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1 INTRODUCTION

The Volume I of this final report has presented the theoretical aspects involved in the computation of the Value of Security using a probabilistic method based on Monte Carlo simulations proposed under the Value of Security Project –EPSRC/ERCOS grant reference no GR/K 80310.

The proposed probabilistic method allows the computation of the Value of Security of operational plans on the basis of the sum of the production cost of the scheduled plant configuration and the expected cost (in terms of necessary redispatch of generation and the impact of load shedding) of unplanned outages.

A Monte Carlo sample simulation computes the Value of Security from a number of trials. The individual trial’s simulation starts from a known state of the system, which results from the implementation of the plan.

Individual trials are generated by random contingency conditions based on this state and the system’s evolution over the analysis period (for example, several hours). The simulation period is broken down into intervals or snapshots to model random outages at different moments over this period.

The initial state of the following interval is derived from the current interval taking into account the contingencies presented and the corrective actions taken by the operators. The new interval starting state considers also the changes in load and in planned schedule generation.

Figure 1.1 shows the simulation of disturbance events for each snapshot in a Monte Carlo trial simulation used for computing the Value of Security. The sequence of events is divided in three parts:

- Generation of disturbances.
- Computation of an equilibrium point.
- Corrective actions and cost evaluation.

The initial system state given by network topology, load demand and generation schedule is modified by random disturbances (outages of lines, transformers, busbars, compensation and generation equipment). These disturbances could also produce other disturbances such as sympathetic and transient instability trips.

After restoring the generation-load balance, the equilibrium point of the new system’s state must be calculated using a load flow. Two outcomes are possible for this computation:

- The power flow converges.
- The power flow diverges. This indicates that the occurrence of this contingency state would result in voltage stability problems. A heuristic technique has been developed to determine how much load must be dropped to restore the feasibility of the power flow. If the load flow diverges, it is assumed that the system or a part of the system (an island)
would have suffered a voltage collapse were the operator not have taken action. It is further assumed that the operator's response to an impeding collapse would have been to shed load in 5% blocks in the area of the biggest mismatch until convergence is achieved. If convergence has still not been achieved after all load has been shed, the island or the system is deemed to have collapsed.

When the system has reached an equilibrium point (EP1, convergence of the load flow), a series of cascade tripping events may occur. In this case, a new load flow computation is required. A divergence of this new load flow indicates a severe problem (voltage collapse) has been caused by events occurred after EP1. As in the computation of EP1, a load shedding is realised until a new equilibrium point (EP2) is reached.

As Figure 1.1 shows, a sequence of load flow calculations and disturbance events may be established in an iterative way. This succession of calculation of EP(i)-disturbances-EP(i+1) can be interpreted as a modelling of successive slow events that provokes a voltage collapse in the system.

Finally, the system reaches a last equilibrium point (EP). The system has a converged load flow with two possible outcomes:

- The resulting state of the system does not exhibit any major violation of normal operating limits. This state does not require any corrective action and has a cost of zero.
- The resulting state has some violations of normal operating constraints. Corrective actions must be taken to bring the system back within acceptable limits. The cost of these actions is computed and tallied.

In response to violations of system operating limits, operators can reschedule generation, change voltage set-points and tap ratios, and, as a last resort, shed load. Since operators reach decisions about what actions to take based on advice given by planners, information gleaned from “what-if” load flow studies, and experience, their actions are represented for the value of security computation by a fuzzy expert system with embedded load flow and linear sensitivity analysis. Three types of corrective actions are modelled:

- Active dispatch: dispatches settings of active power generation, shedding of load (active and reactive components in proportion) and changes to phase shifter settings in order to relieve overloads of transmission lines and cables.

- Reactive dispatch: dispatches settings of reactive control devices in order to correct violations of voltage limits.

- Dispatch of active controls for correction of voltage problems: this is activated to change the active generation and, if necessary, shed load in order to remove any outstanding violations of voltage limits.

Finally, the Value of Security is computed from the rescheduled generation, valued at the system marginal price, and from the interrupted load using the value of lost load (VOLL).

Volume II of this final report presents tests of the Value of Security Assessor program (Assessor) developed under the Value of Security Project –EPSRC/ERCOS grant reference no GR/K 80310 on both a small and a large power system. The south-west portion of the England and Wales system has been used as the small test power system, while a full model of the NGC transmission system for 1996/97 has been employed as the large test power system.

The objectives of these tests were to:

- Test the sequential simulation method that makes possible the computation of the value of security over a time interval (for example, 1 hour or 1 day).

- Test the variance reduction methods developed previously in the context of this sequential simulation

- Test the various methods for computing the value of lost load [5].

- Test the modelling of weather effects [7].

- Test the modelling of the time dependent phenomena [6, Appendix A]

- Develop improvements to the Assessor for the computation of the Value of Security for large power systems.
Chapter 2 presents the study cases and the results of the simulations based on the South-West England-Wales system.

Chapter 3 presents a previous study concerning the selection of simulation parameters and some important aspects related to the application of Value of Security Assessor to large power systems.

Chapter 4 presents the study cases and the results of the simulations based on the NGC System.

Chapter 5 discusses and proposes a method to consider severe outages in the computation of the Value of Security for large power systems, which allows that the Value of Security computation be faster.

Chapter 6 discusses the test results, presents conclusions and perspectives on future work in the value of security.

APPENDIX A – South West England-Wales System data gives the data of the south-west England-Wales test system, while APPENDIX B – NGC System data gives some data of the large test system of the NGC.
2 TESTING THE ASSESSOR OF VALUE OF SECURITY ON A SMALL POWER SYSTEM - THE ENGLAND AND WALES SOUTH-WEST SYSTEM

Firstly, the Value of Security Assessor program has been tested using a model representing the south-western portion of the transmission system of England and Wales (SW System).

