Islanding of 24-bus IEEE Reliability Test System

Paul Trodden

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1 Introduction

The IEEE RTS [1] comprises 24 buses and 38 lines. Of the buses, 17 have loads attached, and the total real power demand is 2850 MW. Generation capacity is 3405 MW from 32 synchronous generators; in addition, there is one synchronous condenser at bus 14.

2 Scenario description

In [2], a number of most-likely contingency scenarios are determined for the RTS, under a set of specified assumptions. The most probable collapse sequence is found to be the consecutive tripping of the transmission line between bus 15 and bus 24 and the line between bus 3 and bus 9. The authors show that load flow computations subsequently fail, since the system fails to supply the load at bus 3.

In this section, we simulate this collapse sequence, and show that further failure may be prevented by a combination of islanding and load shedding. The simulation proceeds as follows. We assume that the line $(15, 24)$ has tripped, and study the network immediately after this first failure. Line $(3, 9)$ is marked as uncertain (and assigned to set $\mathcal{L}_0$), as are bus 3 and bus 24, which are assigned to $\mathcal{B}_0$. No buses are assigned to $\mathcal{B}_1$. Figure

We constrain the generators so that, for each, real power output may either be held at the current operating level or instantaneously decreased to zero. On the other hand, reactive power output may be set to any value between limits for the generator. The current (post-failure) operating point is obtained from solution of a DC OPF. Table 1 shows the generator outputs at nominal operation; the total cost of this generation is \$61k per hour.

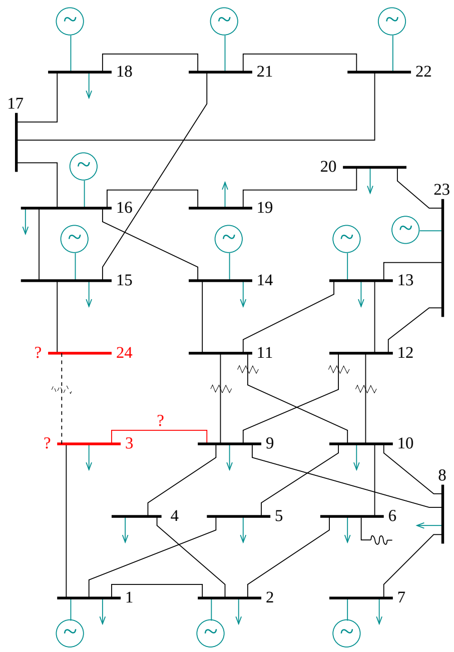


Figure 1: 24-bus IEEE RTS, with line $(3, 24)$ tripped and buses $3, 24$ and line $(3, 9)$ uncertain.

g	b	$P_g^{\mathcal{G}}$ (MW)
1	1	16
2	1	16
3	1	76
4	1	76
5	2	16
6	2	16
7	2	76
8	2	76
9	7	57.1
10	7	57.1
11	7	57.1
12	13	76.3
13	13	76.3
14	13	76.3
15	14	0

(a) Buses 1–14

g	b	$P_g^{\mathcal{G}}$ (MW)
16	15	2.4
17	15	2.4
18	15	2.4
19	15	2.4
20	15	2.4
21	15	155
22	16	155
23	18	400
24	21	400
25	22	50
26	22	50
27	22	50
28	22	50
29	22	50
30	22	50
31	23	155
32	23	155
33	23	350

(b) Buses 15–24

Table 1: Generator outputs at nominal operation

3 Islanding solution

The islanding solution depends on the value of β_d. For $\beta_d = 0.5, \forall d$, the solution is described as follows.

- Lines $(1, 3)$ and $(3, 9)$ have been disconnected, islanding the uncertain buses 3 and 24 in Section 0.
- No generators are present in Section 0, so the load at bus 3 is fully shed.
- The following generators have been switched off
  - One of the two 16 MW generators at bus 2.
  - Four of the five 2.4 MW generators at bus 15. The 155 MW generator at that bus remains.
  - The 155 MW generator at bus 16.
- Consequently, the only load shed in Section 1 at bus 9, where 174.4 MW is supplied against an original demand of 175 MW.

4 Dynamic simulation

This section describes dynamic simulations of the network, from post-fault operation to the situation after islanding. Although the islanding formulation uses a DC model, the simulated network is AC, necessitating the determination of AC operating conditions both prior to and after islanding. Thus, the following sequence of operations is used to determine the parameters for time domain simulation.

1. *Post-failure:* Solve an AC optimal power flow (OPF) with the same penalties on real power generation as for the DC OPF. This provides the **pre-islanding AC operating point**, which differs from the DC solution in that generation is higher (to account for losses), voltages may be off nominal, and reactive power flows are non-zero.
2. *Islanding:* Disconnect lines as proposed by the (DC) islanding optimization.
3. *Post-islanding:* Solve an AC optimal load shedding optimization on the islanded network with the following equality constraints on real power output of generators
   - If the DC islanding optimization switched 'off' generator g, $p_g^{\mathcal{G}} = 0$.
   - Else generator g is constrained to operate at its pre-islanding operating point: $p_g^{\mathcal{G}} = P_g^{\mathcal{G},\text{pre-islanding}}$.

