2 when clearing the fault at 0.050 s. Results from both the textbook and Simpow are shown. See also table 6.

In figure 3 it is a small discrepancy for machine 1 between the swing-curve in the textbook and in Simpow. The following factors are influences for the difference between the textbook and Simpow:

- In the textbook the fixed time step 0.05 s is used, in Simpow a variable time step is used.
- In the textbook, the used integration method is a fourth-order Runge-Kutta procedure while in Simpow the trapezoidal method is used in combination with Gear's method.[2]

Table 6. Computer print-out of swing curves for machines 1 and 2 when clearing the fault at 0.225 and 0.050 s. Values in brackets are corresponding results from Simpow. See also figures 2 and 3.

	Clearing at 0.225 s		Clearing at 0.050 s	
Time	Machine 1 angle (degrees)	Machine 2 angle (degrees)	Machine 1 angle (degrees)	Machine 2 angle (degrees)
0.00	20.8 (20.8)	16.2 (16.2)	20.8 (20.8)	16.2 (16.2)
0.05	25.1 (25.0)	16.6 (16.6)	25.1 (25.1)	16.6 (16.6)
0.10	37.7 (37.7)	17.6 (17.6)	32.9 (32.8)	17.2 (17.1)
0.15	58.7 (58.7)	19.0 (19.0)	37.3 (36.8)	17.2 (17.2)
0.20	88.1 (88.3)	20.3 (20.2)	36.8 (36.3)	16.7 (16.7)
0.25	123.1 (123.7)	20.9 (20.9)	31.7 (31.5)	15.9 (15.9)
0.30	151.1 (152.0)	19.9 (19.9)	23.4 (23.7)	15.0 (15.0)
0.35	175.5 (177.3)	17.4 (17.4)	14.6 (15.3)	14.4 (14.4)
0.40	205.1 (208.2)	14.3 (14.3)	8.6 (9.0)	14.3 (14.3)
0.45	249.9 (255.3)	11.8 (11.8)	6.5 (7.0)	14.7 (14.7)
0.50	319.3 (327.3)	10.7 (10.6)	10.1 (10.0)	15.6 (15.4)
0.55	407.0 (415.5)	11.4 (11.3)	17.7 (16.8)	16.4 (16.3)
0.60	489.9 (497.5)	13.7 (13.7)	26.6 (25.3)	17.1 (17.0)
0.65	566.0 (574.0)	16.8 (16.7)	34.0 (32.7)	17.2 (17.2)
0.70	656.4 (667.0)	19.4 (19.4)	37.6 (36.8)	16.8 (16.9)
0.75	767.7 (779.2)	20.8 (20.8)	36.2 (36.2)	16.0 (16.2)

[2] Gear's method is used for variables that have a 'stiff' relation with its environment. With 'stiff' is meant that it only changes if the environment is changed. Gear's method is rather simple and therefore it demands low computational effort.

The trapezoidal method is used for variables that have a 'non-stiff' relation with its environment. With 'non-stiff' is meant that it may change even though the environment is not changed. The trapezoidal method is more complex than Gear's method and therefore it demands higher computational effort.

Another name for Gear's method that can be found in the literature is backward differentiation method.

Power-angle curves of synchronous machine 1

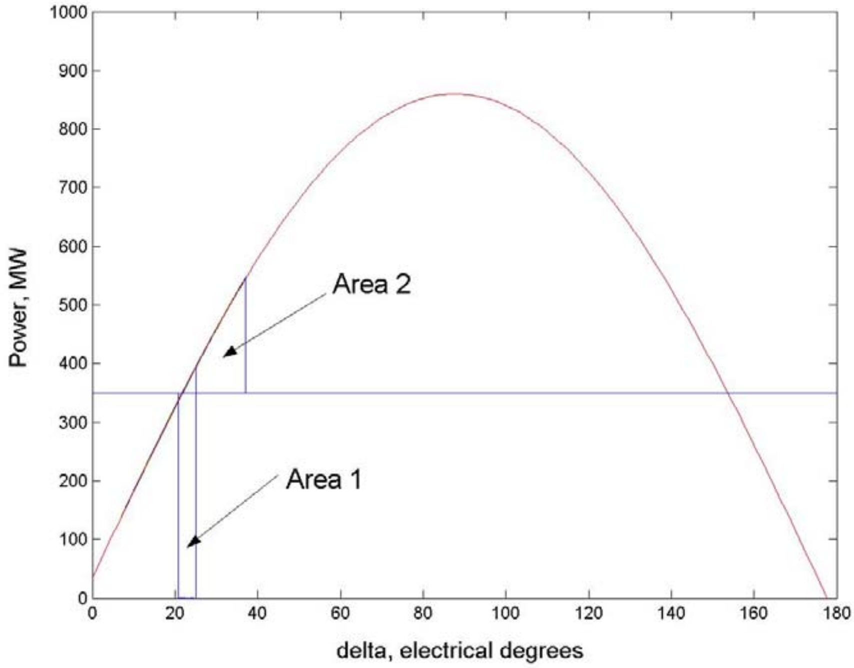

Figure 4. Power-angle curve for synchronous machine 1 with clearing time 0.050 s. Area 1 are equal Area 2, see also figure 5. Values are generated from Simpow.

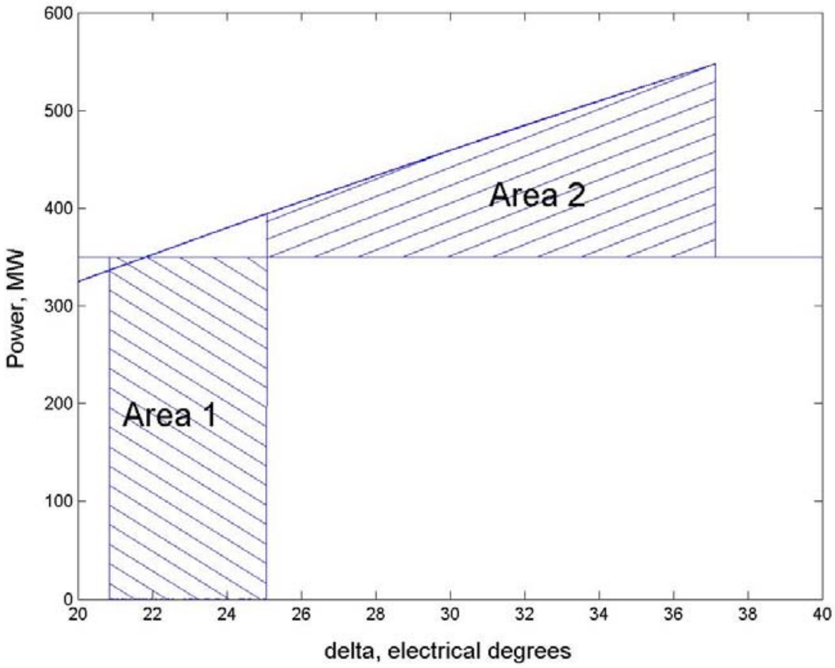

Figure 5. A focused power-angle curve for synchronous machine 1 with clearing time 0.050 s. Area 1 are equal Area 2.