N-1-1 Contingency Analysis using PowerWorld Simulator

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Background and Objective

NERC Standard TPL-001-1 (Transmission System Planning Performance Requirements)[1] proposes several requirements for demonstrating reliable operation of the power system over the planning horizon. Category P3 and P6 planning events described in TPL-001-1 involve an initial loss of a generator or transmission component, possibly followed by system adjustments, followed by another loss of a generator or transmission component. The approach for conducting analysis with PowerWorld Simulator will depend on if and when system adjustments may be applied to mitigate post-contingent violations, and the degree to which effective system adjustments are understood.

Contingencies and system adjustments may be modeled with Simulator's Contingency Analysis tool. System adjustments are modeled explicitly as part of each contingency. Model Criteria may be assigned to actions which only occur under certain system conditions. Analysis using Simulator's optimal power flow (OPF) or security-constrained optimal power flow (SCOPF) may help the system planner identify appropriate actions for system adjustments to mitigate transmission line or interface overloads. (Voltage violations cannot be analyzed with the methods described here.) Contingency Analysis may be performed to evaluate the effectiveness of such system adjustments.

Definitions

Base Case: The power system in its normal steady-state, operation, with all elements in service that are expected to be in service.

Primary Contingency: An loss of one or more system elements that occurs first. A Primary Contingency may be a planned or unplanned event.

Secondary Contingency: An contingency that occurs after the Primary Contingency. This is usually an unplanned event.

System Adjustments: A set of corrective actions executed by automatically by a control system or manually by a system operator to mitigate the effects of a contingency or strengthen the system to withstand a possible future contingency. System adjustments may include the opening or closing of a transmission element; the opening, closing, or redispatch of a generator; the changing of a phase shifting transformer angle; the opening, closing, or changing of the a switched shunt setpoint; or the curtailment of load. System adjustments are sometimes referred to as Remedial Action Schemes (RAS) or Special Protection Schemes (SPS). System adjustments may include actions that occur every time a certain contingency occurs or actions that occur only when certain system conditions are met.

N-1-1 Contingency: A sequence of events consisting of the initial loss of a single generator or transmission component (Primary Contingency), followed by system adjustments, followed by another loss of a single generator or transmission component (Secondary Contingency).

Model Criteria: An evaluation of system conditions in Simulator, that if met, would cause a conditional system adjustment to occur.

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[1] http://www.nerc.com/filez/standards/Assess-Transmission-Future-Needs.html

N-1-1 Contingency Analysis Overview

An overview of a suggested analysis process is shown in Figure 1.