Table 2.1 shows the main characteristics of the system. Two scenarios (the presence or absence of generation at Fawley station) have been used for testing. Figure 2.1 shows the load demand for a period of 24 hours. Generation dispatches for each scenario based on this load demand profile have been used. Detailed data is provided in APPENDIX A – South West England-Wales System data.

Table 2.1 Main characteristics South West System

<table>
<thead>
<tr>
<th>Characteristic</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maximum load [MW]</td>
<td>5566</td>
</tr>
<tr>
<td>Number of buses</td>
<td>53</td>
</tr>
<tr>
<td>Number of branches</td>
<td>115</td>
</tr>
<tr>
<td>Number of generators</td>
<td>25</td>
</tr>
<tr>
<td>Number of areas</td>
<td>1</td>
</tr>
</tbody>
</table>

Figure 2.1 Load demand, South-West System

The data on reliability of transmission equipment provided by [1] has been used as typical data for this system. Failure rates of transmission lines have been computed using their length (See appendix B of [2]). Failure rates of generators have been computed from forced outage rates (FOR) provided in [3] and assuming mean time to repair (MTTR) values given by [4]. The generation prices associated with each generator are given in appendix D of [2].

The same load restoration process has been assumed in all cases. This process corresponds to the restoration by steps described in Figure 5b of [6]. Each step was
given a duration of 30 minutes. The simulation therefore takes 2 subintervals for each period of constant load.

In the tables that follow in this chapter, the confidence that can be associated with the results is given in terms of the ratio of the standard deviation to the mean value of the total cost of value of security ($\sigma/\mu$). Table 2.2 gives the value of this ratio associated with five combinations of degrees of confidence and confidence interval.

<table>
<thead>
<tr>
<th>Confidence degree [%]</th>
<th>Confidence interval [%]</th>
<th>$\sigma / \mu$ [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>80.0</td>
<td>5.0</td>
<td>3.90</td>
</tr>
<tr>
<td>85.0</td>
<td>5.0</td>
<td>3.47</td>
</tr>
<tr>
<td>90.0</td>
<td>5.0</td>
<td>3.04</td>
</tr>
<tr>
<td>95.0</td>
<td>5.0</td>
<td>2.55</td>
</tr>
<tr>
<td>99.0</td>
<td>5.0</td>
<td>1.94</td>
</tr>
<tr>
<td>95.0</td>
<td>1.0</td>
<td>0.51</td>
</tr>
<tr>
<td>99.0</td>
<td>1.0</td>
<td>0.39</td>
</tr>
</tbody>
</table>

It is important to remember that the confidence interval is defined as a function of the mean ($\mu$) and standard deviation ($\sigma$) values and the degree of confidence. Thus,

$$\text{Confidence Interval} = [\mu - \alpha \times \sigma, \mu + \alpha \times \sigma]$$  \hspace{1cm} (2.1)

where $\alpha$ is equal to 1.96 for a 95% degree of confidence and 1.645 for a 90% degree of confidence. The confidence interval in Table 2.2 is defined as an interval around the mean value expressed as a percentage of the mean value.

On the other hand, the standard deviation value mentioned here is not the standard deviation of the population sampling but it is the standard deviation of the mean value interpreted as another random variable.

2.1 Case 1

This is the base case where:

- VOLL has a constant value (2.5 £/kWh).
- No weather effect is considered, i.e. the failure rates for average weather conditions are used.
- Cascade and sympathetic tripping are not simulated.
- The simulation extends over 24 hours.

Table 2.3 presents the results obtained for case 1 using the naïve Monte Carlo simulation, without any variance reduction method. 100000 trials were used as the maximum number of trials for each sample. A convergence criterion of 5% of the mean value for a 95% degree of confidence was used. These simulations require a relative low consumption of CPU time (a SUN ULTRA SPARC 1 workstation was used).

The estimated total cost or value of security is given in the total row of each scenario in Table 2.3 with a degree of confidence higher than 99%. Statistically the total cost is
given as an interval and the probability that the true value is in the interval. The interval is defined by equation (2.1) and the probability is equal to the degree of confidence. Table 2.4 gives the confidence intervals for both scenarios. The interval of confidence for the Fawley scenario includes the interval of confidence for the No-Fawley scenario. The best scenario therefore cannot be determined from this analysis.

### Table 2.3 Monte Carlo Simulation Case 1 SW System

<table>
<thead>
<tr>
<th>Sample</th>
<th>Trials</th>
<th>Total Cost (k£)</th>
<th>Interruption Cost (k£)</th>
<th>Generation Cost (k£)</th>
<th>Standard Dev. σ (k£)</th>
<th>σ / µ [%]</th>
<th>CPU Time [min]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>300</td>
<td>3250</td>
<td>160</td>
<td>3090</td>
<td>81</td>
<td>2.48</td>
<td>2.6</td>
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<td>2</td>
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<td>3182</td>
<td>94</td>
<td>3088</td>
<td>47</td>
<td>1.47</td>
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<td>3</td>
<td>692</td>
<td>3363</td>
<td>276</td>
<td>3088</td>
<td>86</td>
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<td>7.7</td>
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<td>465</td>
<td>3308</td>
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<td>3091</td>
<td>84</td>
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<td>479</td>
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<td>302</td>
<td>3091</td>
<td>86</td>
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<td>6.9</td>
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<td>Total</td>
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<td>226</td>
<td>3090</td>
<td>35</td>
<td>1.06</td>
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</table>

### CASE 1- SCENARIO NO FAWLEY

<table>
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<tr>
<th>Sample</th>
<th>Trials</th>
<th>Total Cost (k£)</th>
<th>Interruption Cost (k£)</th>
<th>Generation Cost (k£)</th>
<th>Standard Dev. σ (k£)</th>
<th>σ / µ [%]</th>
<th>CPU Time [min]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>4517</td>
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<td>3016</td>
<td>84</td>
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<td>300</td>
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<td>133</td>
<td>3019</td>
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<td>1.83</td>
<td>3.5</td>
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<td>3017</td>
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<td>247</td>
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<td>83</td>
<td>2.54</td>
<td>5.6</td>
</tr>
<tr>
<td>Total</td>
<td>10700</td>
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<td>298</td>
<td>3017</td>
<td>53</td>
<td>1.60</td>
<td></td>
</tr>
</tbody>
</table>