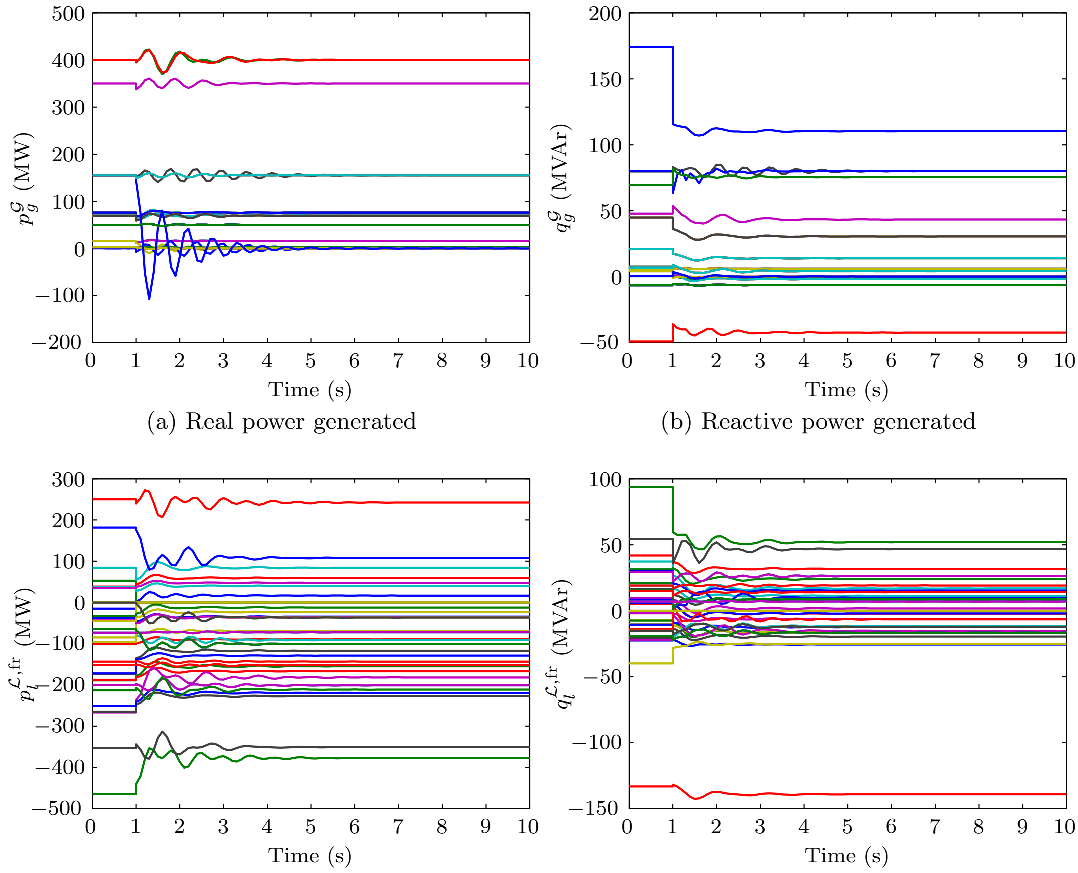
   The reactive power is permitted to vary between limits. This determines the **post-islanding AC operating point**, and includes – among other things – the correct proportion of loads to shed at each bus.

The time domain simulation is executed between the two operating points. Dynamic data for the generators may be found in [3]; the synchronous machines are assumed be governed by second-order, lossless dynamics, with varying magnitudes of inertia depending on the rated output of each machine. Since a lossless, undamped machine is not realistic, we have assumed a damping coefficient $D = 15$ for each machine.

The switching 'off' of generators is simulated by reducing to zero their mechanical power inputs instantanously. Thus, the machines remain electrically connected to the network, and reactive power output changes are realized by changing the field voltages. Lines are disconnected by use of the "breaker" feature in PSAT, which trips a line at some user-specified time. Loads are shed instaneously upon request.

Results for the solution corresponding to $\beta = 0.5$ – the islanding of buses 3 and 24 are shown in Figures 2–6. Salient points are as follows:

- The islanding solution is transient stable, both in terms of frequency and voltage.
- Generator frequencies oscillate but all settle to 1 p.u. (60 Hz).
- The largest swings are associated with the generators at buses 15 and 16 and the line between, with fast (≈ 2 Hz) oscillations.
  - The 182 MVA generator at bus 16 is switched off; the zeroing of mechanical input power leads to large swings in the electrical power output around zero.
  - The 182 MVA generator at bus 15 maintains its mechanical input power at 155 MW; the electrical output swings about this value.
  - The line $(15, 16)$ – which carried 250 MW from 15 to 16 prior to islanding – swings wildly before settling at a value close to 240 MW.
- Buses 18, 21 and 23 – associated with the largest generators – also see quite large swings, despite none of these generators being switched.
- Voltages temporarily violate upper limits, before settling. (Note that the two very low voltages – at buses 3 and 24 – are irrelevant, since no load or generation is present in this island.