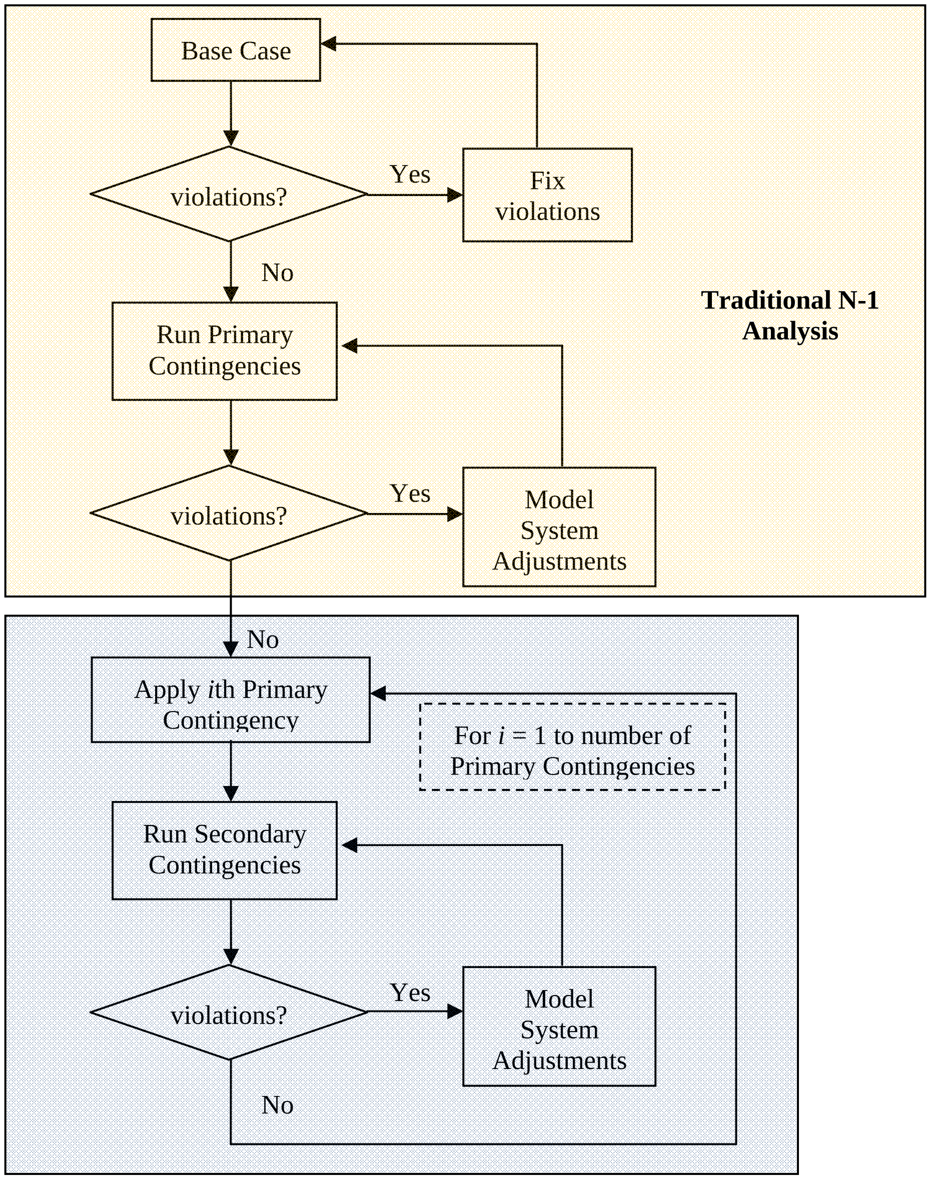


Figure 1 - N-1-1 Analysis Process

Several tools and techniques may be used in PowerWorld Simulator for performing each analysis step. Contingency analysis may be used to model the outages and the system adjustments. If all effective system adjustments are well-understood, contingency analysis may be the only tool needed. A system that meets N-1-1 criteria would not reveal any violations during any of the Primary Contingencies, or during any of the Secondary Contingencies, with each of the Primary Contingencies as the reference case. Simulator's OPF and SCOPF tools tool may be used to identify possible system adjustments if they are not known.

Contingency Analysis

Contingency analysis may be used to model the entire process depicted in Figure 1. Future versions of Simulator will include tools for automatically processing the Primary and Secondary Contingency lists. The user will be able to define both lists, and each Secondary Contingency will be processed after each Primary Contingency and all results compiled in a single table. With Simulator 14 and earlier versions, the user must separately perform the traditional N-1 sub-process shown in the orange shaded region of Figure 1, and the remainder in the blue shaded region as a separate sub-process.

To conduct N-1 analysis (orange sub-process), simply define all of the Primary Contingencies in Simulator's Contingency Analysis tool and run. System adjustments may be incorporated as contingency actions. For system adjustments that are conditional, use Simulator's Model Criteria to define the conditions under which the actions occur. An example is shown in Figure 2.

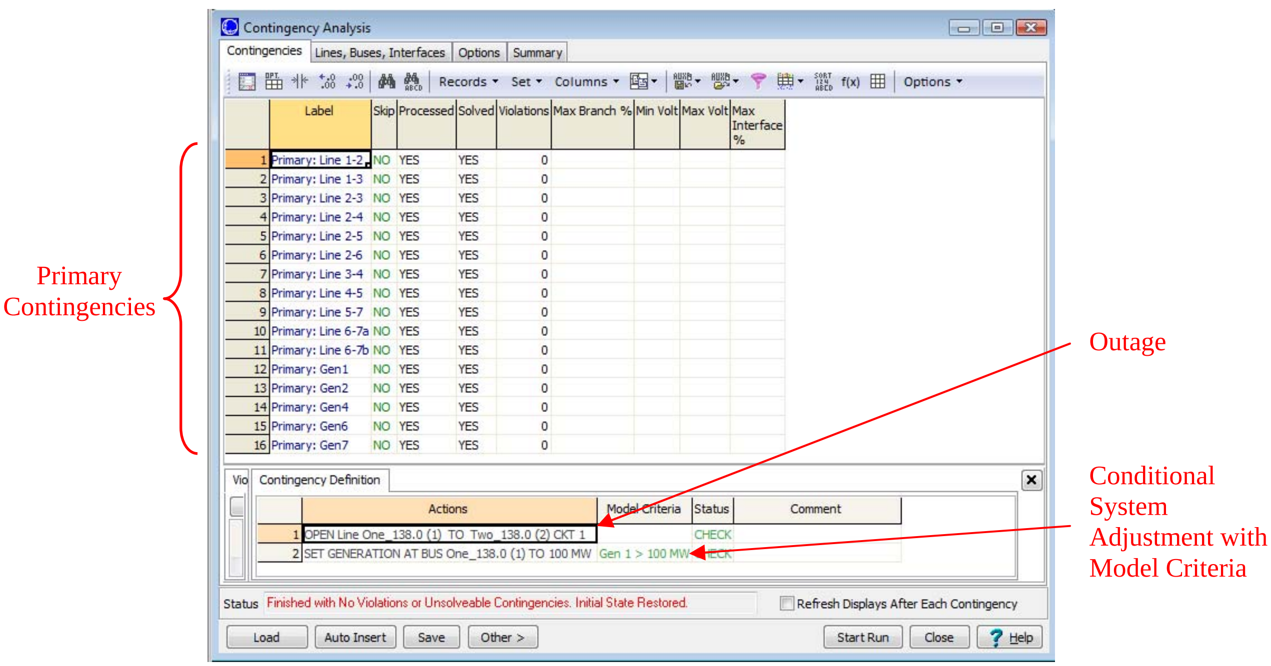


Figure 2 - N-1 Contingency Analysis

Figure 3 details the process for analyzing the Secondary Contingencies (the blue-shaded sub-process in Figure 1) with Simulator versions 14 and earlier.