1- The maximum number of trials was 100000. Convergence criterion of 95% of degree of confidence and 5% of confidence interval

### Table 2.4 Case 1 SW System - Total Costs Intervals

<table>
<thead>
<tr>
<th>Probability [%]</th>
<th>Fawley [k£]</th>
<th>No-Fawley [k£]</th>
</tr>
</thead>
<tbody>
<tr>
<td>95.0</td>
<td>[3211, 3418]</td>
<td>[3247, 3385]</td>
</tr>
</tbody>
</table>

In order to determine the best scenario, the correlated sampling method was used [8]. This method computes the differences between scenarios without computing the total cost of each scenario with a high degree of confidence. Table 2.5 shows the results obtained for this case. A 95% degree of confidence criterion on the difference in cost was used.

Using correlated sampling allows the selection of the best scenario. The simulation’s stopping criterion establishes that the interval of confidence is less than the mean value, i.e. the interval of confidence does not include the zero value. The Assessor can therefore predict the best scenario. In this case, the No-Fawley scenario has the smaller total cost.
### Table 2.5 Case 1 SW System – Correlation Sampling

#### CASE 1- SCENARIO FAWLEY

<table>
<thead>
<tr>
<th>Sample</th>
<th>Trials</th>
<th>Total Cost (k£)</th>
<th>Interruption Cost (k£)</th>
<th>Generation Cost (k£)</th>
<th>Standard Dev. σ (k£)</th>
<th>σ / µ [%]</th>
<th>CPU Time [min]</th>
</tr>
</thead>
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<td>201</td>
<td>3092</td>
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<td>2.16</td>
<td>8.3</td>
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<td>300</td>
<td>3354</td>
<td>262</td>
<td>3092</td>
<td>103</td>
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<td>7.1</td>
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<td>101</td>
<td>3092</td>
<td>33</td>
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<tr>
<td>Total</td>
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#### CASE 1- SCENARIO NO FAWLEY

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<th>Interruption Cost (k£)</th>
<th>Generation Cost (k£)</th>
<th>Standard Dev. σ (k£)</th>
<th>σ / µ [%]</th>
<th>CPU Time [min]</th>
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1- The maximum number of trials was 100000
2- CPU Time in this case is the total time used to simulate the two scenarios

#### DIFFERENCE : Fawley Scenario - No Fawley Scenario

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<th>Interruption Cost (k£)</th>
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<th>Best Scenario</th>
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### 2.2 Case 2

This case considers the following:

- **VOLL** is a function of duration of interruption (Data from [5]). A consumer distribution of 35% residential consumers, 27% commercial consumers, 34% industrial consumers and 4% large users is assumed. The assumed busbar’s load factor is 0.65.
- No weather effect is considered, i.e. the failure rates for average weather conditions are used.
• Cascade and sympathetic tripping are not simulated.
• The simulation extends over 24 hours

Table 2.6 Monte Carlo Simulation Case 2 SW System

<table>
<thead>
<tr>
<th>Sample</th>
<th>Trials</th>
<th>Total Cost (k£)</th>
<th>Interruption Cost (k£)</th>
<th>Generation Cost (k£)</th>
<th>Standard Dev. σ (k£)</th>
<th>σ / μ [%]</th>
<th>CPU Time [min]</th>
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<td>4531</td>
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<td>3090</td>
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<td>174.9</td>
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Table 2.7 Case 2 SW System - Total Costs Intervals

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<th>Probability [%]</th>
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<th>No-Fawley [k£]</th>
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<td>[4281, 4464]</td>
<td>[4343, 4528]</td>
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</table>

The maximum number of trials was 100000. Convergence criterion of 95% of degree of confidence and 5% of confidence interval.

The estimated total cost or value of security is given in the total row of each scenario in Table 2.6 with a degree of confidence higher than 99%. Table 2.7 gives the confidence intervals for both scenarios under the case 2 assumptions. Note that these confidence intervals intersect and the interval for one case includes the average value of the other case. The best scenario therefore cannot be determined from this analysis.

Table 2.6 shows the results obtained for this case using the naive Monte Carlo simulation (i.e. without any of the variance reduction methods available in the program). As in case 1, the maximum number of trials was set at 100000 for each sample. A convergence criterion of 5% of the mean value for the 95% degree of confidence was used.

The expected generation cost of case 2 is the same as in case 1 (Table 2.3). The cost variation from case 1 to case 2 is less than 0.03%. This result is not surprising since the modelling of VOLL does not modify computation of generation cost.

The interruption cost computed with a VOLL function of the duration of interruption is higher than the interruption cost computed with a constant VOLL. This result was also expected because the lowest VOLL value (see section 9.3) is 5.6£/kWh (for an...
interruption of 24 hr) which is 2.24 times higher than the constant VOLL that was used (2.5 £/kWh).

The ratio of the interruption costs computed with the variable VOLL (case 2) and the constant VOLL (case 1) is 5.68 for the Fawley scenario and 4.76 for the No-Fawley scenario. These ratios imply an average VOLL, in case 2, of 14.21£/kWh for the first scenario and 11.90 £/kWh for No-Fawley scenario.

Comparison of these average VOLL with the variable VOLL function (see section 9.3) indicates that when an interruption occurs its average duration is around 4 hours with the Fawley scenario, while in No-Fawley scenario this average duration is around 8 hours. However, note that the events in case 2 and case 1 are different.

### 2.2.1 Selection of the Best Scenario

Correlated sampling was used to determine the best scenario. Table 2.8 shows results of different samples that use the quick comparison option. A 95% confidence degree criterion was used in the simulation. The general conclusion is that the best scenario is the No-Fawley scenario.