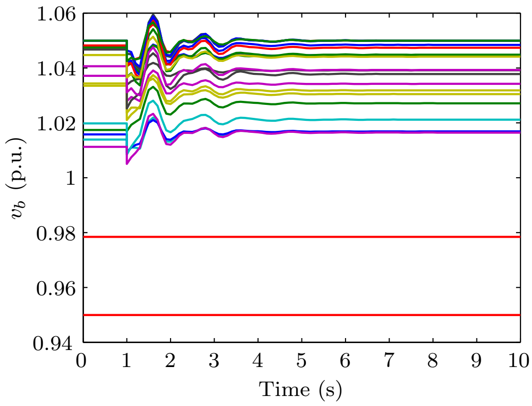
(a) Real power generated

(b) Reactive power generated

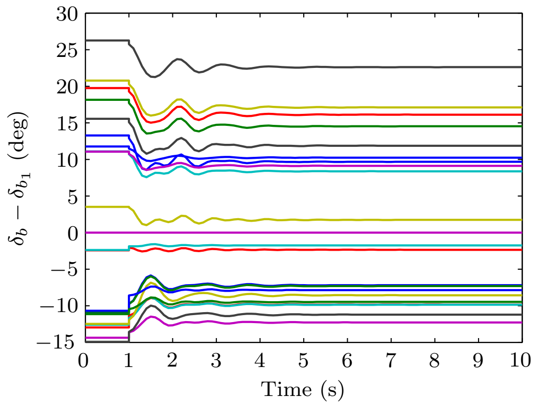
(c) Line real power flows

(d) Line reactive power flows

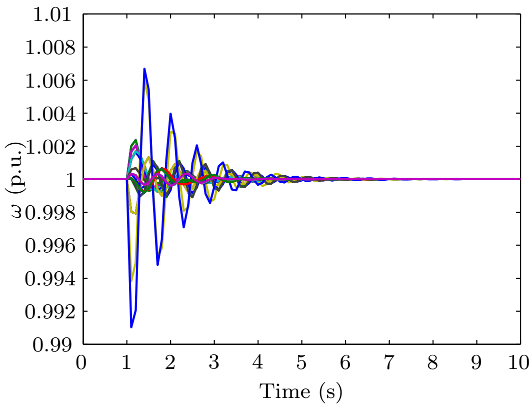
Figure 2: Dynamic simulation results for islanding of buses 3 and 24.



(e) Bus voltages

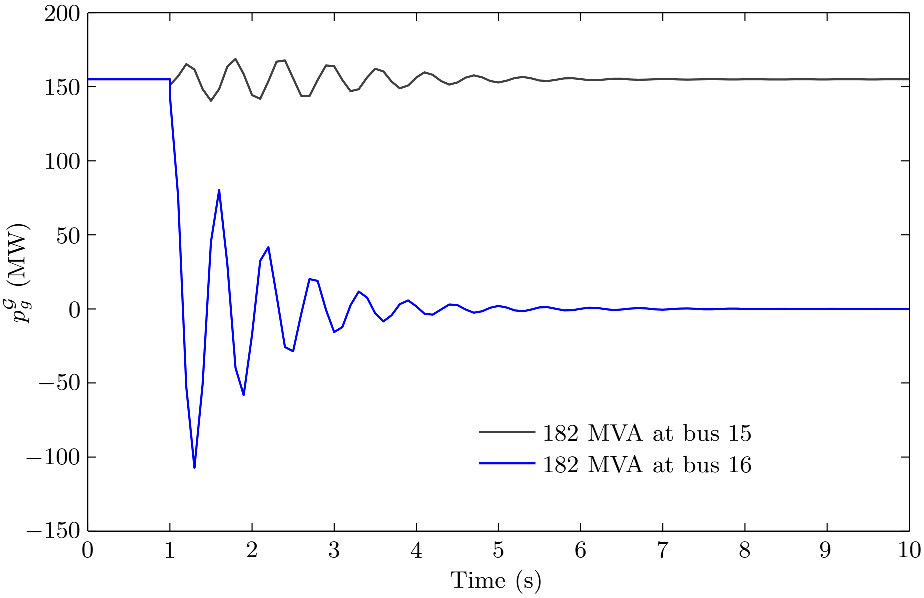


(f) Bus relative phase angles

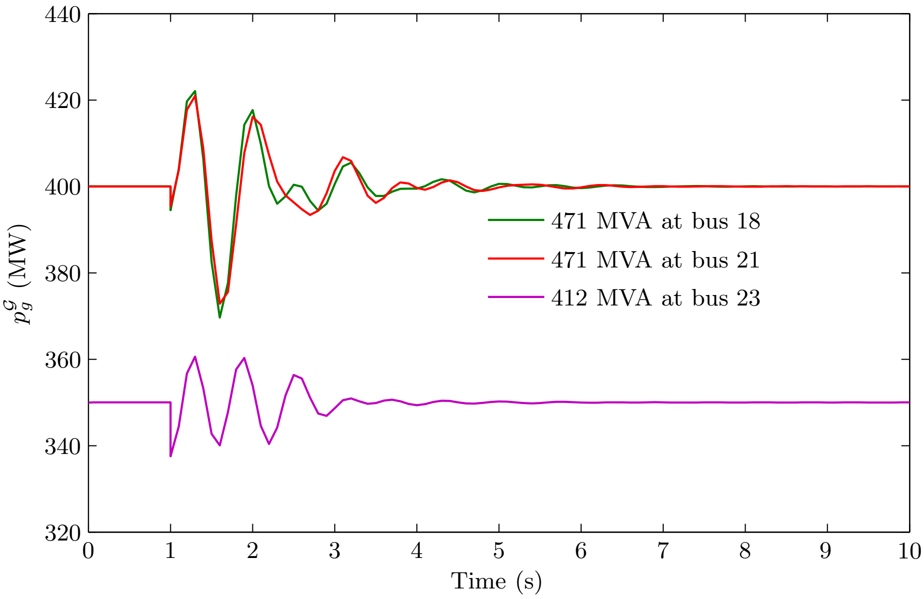


(g) Angular frequencies

Figure 2: (continued) Dynamic simulation results for islanding of buses 3 and 24.