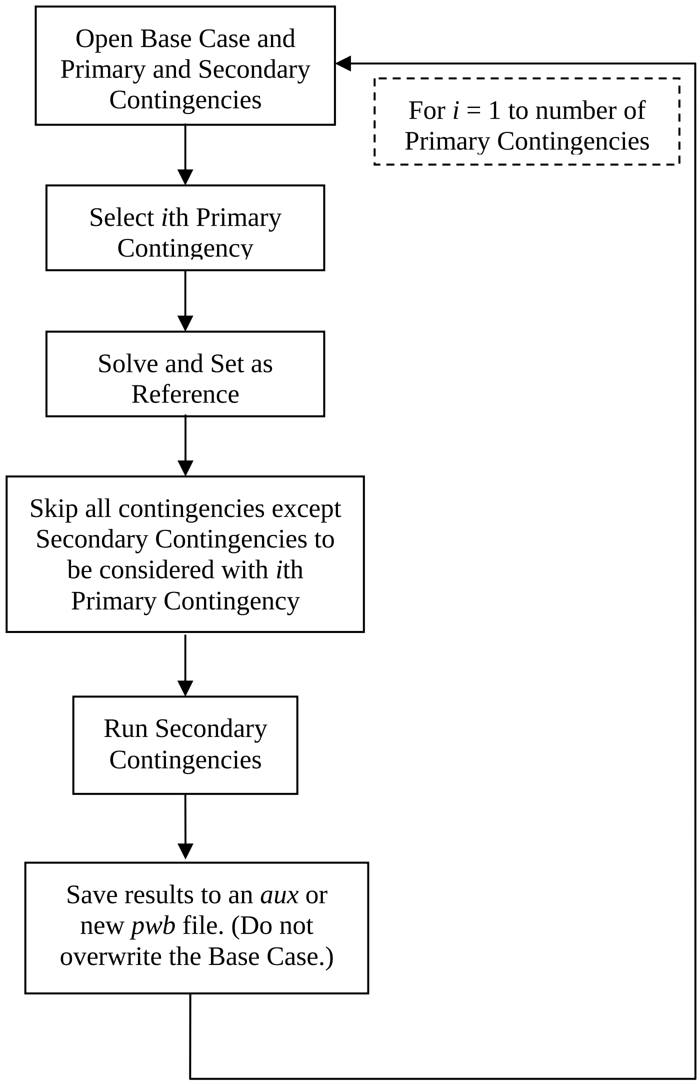


Figure 3 - Secondary Contingency Analysis in PowerWorld Simulator

OPF and SCOPF

The OPF and SCOPF tools may be used with the contingency analysis to help identify effective system adjustments to occur in either the base case, following a Primary Contingency or any of the Secondary Contingencies. This is just one possible approach, as other tools such as sensitivity analysis and the line loading replicator may also provide valuable insight.

NERC Standard TPL-001-1 indicates that "planned system adjustments... are allowed if such adjustments are executable within the time duration applicable to the Facility Ratings." System adjustments might then occur:

1. after the Secondary Contingency, in response to the N-1-1 system state; OR
2. after the Primary Contingency, to adjust the system such that no violations will occur following *any* possible Secondary Contingency; OR
3. not at all. The system must then be operated such that *any* possible combination of Primary and Secondary Contingency will not cause a violation.

In addition, the OPF and SCOPF may be operated with various mixes of controls. Possible controls include redispatch of generation, curtailment of load, adjustment of phase-shifting transformer angles, adjustment of DC line setpoints, or changes in control area import schedules. The opening and closing of transmission lines cannot be considered as OPF or SCOPF controls, but could be analyzed with line outage or line closure distribution factors.

Following adjustments to the Base Case, Primary Contingencies, and Secondary Contingencies, Contingency Analysis may be run as described previously to verify compliance of the system with the appropriate planning requirements. The following describes methods for applying Simulator's tools to the various situations described above.

System Adjustments after a Secondary Contingency

In this situation, the OPF is applied to mitigate violations in the post-contingent system state, without considering violations that could exist under further contingencies. Figure 4 illustrates a possible procedure for this analysis.

Notes:

1. The system state following the Primary Contingency can be restored by simply restoring the reference state in Simulator.
2. The OPF will use the Contingency Rating Sets selected in the Limit Monitoring Settings for lines, transformers, and interfaces. To model sufficient system adjustments with the OPF controls, make sure that the selected Contingency Rating Sets are appropriate for the system state following the Secondary Contingency.