As shown in Table 2.8, correlated sampling gives an estimate of the total cost with a high standard deviation and, hence, a low degree of confidence is obtained (71 %). This is explained by two facts: correlated sampling uses a small number of trials and the purpose of analysis is different. The method compares different scenarios using the same trial in each one. The trial can be either of low cost or of high cost and the purpose is to define the cheapest scenario. That is the reason also of the high value of the $\frac{\sigma}{\mu}$ ratio.

The interruption cost is lower in the No-Fawley scenario, under the system conditions specified in this study case. However, there are samples from which the opposite conclusion could be drawn (Sample 4).
### Table 2.8 Case 2 SW System – Correlation Sampling

#### CASE 2 - SCENARIO FAWLEY

<table>
<thead>
<tr>
<th>Sample</th>
<th>Trials</th>
<th>Total Cost ((k£))</th>
<th>Interruption Cost ((k£))</th>
<th>Generation Cost ((k£))</th>
<th>Standard Dev. (\sigma) ((k£))</th>
<th>(\sigma / \mu) [%]</th>
<th>CPU Time ([\text{min}]^2)</th>
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#### CASE 2 - SCENARIO NO FAWLEY

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<th>Interruption Cost ((k£))</th>
<th>Generation Cost ((k£))</th>
<th>Standard Dev. (\sigma) ((k£))</th>
<th>(\sigma / \mu) [%]</th>
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1- The maximum number of trials was 100000
2- CPU Time in this case is the total time used to simulate the two scenarios

### DIFFERENCE : Fawley Scenario - No Fawley Scenario

<table>
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<th>Sample</th>
<th>Total Cost ((k£))</th>
<th>Interruption Cost ((k£))</th>
<th>Generation Cost ((k£))</th>
<th>Standard Dev. (\sigma) ((k£))</th>
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### 2.2.2 Computing the Value of Security using Variance Reduction Methods

While the correlated sampling approach identifies the best scenario, it does not provide a reliable estimate of the total cost of this scenario. The naive Monte Carlo simulation (Table 2.6) provides such an answer but requires an excessive amount of CPU time.

The following variance reduction methods were thus tested to see if they appreciably reduce the necessary CPU time:

- MVA stratified sampling (Table 2.9).
MW/MVAr stratified sampling (Table 2.10).
Adaptive stratified (Table 2.11).
Auto cycle dagger (Table 2.12).
Fast cycle dagger (Table 2.13).

A 95 % degree of confidence and a 5 % interval of confidence were used for these studies.

Figure 2.2 compares the total and interruption costs obtained for the Fawley scenario using different stratified variance reduction methods, while Figure 2.3 makes the same comparison for the No-Fawley scenario. Figure 2.4 compares the required number of trials by stratified methods as a percentage of the number of trials employed by the naïve Monte Carlo Simulation.

Table 2.9 Case 2 SW System - Variance Reduction: MVA Stratified -

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<th>Generation Cost (k£)</th>
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<td>4514</td>
<td>1498</td>
<td>3016</td>
<td>55</td>
<td>1.22</td>
<td></td>
</tr>
</tbody>
</table>

1- The maximum number of trials was 100000
2- Covergence criterion of 95% degree of confidence and 5% confidence interval

The following observations can be made on the application of stratified sampling:

- The different types of stratified sampling methods give an accurate estimation of the total and interruption costs, based on a comparison with the naïve Monte Carlo simulation.

- The CPU time consumption can be greatly reduced (around 45% to 65%). In some cases, the reduction can be very significant.

- The range of interruption costs obtained by the different stratified methods is very similar to the range obtained with the naïve Monte Carlo. The dispersion is also very similar.

- The total cost mean obtained by naïve Monte Carlo simulation is included in all total cost intervals associated with the stratified sampling methods. Reciprocally, the
total cost interval associated with naïve Monte Carlo simulation includes all the mean values obtained by each alternative of stratified sampling method.

Table 2.10 Case 2 SW System - Variance Reduction: MW/MVAr Stratified -

<table>
<thead>
<tr>
<th>Method</th>
<th>Trials</th>
<th>Total Cost (k£)</th>
<th>Interruption Cost (k£)</th>
<th>Generation Cost (k£)</th>
<th>Standard Dev. (k£)</th>
<th>σ / µ [%]</th>
<th>CPU Time [min]</th>
</tr>
</thead>
<tbody>
<tr>
<td>MW/MVAr Strat</td>
<td>2050</td>
<td>4216</td>
<td>1125</td>
<td>3091</td>
<td>108</td>
<td>2.55</td>
<td>23.6</td>
</tr>
<tr>
<td>MW/MVAr Strat</td>
<td>15391</td>
<td>4488</td>
<td>1400</td>
<td>3089</td>
<td>115</td>
<td>2.55</td>
<td>183.8</td>
</tr>
<tr>
<td>MW/MVAr Strat</td>
<td>19347</td>
<td>4587</td>
<td>1499</td>
<td>3089</td>
<td>117</td>
<td>2.55</td>
<td>219.7</td>
</tr>
<tr>
<td>MW/MVAr Strat</td>
<td>5982</td>
<td>4419</td>
<td>1330</td>
<td>3089</td>
<td>113</td>
<td>2.55</td>
<td>61.8</td>
</tr>
<tr>
<td>MW/MVAr Strat</td>
<td>2005</td>
<td>4197</td>
<td>1107</td>
<td>3090</td>
<td>107</td>
<td>2.55</td>
<td>21.2</td>
</tr>
<tr>
<td>Total</td>
<td>44775</td>
<td>4496</td>
<td>1408</td>
<td>3089</td>
<td>66</td>
<td>1.47</td>
<td></td>
</tr>
</tbody>
</table>