(a) Real power outputs of generators at buses 15 and 16



(b) Real power outputs of generators at buses 18, 21 and 23

Figure 3: Generator swings as a consequence of breaking line $(15, 24)$ and switching off the 182 MVA generator at bus 16.

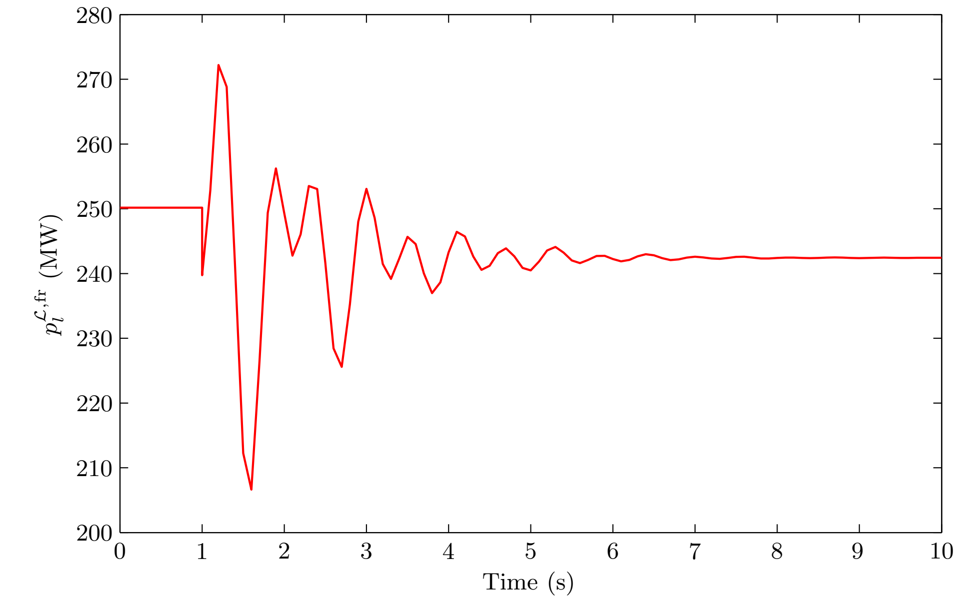


Figure 4: Power swings on line $(15, 16)$ as a consequence of breaking line $(15, 24)$ and switching off the 182 MVA generator at bus 16.