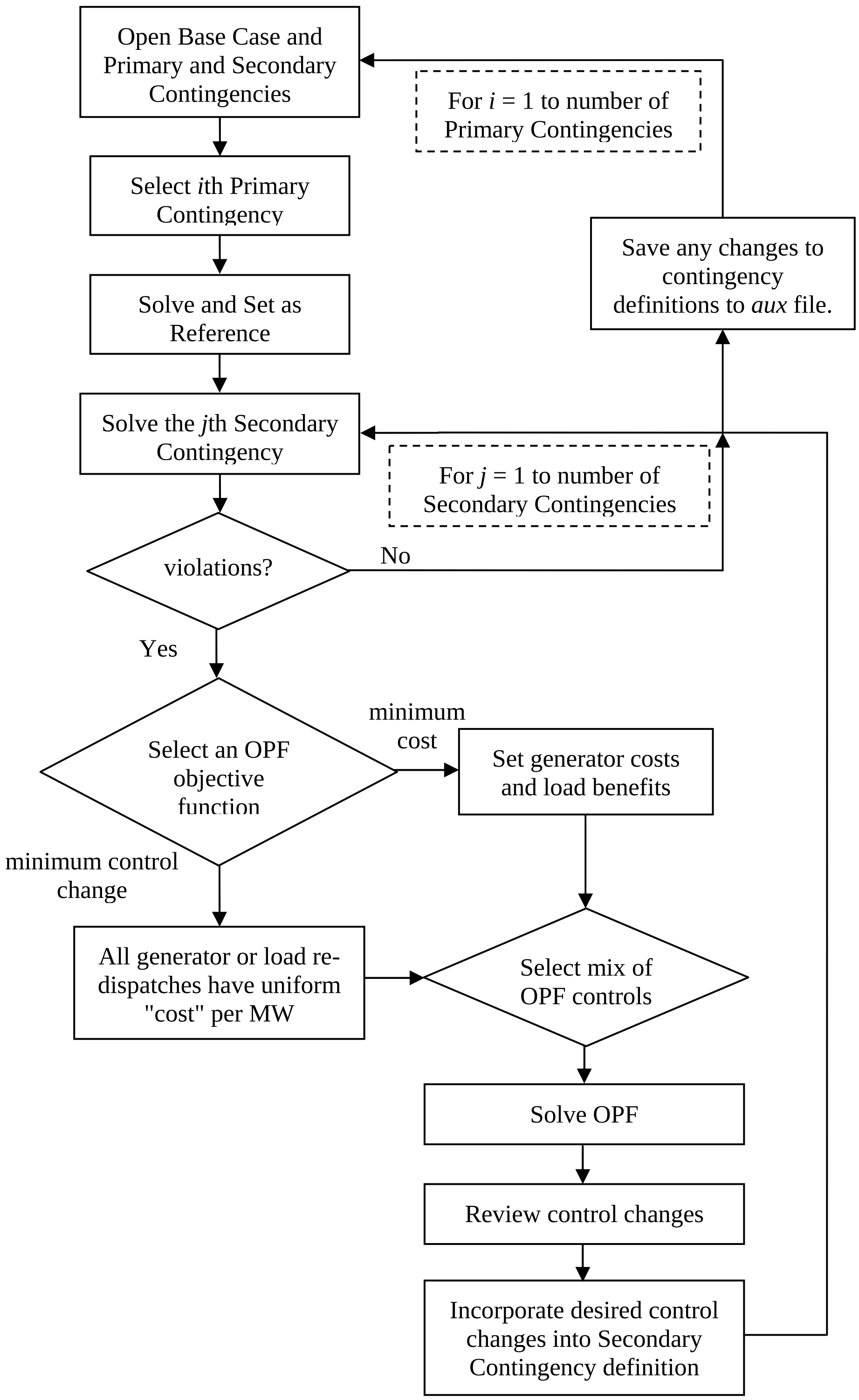


Figure 4 - System Adjustments after a Secondary Contingency with OPF

The following figures illustrate an example on a 7-bus test case. The outage of the line between buses Four and Five occurred in the Primary Contingency. The outage of the line between buses Seven and Five occurred in the Secondary Contingency, resulting in an overload on the line between buses Two and Five. Figure 5 shows the application of the Secondary Contingency in the Contingency Analysis dialog and Figure 6 shows the resulting post-contingent system, without System Adjustments.