Table 2.11 Case 2 SW System- Variance Reduction: Adaptive Stratified -

<table>
<thead>
<tr>
<th>Method</th>
<th>Trials</th>
<th>Total Cost (k£)</th>
<th>Interruption Cost (k£)</th>
<th>Generation Cost (k£)</th>
<th>Standard Dev. (k£)</th>
<th>σ / µ [%]</th>
<th>CPU Time [min]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Adaptive Strat.</td>
<td>1201</td>
<td>4205</td>
<td>1115</td>
<td>3090</td>
<td>96</td>
<td>2.29</td>
<td>14.4</td>
</tr>
<tr>
<td>Adaptive Strat.</td>
<td>11298</td>
<td>4282</td>
<td>1193</td>
<td>3089</td>
<td>108</td>
<td>2.53</td>
<td>130.6</td>
</tr>
<tr>
<td>Adaptive Strat.</td>
<td>8834</td>
<td>4219</td>
<td>1128</td>
<td>3090</td>
<td>107</td>
<td>2.53</td>
<td>104.2</td>
</tr>
<tr>
<td>Adaptive Strat.</td>
<td>1985</td>
<td>3987</td>
<td>897</td>
<td>3090</td>
<td>99</td>
<td>2.48</td>
<td>23.2</td>
</tr>
<tr>
<td>Adaptive Strat.</td>
<td>15001</td>
<td>4552</td>
<td>1463</td>
<td>3089</td>
<td>97</td>
<td>2.13</td>
<td>164.0</td>
</tr>
<tr>
<td>Total</td>
<td>38319</td>
<td>4356</td>
<td>1266</td>
<td>3089</td>
<td>56</td>
<td>1.28</td>
<td></td>
</tr>
</tbody>
</table>

1- The maximum number of trials was 100000
2- Coverage criterion of 95% degree of confidence and 5% confidence interval
Figure 2.2 Case 2 SW System, Fawley – Comparison of Variants of the Stratified Sampling Variance Reduction Method

Figure 2.3 Case 2 SW System, No Fawley – Comparison of Variants of the Stratified Sampling Variance Reduction Method

Figure 2.4 Case 2 SW System– Number of Trials required for the Variants of the Stratified Sampling Variance Reduction Method
Figure 2.5 compares the total and interruption costs obtained for the two scenarios using two variants of dagger sampling method of variance reduction. Figure 2.6 compares the required number of trials by dagger sampling variants as a percentage of the number of trials required by the naïve Monte Carlo Simulation.

The following observations can be made about the dagger sampling variance reduction method:

- The different variants of dagger sampling give an accurate estimate of the total and interruption costs based on a comparison with naïve Monte Carlo simulation.
- The reduction of CPU time consumption is small (5% to 25%).
- The slow cycle dagger option requires a number of trials higher than the maximum number of trials (100000). For this reason, this variant has not been tested.
- The total cost mean obtained by naïve Monte Carlo simulation is included in all the total cost intervals associated with the dagger variants. On the other hand, the total cost intervals associated with the naïve Monte Carlo simulation includes, with only one exception that is close to the superior limit, the mean values obtained by the variants of the dagger sampling method.

Table 2.12 Case 2 SW System– Variance Reduction: Auto Cycle Dagger –

<table>
<thead>
<tr>
<th>Method</th>
<th>Trials</th>
<th>Total Cost (k£)</th>
<th>Interruption Cost (k£)</th>
<th>Generation Cost (k£)</th>
<th>Standard Dev. (k£)</th>
<th>σ / µ [%]</th>
<th>CPU Time [min]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Auto Cycle Dagger</td>
<td>680</td>
<td>3438</td>
<td>350</td>
<td>3088</td>
<td>80</td>
<td>2.31</td>
<td>8.4</td>
</tr>
<tr>
<td>Auto Cycle Dagger</td>
<td>10720</td>
<td>4363</td>
<td>1273</td>
<td>3090</td>
<td>111</td>
<td>2.54</td>
<td>127.1</td>
</tr>
<tr>
<td>Auto Cycle Dagger</td>
<td>18440</td>
<td>4360</td>
<td>1271</td>
<td>3090</td>
<td>111</td>
<td>2.54</td>
<td>203.2</td>
</tr>
<tr>
<td>Auto Cycle Dagger</td>
<td>5920</td>
<td>4319</td>
<td>1229</td>
<td>3090</td>
<td>109</td>
<td>2.53</td>
<td>61.9</td>
</tr>
<tr>
<td>Auto Cycle Dagger</td>
<td>28560</td>
<td>4536</td>
<td>1447</td>
<td>3089</td>
<td>116</td>
<td>2.55</td>
<td>321.0</td>
</tr>
<tr>
<td>Total</td>
<td>64320</td>
<td>4425</td>
<td>1336</td>
<td>3089</td>
<td>64</td>
<td>1.44</td>
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</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Method</th>
<th>Trials</th>
<th>Total Cost (k£)</th>
<th>Interruption Cost (k£)</th>
<th>Generation Cost (k£)</th>
<th>Standard Dev. (k£)</th>
<th>σ / µ [%]</th>
<th>CPU Time [min]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Auto Cycle Dagger</td>
<td>24520</td>
<td>4582</td>
<td>1566</td>
<td>3016</td>
<td>117</td>
<td>2.54</td>
<td>281.7</td>
</tr>
<tr>
<td>Auto Cycle Dagger</td>
<td>20920</td>
<td>4398</td>
<td>1382</td>
<td>3016</td>
<td>112</td>
<td>2.54</td>
<td>227.6</td>
</tr>
<tr>
<td>Auto Cycle Dagger</td>
<td>19160</td>
<td>4301</td>
<td>1284</td>
<td>3017</td>
<td>109</td>
<td>2.54</td>
<td>204.1</td>
</tr>
<tr>
<td>Auto Cycle Dagger</td>
<td>1320</td>
<td>3650</td>
<td>632</td>
<td>3018</td>
<td>87</td>
<td>2.39</td>
<td>11.8</td>
</tr>
<tr>
<td>Auto Cycle Dagger</td>
<td>21200</td>
<td>4361</td>
<td>1344</td>
<td>3016</td>
<td>111</td>
<td>2.55</td>
<td>245.2</td>
</tr>
<tr>
<td>Total</td>
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<td>4408</td>
<td>1392</td>
<td>3016</td>
<td>56</td>
<td>1.27</td>
<td></td>
</tr>
</tbody>
</table>