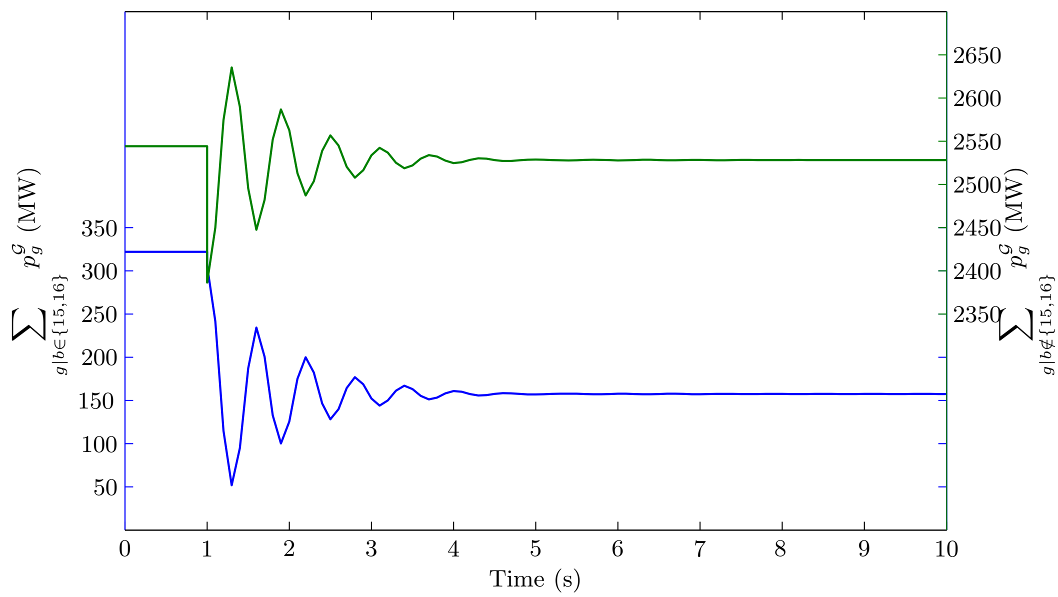
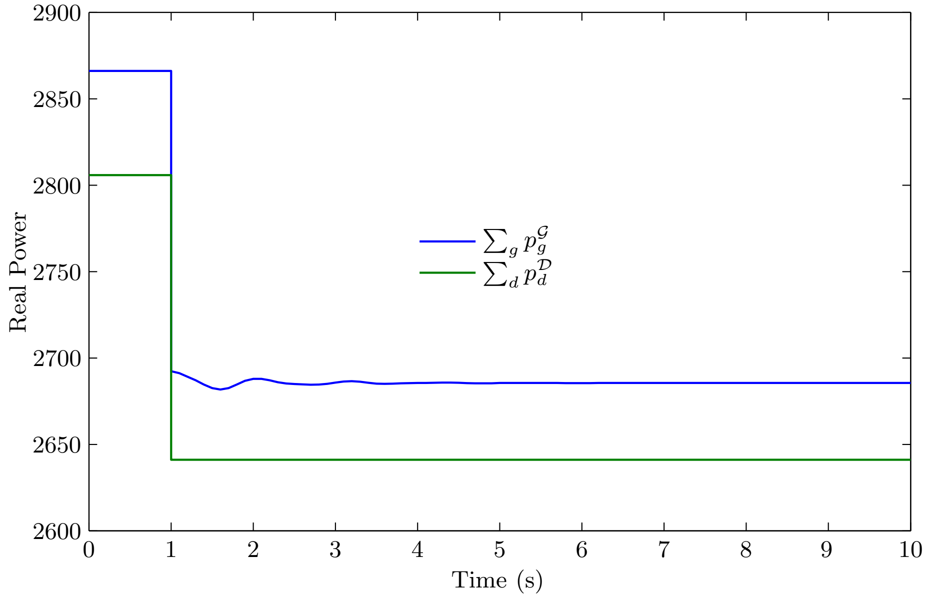
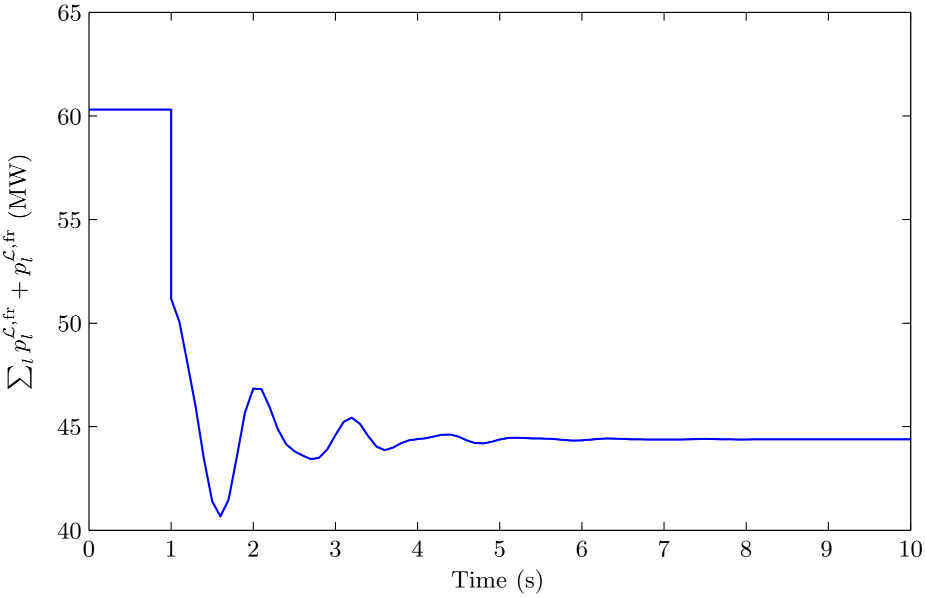


Figure 5: Comparison of total real power generation at buses 15 and 16 with generation from all other buses.

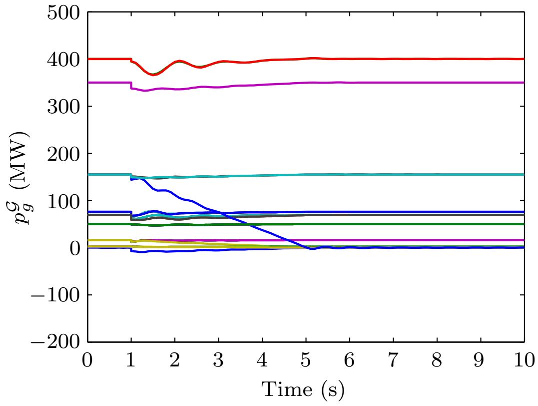


(a) Total real power generation and demand

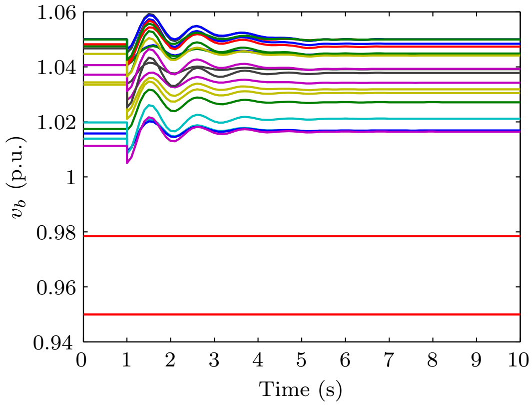


(b) Total real power line losses

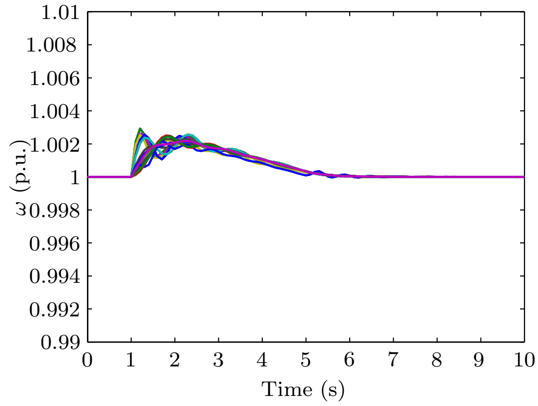
Figure 6: Real power in the network: total generation, demand, and losses.