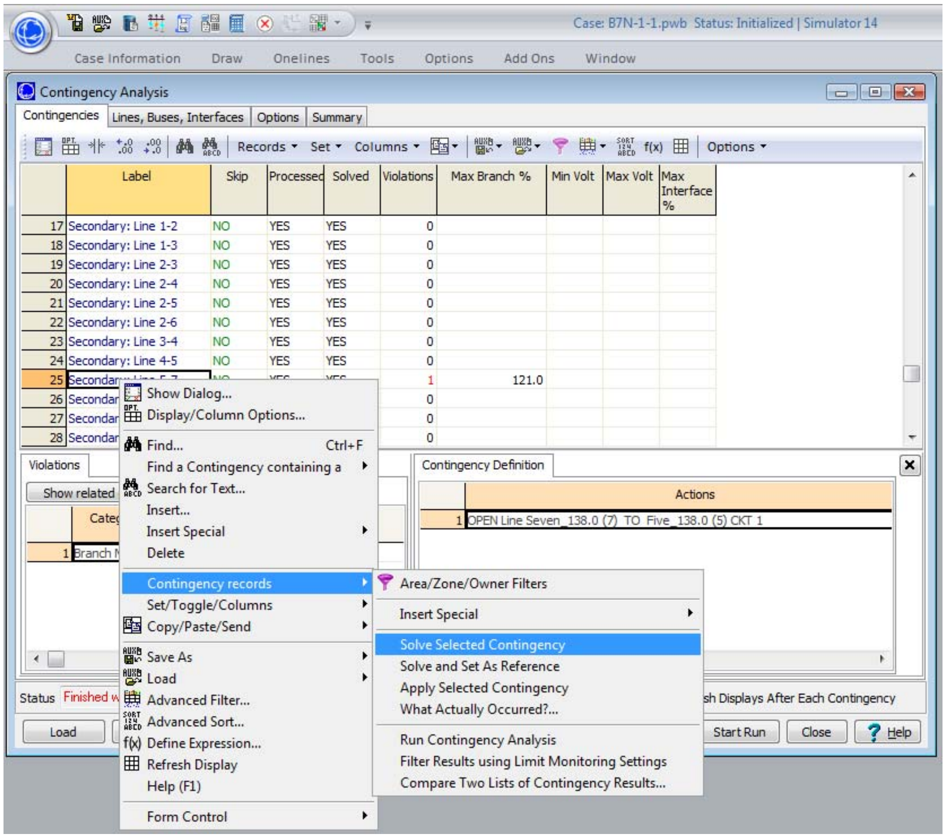


Figure 5 - Applying Secondary Contingency in Simulator

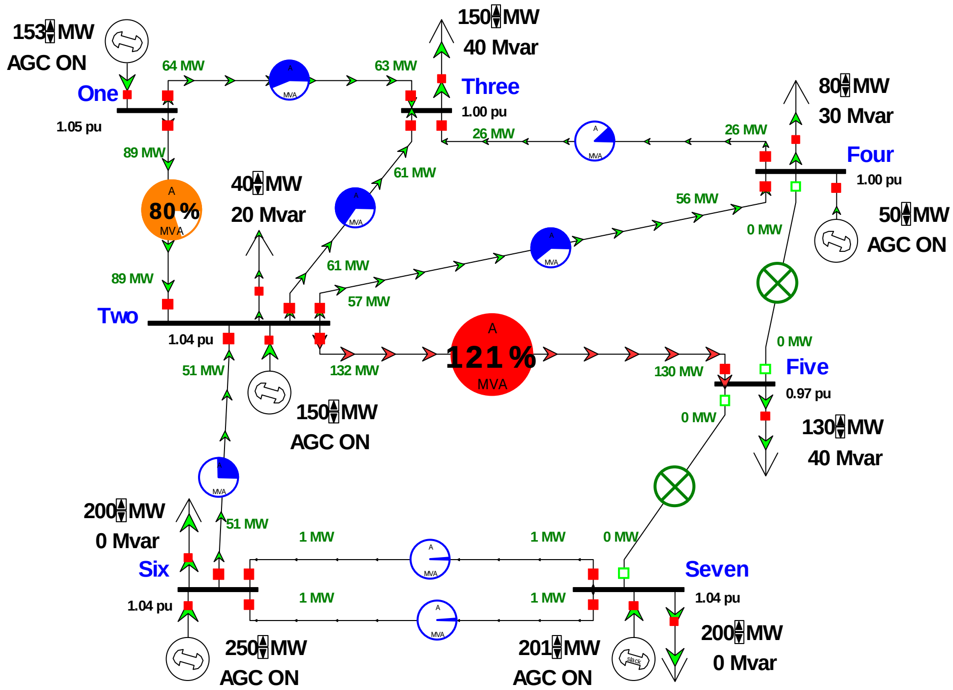
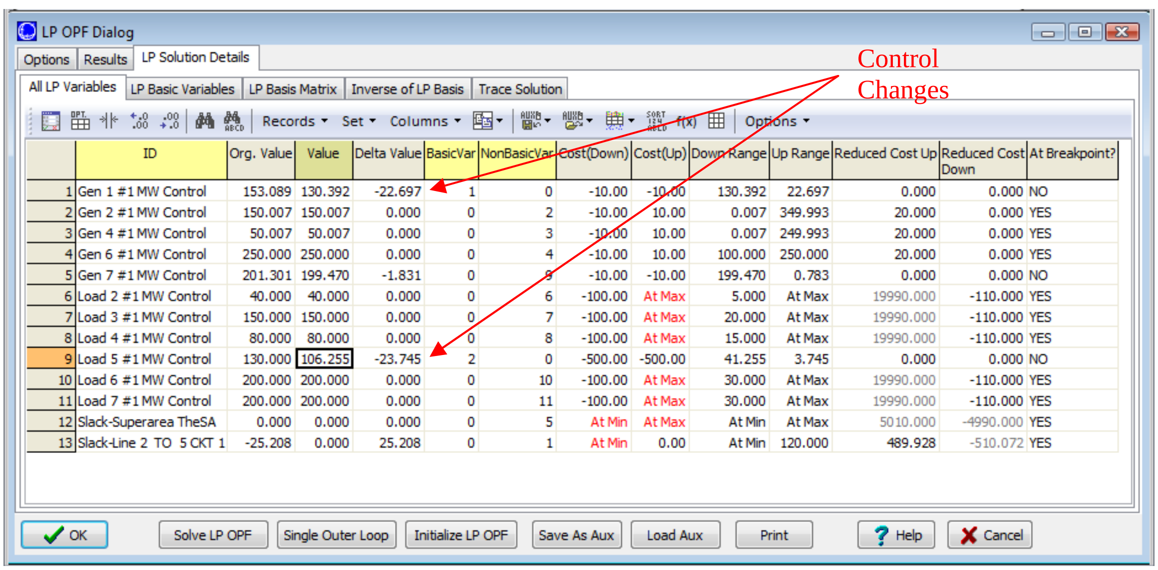


Figure 6 - One-line Diagram of Post-Contingent System

Following the application of the OPF, the load at Bus 5 is curtailed and the generator outputs at Buses 1 and 7 are adjusted accordingly. The changes may be viewed in the OPF Dialog as shown in Figure 7.