1- The maximum number of trials was 100000
2- Coverage criterion of 95% degree of confidence and 5% confidence interval
Table 2.13 Case 2 SW System – Variance Reduction: Fast Cycle Dagger –

<table>
<thead>
<tr>
<th>Method</th>
<th>Trials</th>
<th>Total Cost (k£)</th>
<th>Interruption Cost (k£)</th>
<th>Generation Cost (k£)</th>
<th>Standard Dev. σ (k£)</th>
<th>σ / µ [%]</th>
<th>CPU Time [min]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fast Cycle Dagger</td>
<td>19960</td>
<td>4562</td>
<td>1472</td>
<td>3089</td>
<td>116</td>
<td>2.54</td>
<td>235.3</td>
</tr>
<tr>
<td>Fast Cycle Dagger</td>
<td>1560</td>
<td>3906</td>
<td>815</td>
<td>3091</td>
<td>96</td>
<td>2.46</td>
<td>15.4</td>
</tr>
<tr>
<td>Fast Cycle Dagger</td>
<td>21160</td>
<td>4548</td>
<td>1459</td>
<td>3089</td>
<td>116</td>
<td>2.55</td>
<td>222.1</td>
</tr>
<tr>
<td>Fast Cycle Dagger</td>
<td>5720</td>
<td>4051</td>
<td>960</td>
<td>3090</td>
<td>102</td>
<td>2.53</td>
<td>57.6</td>
</tr>
<tr>
<td>Fast Cycle Dagger</td>
<td>17480</td>
<td>4469</td>
<td>1379</td>
<td>3090</td>
<td>114</td>
<td>2.54</td>
<td>188.4</td>
</tr>
<tr>
<td>Total</td>
<td>65880</td>
<td>4473</td>
<td>1383</td>
<td>3089</td>
<td>60</td>
<td>1.34</td>
<td>719</td>
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</table>

Sample Trials 1

<table>
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<tr>
<th>Method</th>
<th>Trials</th>
<th>Total Cost (k£)</th>
<th>Interruption Cost (k£)</th>
<th>Generation Cost (k£)</th>
<th>Standard Dev. σ (k£)</th>
<th>σ / µ [%]</th>
<th>CPU Time [min]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fast Cycle Dagger</td>
<td>8080</td>
<td>4285</td>
<td>1267</td>
<td>3017</td>
<td>109</td>
<td>2.53</td>
<td>87.9</td>
</tr>
<tr>
<td>Fast Cycle Dagger</td>
<td>28400</td>
<td>4500</td>
<td>1483</td>
<td>3016</td>
<td>115</td>
<td>2.54</td>
<td>332.9</td>
</tr>
<tr>
<td>Fast Cycle Dagger</td>
<td>23680</td>
<td>4499</td>
<td>1482</td>
<td>3016</td>
<td>115</td>
<td>2.55</td>
<td>270.1</td>
</tr>
<tr>
<td>Fast Cycle Dagger</td>
<td>20880</td>
<td>4563</td>
<td>1547</td>
<td>3016</td>
<td>114</td>
<td>2.50</td>
<td>236.7</td>
</tr>
<tr>
<td>Fast Cycle Dagger</td>
<td>26320</td>
<td>4615</td>
<td>1599</td>
<td>3016</td>
<td>118</td>
<td>2.55</td>
<td>298.0</td>
</tr>
<tr>
<td>Total</td>
<td>107360</td>
<td>4524</td>
<td>1508</td>
<td>3016</td>
<td>54</td>
<td>1.20</td>
<td>1225</td>
</tr>
</tbody>
</table>

1- The maximum number of trials was 100000
2- Convergence criterion of 95% degree of confidence and 5% confidence interval

Figure 2.5 Case 2 SW System - Comparison of Variants of the Dagger Sampling Variance Reduction Method
Table 2.14 Case 2 SW System – Total costs intervals by scenario (95% of confidence)

<table>
<thead>
<tr>
<th>Method</th>
<th>Fawley [k£]</th>
<th>No-Fawley [k£]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Naïve Monte Carlo</td>
<td>[4281, 4464]</td>
<td>[4343, 4528]</td>
</tr>
<tr>
<td>MVA Strat</td>
<td>[4212, 4444]</td>
<td>[4406, 4623]</td>
</tr>
<tr>
<td>MW/MVAr Strat</td>
<td>[4367, 4626]</td>
<td>[4395, 4608]</td>
</tr>
<tr>
<td>Adaptive Stratified</td>
<td>[4215, 4433]</td>
<td>[4269, 4495]</td>
</tr>
<tr>
<td>Dagger Fast Cycle</td>
<td>[4355, 4591]</td>
<td>[4417, 4630]</td>
</tr>
<tr>
<td>Dagger AutoCycle</td>
<td>[4300, 4550]</td>
<td>[4299, 4517]</td>
</tr>
</tbody>
</table>

Table 2.14 compares the intervals of confidence for the total cost in both scenarios. It is important to mention that the simulations of both scenarios with the same method and criterion did not use the same simulated events.

2.3 Case 3

This case uses the following modelling characteristics:

- VOLL is a function of the duration of interruption defined as in Case 2.
- Adverse weather conditions between 17 and 21 hours.
- Cascade and sympathetic tripping are not simulated.
- The simulation extends over 24 hours

This case differs from case 2 only in the consideration of adverse weather effects.

The last two sections (sections 2.1 and 2.2) have shown that correlated sampling is a quick way to determine the best scenario in a set of possible dispatches. However, it gives an estimate of the total cost with only a low degree of confidence. Hence, another method must be used to compute the value of security, but only for the best scenario.