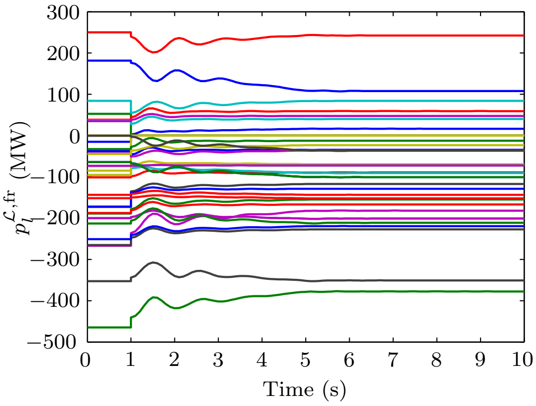
(a) Real power output generated



(b) Bus voltages



(c) Angular frequency



(d) Line real power flows

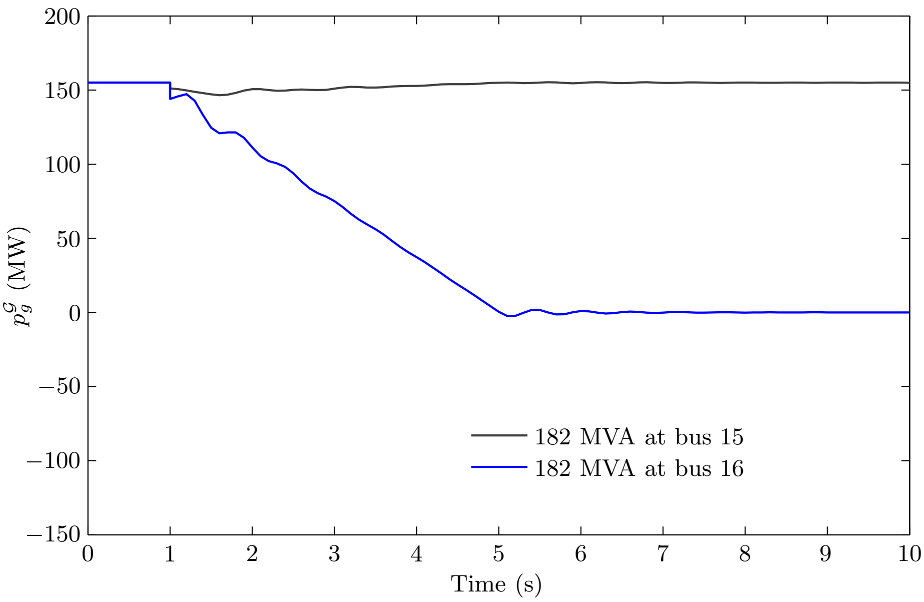
Figure 7: Dynamic simulation results when mechanical power is ramped down rather than switched.

4.1 Ramp-down of generation

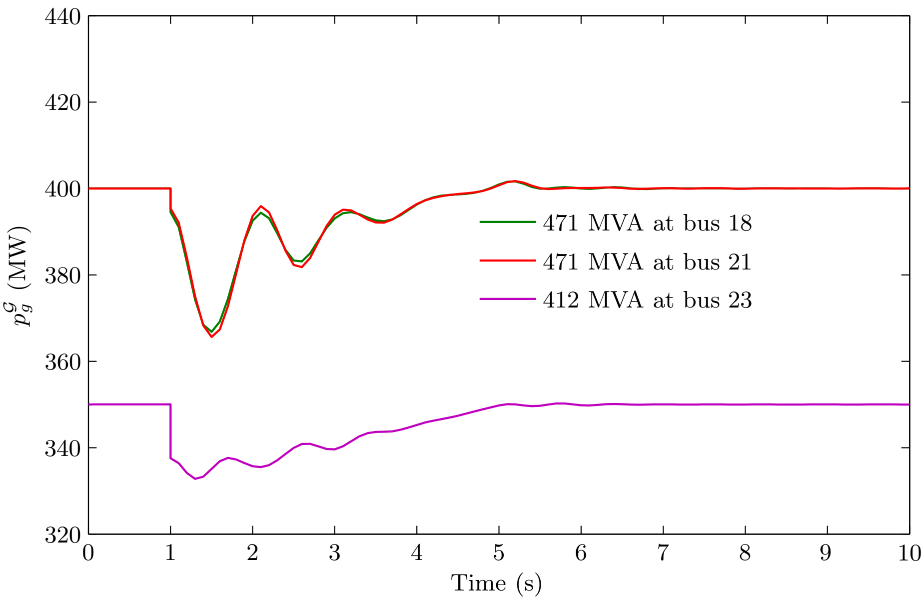
Figures 7–9 show the results for when mechanical power input to the "switched off" generators is allowed to ramp down (over five seconds) rather than instantaneously change. Line cuts are still made instantaneously after one second.