	ID	Org. Value	Value	Delta Value	BasicVar	NonBasicVar	Cost(Down)	Cost(Up)	Down Range	Up Range	Reduced Cost Up	Reduced Cost Down	At Breakpoint?
1	Gen 1 #1 MW Control	153.089	130.392	-22.697	1	0	-10.00	-10.00	130.392	22.697	0.000	0.000	NO
2	Gen 2 #1 MW Control	150.007	150.007	0.000	0	2	-10.00	10.00	0.007	349.993	20.000	0.000	YES
3	Gen 4 #1 MW Control	50.007	50.007	0.000	0	3	-10.00	10.00	0.007	249.993	20.000	0.000	YES
4	Gen 6 #1 MW Control	250.000	250.000	0.000	0	4	-10.00	10.00	100.000	250.000	20.000	0.000	YES
5	Gen 7 #1 MW Control	201.301	199.470	-1.831	0	9	-10.00	-10.00	199.470	0.783	0.000	0.000	NO
6	Load 2 #1 MW Control	40.000	40.000	0.000	0	6	-100.00	At Max	5.000	At Max	19990.000	-110.000	YES
7	Load 3 #1 MW Control	150.000	150.000	0.000	0	7	-100.00	At Max	20.000	At Max	19990.000	-110.000	YES
8	Load 4 #1 MW Control	80.000	80.000	0.000	0	8	-100.00	At Max	15.000	At Max	19990.000	-110.000	YES
9	Load 5 #1 MW Control	130.000	106.255	-23.745	2	0	-500.00	-500.00	41.255	3.745	0.000	0.000	NO
10	Load 6 #1 MW Control	200.000	200.000	0.000	0	10	-100.00	At Max	30.000	At Max	19990.000	-110.000	YES
11	Load 7 #1 MW Control	200.000	200.000	0.000	0	11	-100.00	At Max	30.000	At Max	19990.000	-110.000	YES
12	Slack-Superarea TheSA	0.000	0.000	0.000	0	5	At Min	At Max	At Min	At Max	5010.000	-4990.000	YES
13	Slack-Line 2 TO 5 CKT 1	-25.208	0.000	25.208	0	1	At Min	0.00	At Min	120.000	489.928	-510.072	YES

Figure 7 - LP OPF Dialog

Simulator's Difference Flows tool may also be used to show changes in generators, loads, and flows. Figure 8 shows the change in load and generation with the one-line diagram. These system adjustments may then be incorporated into the Secondary Contingency definition and the contingency analysis re-run to verify compliance with N-1-1 criteria.

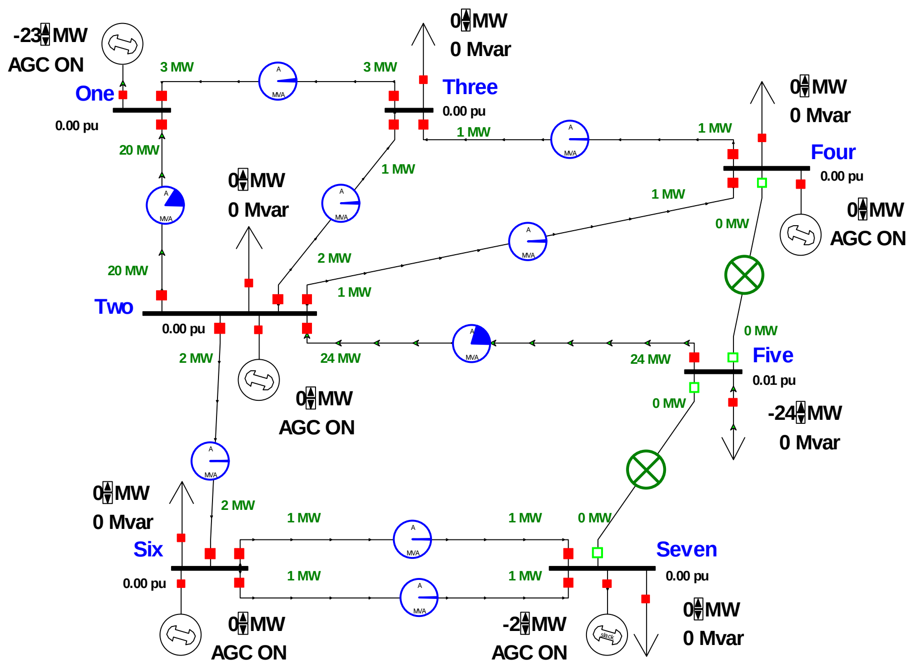


Figure 8 - Viewing OPF System Adjustments and Flow Changes with Difference Flows

System Adjustments after a Primary Contingency

In this situation, it is assumed that the system must be able to withstand a Secondary Contingency subsequent to the Primary Contingency, with no violations. Here, the SCOPF is applied to the post-Primary Contingency system state, considering the entire set of Secondary Contingencies, to determine if any system adjustments are needed following the Primary Contingency, such that all Secondary Contingencies can occur without overloads. It is assumed that system adjustments will not occur following the Secondary Contingency. Figure 9 illustrates a possible procedure for this analysis.