This strategy is used in the analysis of case 3. Table 2.15 presents the application of correlated sampling for selection of the best scenario. 7 out of 8 samples suggest that the best scenario is the Fawley scenario.
Table 2.15 Case 3 SW System– Correlated Sampling – Selection of the Best Scenario

**CASE 3- SCENARIO FAWLEY**

<table>
<thead>
<tr>
<th>Sample</th>
<th>Trials 1</th>
<th>Total Cost (k£)</th>
<th>Interruption Cost (k£)</th>
<th>Generation Cost (k£)</th>
<th>Standard Dev. σ (k£)</th>
<th>σ / μ [%]</th>
<th>CPU Time [min] 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
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<td>6474</td>
<td>3386</td>
<td>3088</td>
<td>727</td>
<td>11.23</td>
<td>13.4</td>
</tr>
<tr>
<td>2</td>
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<td>4995</td>
<td>1905</td>
<td>3090</td>
<td>612</td>
<td>12.26</td>
<td>6.7</td>
</tr>
<tr>
<td>3</td>
<td>3151</td>
<td>6469</td>
<td>3380</td>
<td>3090</td>
<td>313</td>
<td>4.84</td>
<td>81.3</td>
</tr>
<tr>
<td>4</td>
<td>6672</td>
<td>5948</td>
<td>2859</td>
<td>3090</td>
<td>184</td>
<td>3.09</td>
<td>165.5</td>
</tr>
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<td>5</td>
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<td>12692</td>
<td>5738</td>
<td>2648</td>
<td>3090</td>
<td>124</td>
<td>2.16</td>
<td>318.7</td>
</tr>
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<td>7</td>
<td>2548</td>
<td>5997</td>
<td>2907</td>
<td>3090</td>
<td>260</td>
<td>4.34</td>
<td>90.0</td>
</tr>
<tr>
<td>8</td>
<td>2650</td>
<td>6177</td>
<td>3090</td>
<td>3088</td>
<td>319</td>
<td>5.16</td>
<td>96.0</td>
</tr>
<tr>
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<td>5937</td>
<td>2848</td>
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<td>83</td>
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</tr>
</tbody>
</table>

**CASE 3- SCENARIO NO FAWLEY**

<table>
<thead>
<tr>
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<th>Trials 1</th>
<th>Total Cost (k£)</th>
<th>Interruption Cost (k£)</th>
<th>Generation Cost (k£)</th>
<th>Standard Dev. σ (k£)</th>
<th>σ / μ [%]</th>
<th>CPU Time [min] 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
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<td>762</td>
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<td>1902</td>
<td>3017</td>
<td>614</td>
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<td>3151</td>
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<td>5.05</td>
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<td>3016</td>
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<td>6083</td>
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<td>3016</td>
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<td>90.0</td>
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</tr>
</tbody>
</table>

1- The maximum number of trials was 100000
2- CPU Time in this case is the total time used to simulate the two scenarios

**DIFFERENCE : Fawley Scenario - No Fawley Scenario**

<table>
<thead>
<tr>
<th>Sample</th>
<th>Total Cost (k£)</th>
<th>Interruption Cost (k£)</th>
<th>Generation Cost (k£)</th>
<th>Standard Dev. σ (k£)</th>
<th>σ / μ [%]</th>
<th>Best Scenario</th>
</tr>
</thead>
<tbody>
<tr>
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<td>100.9</td>
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</tr>
<tr>
<td>2</td>
<td>76.8</td>
<td>3.7</td>
<td>73.1</td>
<td>8.4</td>
<td>10.9</td>
<td>No Fawley</td>
</tr>
<tr>
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<td>-114.7</td>
<td>-188.5</td>
<td>73.8</td>
<td>57.2</td>
<td>-49.9</td>
<td>Fawley</td>
</tr>
<tr>
<td>4</td>
<td>-96.3</td>
<td>-169.9</td>
<td>73.6</td>
<td>49.1</td>
<td>-51.0</td>
<td>Fawley</td>
</tr>
<tr>
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<td>-88.2</td>
<td>-161.7</td>
<td>73.5</td>
<td>42.9</td>
<td>-48.6</td>
<td>Fawley</td>
</tr>
<tr>
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<td>-63.8</td>
<td>-137.3</td>
<td>73.5</td>
<td>32.6</td>
<td>-51.1</td>
<td>Fawley</td>
</tr>
<tr>
<td>7</td>
<td>-86.6</td>
<td>-160.3</td>
<td>73.7</td>
<td>43.8</td>
<td>-50.6</td>
<td>Fawley</td>
</tr>
<tr>
<td>8</td>
<td>-71.3</td>
<td>-144.6</td>
<td>73.3</td>
<td>35.4</td>
<td>-49.6</td>
<td>Fawley</td>
</tr>
<tr>
<td>Total</td>
<td>-81.5</td>
<td>-155.0</td>
<td>73.6</td>
<td>35.4</td>
<td>-49.6</td>
<td>Fawley</td>
</tr>
</tbody>
</table>

Correlated sampling requires a large number of trials (see total rows) in this case. Hence, the σ/μ ratio satisfies the 95% degree of confidence criterion for the 5% confidence interval. This observation is used in Table 2.16, which shows the interval of confidence for total costs for both scenarios. Note that sample 6 also satisfies the convergence criterion.

The following conclusions can be drawn from this test:
• A 95% degree of confidence is not the same thing as a certainty. In some cases, the conclusions shown by a sample will be contradicted by other samples.

• Adverse weather conditions can change the best operating condition and the Assessor of Value of Security program can detect this change. Under the condition of case 2, the No Fawley scenario has a lower total cost that the Fawley scenario. Under the conditions of case 3, this conclusion is reversed.

• The total cost can be obtained directly from correlated sampling if and only if the ratio $\sigma/\mu$ satisfies the specified convergence criterion. In such a case, an additional computation of total cost by other method is not necessary.