The gentler input change does not excite the large swings seen previously at buses 15 and 16, these generators showing only small oscillations. On the other hand, while reduced in amplitude, oscillations remain on the large generators at buses 18, 21 and 23.

During the ramp down, the frequency rises by a small amount (0.3%) as a consequence of the network being temporarily rich in generation. The oscillations on frequency, however, are greatly reduced. The voltage profile is almost exactly the same as before, since reactive powers are instantaenously changed as required.



(a) Real power outputs of generators at buses 15 and 16



(b) Real power outputs of generators at buses 18, 21 and 23

Figure 8: Generator swings as a consequence of breaking line $(15, 24)$ and *ramping down* the 182 MVA generator at bus 16.

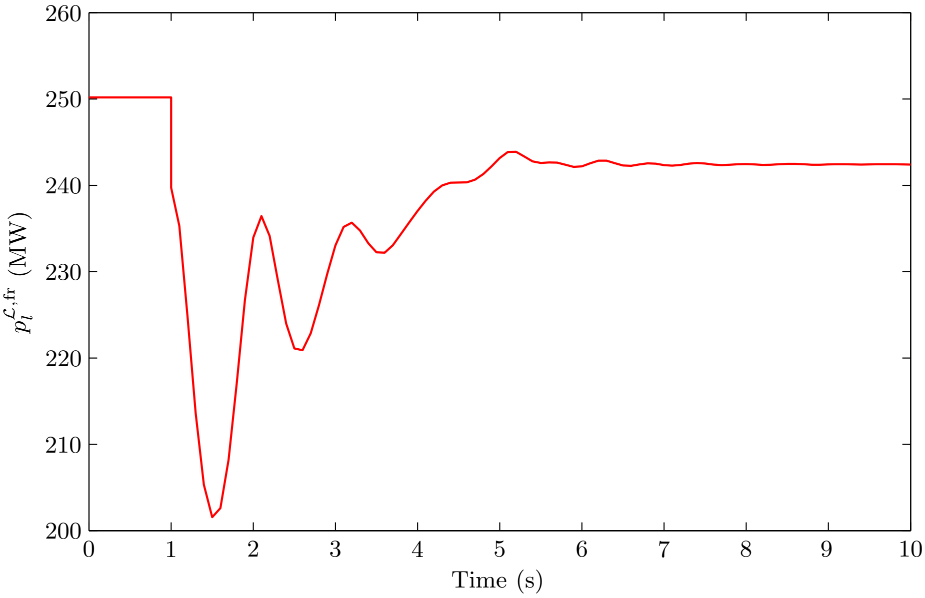


Figure 9: Power swings on line $(15, 16)$ as a consequence of breaking line $(15, 24)$ and *ramping down* the 182 MVA generator at bus 16.

4.2 Full disconnection of generators

Now when a generator is "switched off" it is electrically isolated from the network, so provides no reactive power. Figure 10 shows the results. Disconnection is done instantaneously, at the same time as line cuts, and real power is not ramped down as in the previous sub-section.

Key points:

- Real power swings are far less severe than for the case where the generators remain electrically connected.
- In general, more generators have to change their reactive power outputs to compensate for the loss of capability of the disconnected machines.
- Voltage oscillation is the most severe so far.
- Frequency oscillations are small.

References

[1] Reliability Test System Task Force of the Application of Probability Methods Subcommittee, "IEEE reliability test system," *IEEE Transactions on Power Apparatus and Systems*, vol. PAS-98, no. 6, pp. 2047–2054, 1979.

[2] J. Hazra and A. K. Sinha, "Prognosis of catastrophic failures in electric power systems," in *IEEE International Conference on Industrial Technology*, December 2006, pp. 1349–1354.

[3] Reliability Test System Task Force of the Application of Probability Methods Subcommittee, "IEEE reliability test system – 1996," *IEEE Transactions on Power Systems*, vol. 14, no. 3, pp. 1010–1020, 1999.