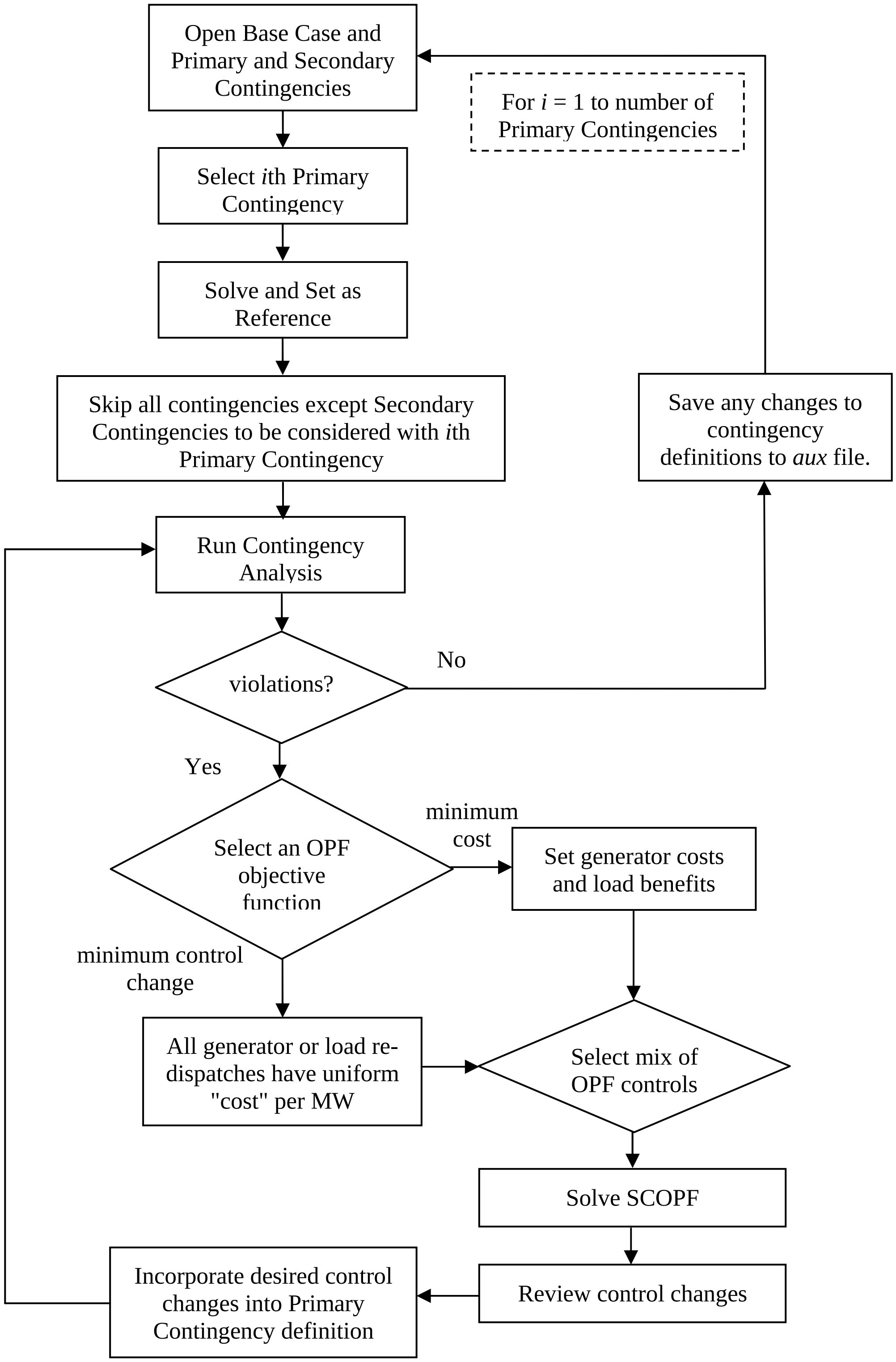


Figure 9 - System Adjustments after a Primary Contingency with SCOPF

No Post-Contingency System Adjustments

In this situation, it is assumed that the Base Case must be able to withstand any sequence of Primary and Secondary Contingencies with no violations. Here, the SCOPF is applied to the Base Case, with the goal of identifying system adjustments for the Base Case. Figure 10 illustrates a possible procedure for this analysis.