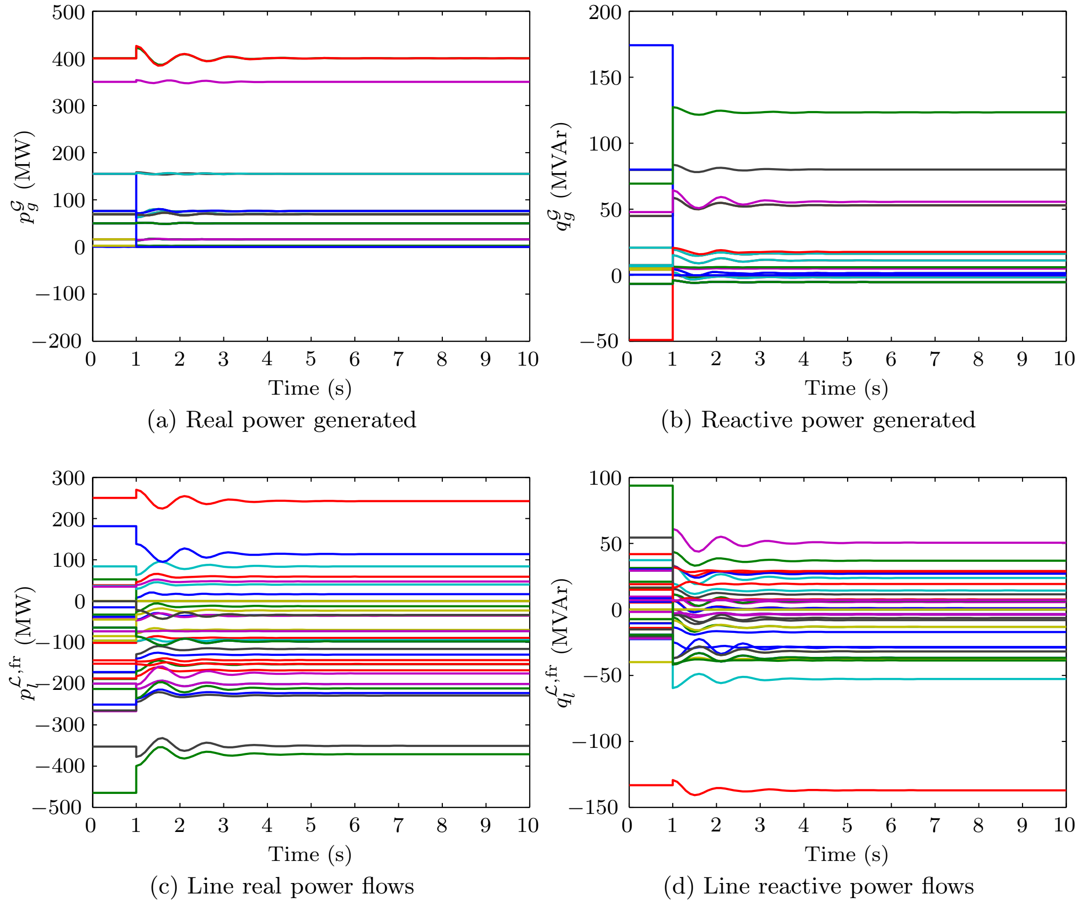


Figure 10: Dynamic simulation results for the electrical isolation from the network of switched-off generators.

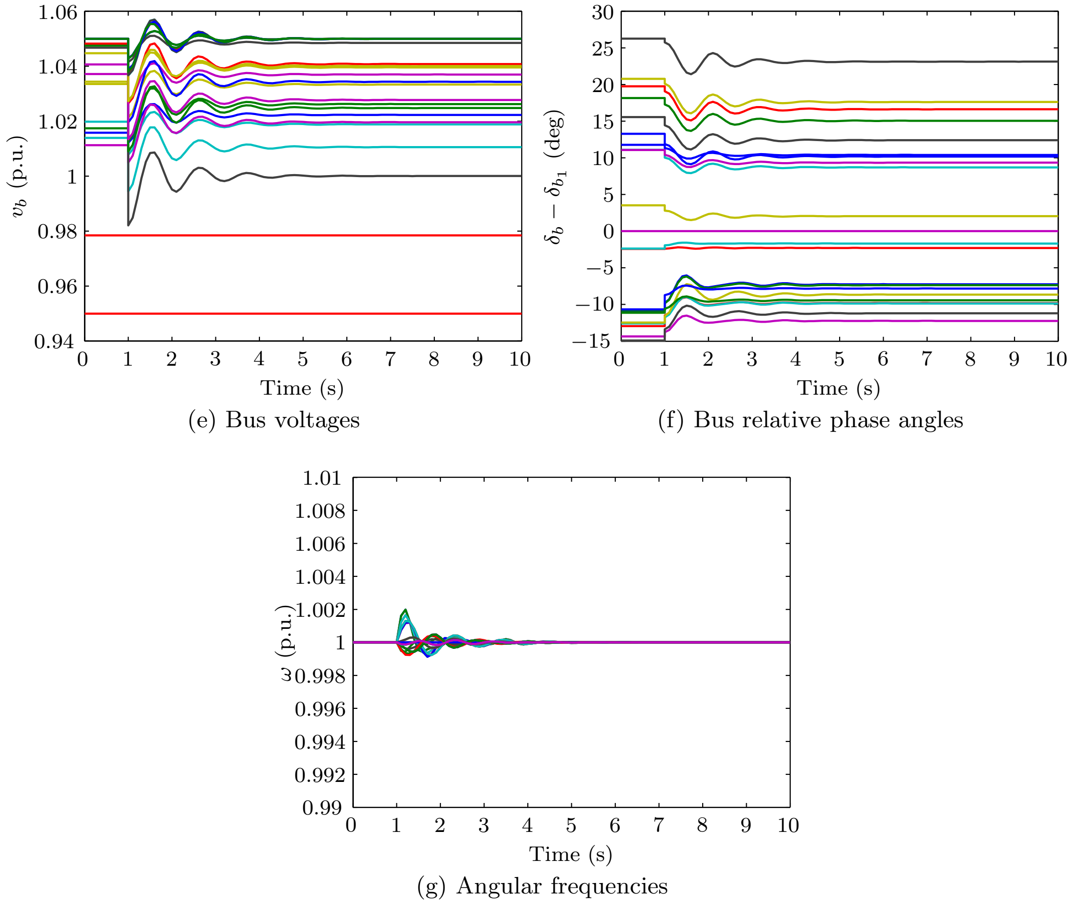


Figure 10: (continued) Dynamic simulation results for the electrical isolation from the network of switched-off generators.