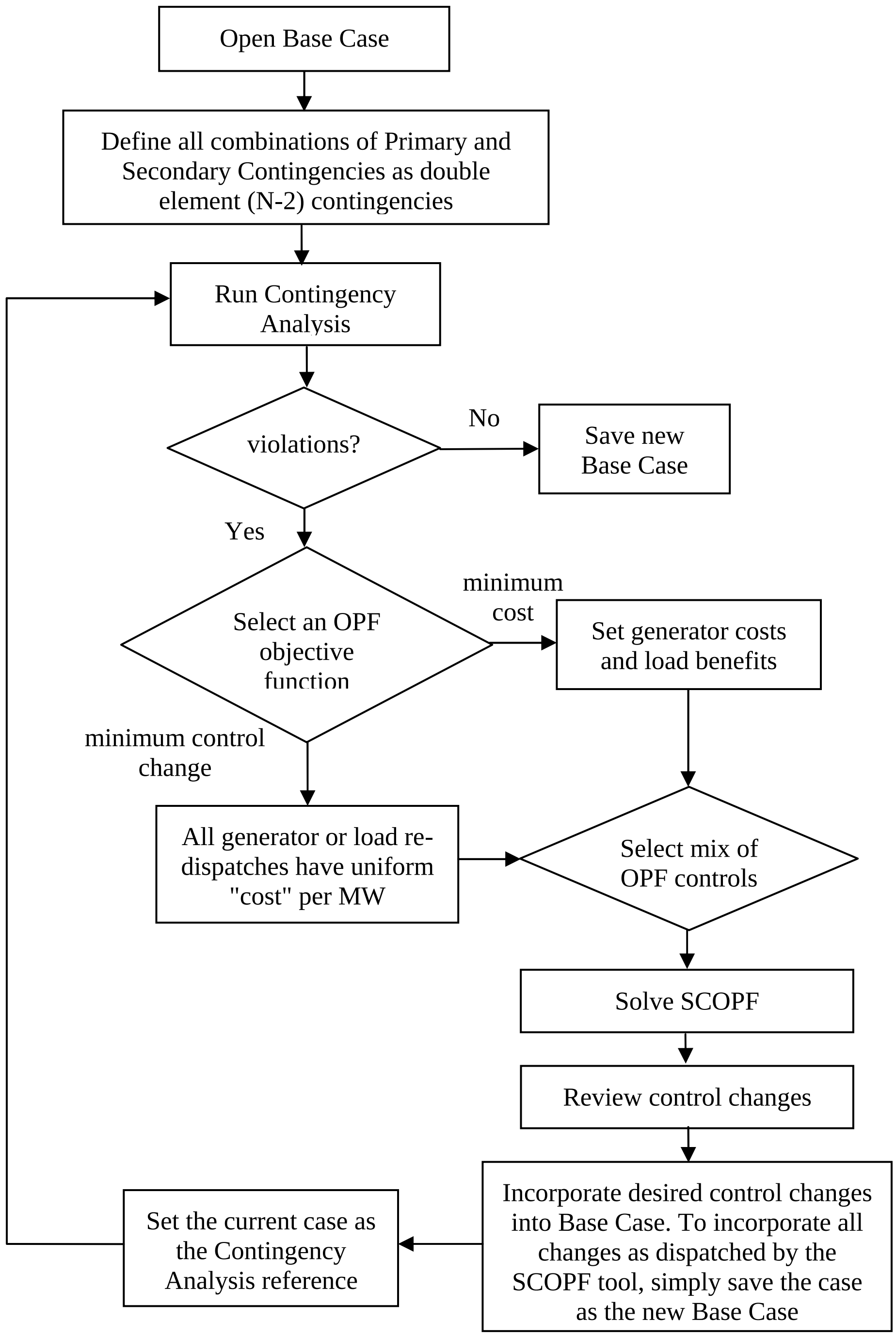


Figure 10 - System Adjustments to Base Case with SCOPF

Objective Functions and Cost Curves

Simulator OPF offers two options for the objective function, or the quantity that is being optimized subject to transmission constraints: minimum control change and minimum cost. When considering only generation redispatch for contingency system adjustments, minimum control change is usually the most straightforward and easiest to implement. Here, the OPF relieves the constraints with the minimum redispatch from the starting point. Increasing the output of a generator by one MW incurs the same "cost" as decreasing the output of a generator by one MW. In addition, all controllable generators have the same cost. If loads are incorporated as OPF controls, they also have the same uniform cost per MW to change their value from the present level.

However, it may be preferable to associate a higher cost with load curtailment than with generator redispatch or to differentiate costs across different loads and generators. The minimum cost OPF objective function must be used in this case. Curtailable loads may then be assigned appropriate piecewise-linear benefit functions. Generators may be assigned normal piecewise-linear or cubic cost functions. To bias the OPF toward keeping generator controls at the current operating point, a generator may be assigned a piecewise linear cost function with a MW breakpoint at the current operating point. The cost function associated with output below the current output would have a slope equal to the negative of the slope above the current output. A minimum of two breakpoints would be used: one at the generator's minimum output and one at the generator's current output. This is shown graphically in Figure 11.

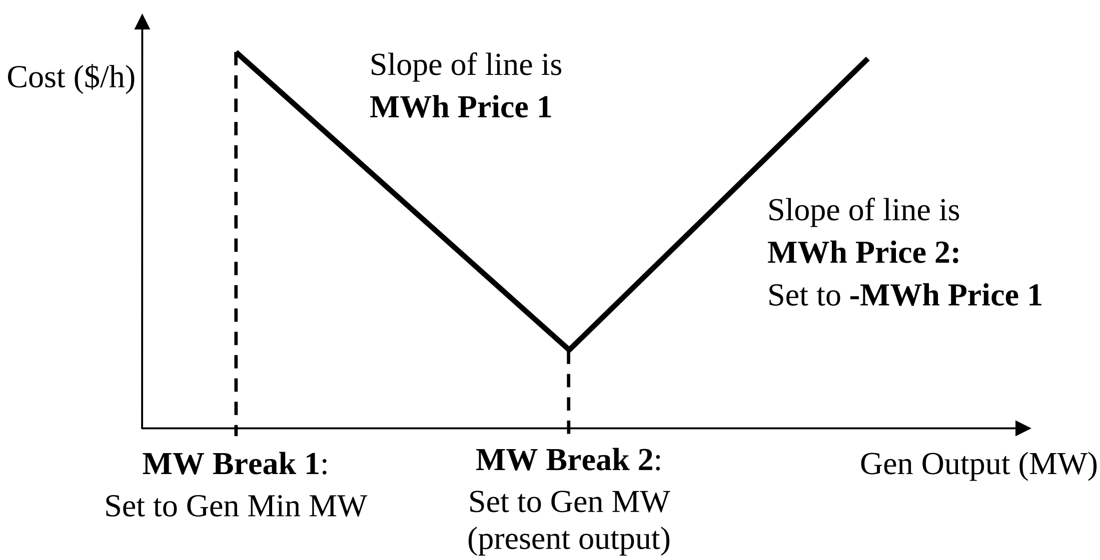


Figure 11 - Example Generator Cost Function to Bias Minimum Cost OPF to Present Generator Output; Values in Bold are Input Variables for the Piecewise Linear Cost Curve

If the base case changes and the load or current operating point of the generators is different from that which existed when the generator cost curves were created, then the cost curves would require updating to bias the controls to the current operating point. This task can be simplified with the use of auxiliary files. For example, the following auxiliary script would give all generators a cost of $10/MWh to deviate from their present outputs:

```
SCRIPT
{
SelectAll(GEN);
SetData(GEN, [GenBidMW, GenBidMWHR, GenBidMW:1, GenBidMWHR:1],
      ["@GenMWMin", -10, "@GenMW", 10], Selected);
UnSelectAll(GEN);
}
```

The case should be solved before establishing the breakpoints since redispatch may be needed to meet the current level of load and losses.

When using loads as controls, it is also important to set appropriate minimum and maximum values for each controllable load. The maximum would normally be set to the nominal or starting value of the load, so that a load may be curtailed, but not increased as a system adjustment.