<table>
<thead>
<tr>
<th>Table 2.16 Case 3 SW System - Total Costs Intervals</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Probability [%]</strong></td>
</tr>
<tr>
<td>----------------------</td>
</tr>
<tr>
<td>95.0</td>
</tr>
</tbody>
</table>

2.4 Case 4

This case considers the following conditions:

• VOLL is a function of the duration of interruptions as defined in Case 2.
• Average weather conditions hold during the full 24 hours period.
• Cascade and sympathetic tripping are simulated.
• The simulation extends over 24 hours

This case differs from study case 2 only in the consideration of cascade and sympathetic tripping effects.

The analysis was carried out in two steps: determination of the best scenario using correlated sampling and computation of value of security for this scenario.

The selection of the best scenario step by correlated sampling (Table 2.17) determines that the No-Fawley scenario is the best. In this case, none of the samples satisfies the convergence criterion needed to determine the value of security.

The second step relies on the adaptive stratified sampling method because this method has been shown to require the smallest number of trials for computing the value of security in the South-Western system. Table 2.18 shows the results for this step. The value of security interval is [4510, 4731] in k£.

Comparison with the total cost obtained in study case 2 (adaptive sampling from Table 2.11 and total cost interval from Table 2.14) concludes that consideration of sympathetic tripping has an important effect on the computation of value of security.
### Table 2.17 Case 4 SW System - Correlated Sampling - Selection of the Best Scenario

#### CASE 4- SCENARIO FAWLEY

<table>
<thead>
<tr>
<th>Sample</th>
<th>Trials</th>
<th>Total Cost (k£)</th>
<th>Interruption Cost (k£)</th>
<th>Generation Cost (k£)</th>
<th>Standard Dev. (k£)</th>
<th>σ / µ [%]</th>
<th>CPU Time [min]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>507</td>
<td>4388</td>
<td>1295</td>
<td>3093</td>
<td>326</td>
<td>7.44</td>
<td>13.1</td>
</tr>
<tr>
<td>2</td>
<td>694</td>
<td>4828</td>
<td>1742</td>
<td>3086</td>
<td>1094</td>
<td>22.66</td>
<td>12.7</td>
</tr>
<tr>
<td>3</td>
<td>3611</td>
<td>4702</td>
<td>1613</td>
<td>3088</td>
<td>288</td>
<td>6.13</td>
<td>78.9</td>
</tr>
<tr>
<td>4</td>
<td>423</td>
<td>4108</td>
<td>1017</td>
<td>3091</td>
<td>319</td>
<td>7.76</td>
<td>8.6</td>
</tr>
<tr>
<td>5</td>
<td>300</td>
<td>4282</td>
<td>1190</td>
<td>3092</td>
<td>441</td>
<td>10.31</td>
<td>7.5</td>
</tr>
<tr>
<td>6</td>
<td>1097</td>
<td>4353</td>
<td>1262</td>
<td>3092</td>
<td>211</td>
<td>4.84</td>
<td>28.8</td>
</tr>
<tr>
<td>7</td>
<td>300</td>
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<td>1315</td>
<td>3094</td>
<td>409</td>
<td>9.28</td>
<td>5.2</td>
</tr>
<tr>
<td>8</td>
<td>300</td>
<td>3729</td>
<td>642</td>
<td>3087</td>
<td>219</td>
<td>5.88</td>
<td>4.1</td>
</tr>
<tr>
<td>Total</td>
<td>7232</td>
<td>4534</td>
<td>1445</td>
<td>3089</td>
<td>185</td>
<td>4.08</td>
<td></td>
</tr>
</tbody>
</table>

#### CASE 4- SCENARIO NO FAWLEY

<table>
<thead>
<tr>
<th>Sample</th>
<th>Trials</th>
<th>Total Cost (k£)</th>
<th>Interruption Cost (k£)</th>
<th>Generation Cost (k£)</th>
<th>Standard Dev. (k£)</th>
<th>σ / µ [%]</th>
<th>CPU Time [min]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>507</td>
<td>4318</td>
<td>1299</td>
<td>3019</td>
<td>343</td>
<td>7.95</td>
<td>13.1</td>
</tr>
<tr>
<td>2</td>
<td>694</td>
<td>4777</td>
<td>1765</td>
<td>3013</td>
<td>1096</td>
<td>22.95</td>
<td>12.7</td>
</tr>
<tr>
<td>3</td>
<td>3611</td>
<td>4633</td>
<td>1618</td>
<td>3015</td>
<td>295</td>
<td>6.38</td>
<td>78.9</td>
</tr>
<tr>
<td>4</td>
<td>423</td>
<td>4058</td>
<td>1040</td>
<td>3018</td>
<td>331</td>
<td>8.16</td>
<td>8.6</td>
</tr>
<tr>
<td>5</td>
<td>300</td>
<td>4210</td>
<td>1191</td>
<td>3019</td>
<td>441</td>
<td>10.47</td>
<td>5.2</td>
</tr>
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<td>1097</td>
<td>4297</td>
<td>1279</td>
<td>3018</td>
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</tr>
<tr>
<td>7</td>
<td>300</td>
<td>4324</td>
<td>1303</td>
<td>3021</td>
<td>413</td>
<td>9.55</td>
<td>5.2</td>
</tr>
<tr>
<td>8</td>
<td>300</td>
<td>3465</td>
<td>449</td>
<td>3016</td>
<td>152</td>
<td>4.40</td>
<td>4.1</td>
</tr>
<tr>
<td>Total</td>
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<td>4461</td>
<td>1445</td>
<td>3016</td>
<td>189</td>
<td>4.23</td>
<td></td>
</tr>
</tbody>
</table>

1- The maximum number of trials was 100000
2- CPU Time in this case is the total time used to simulate the two scenarios

### DIFFERENCE : Fawley Scenario - No Fawley Scenario

<table>
<thead>
<tr>
<th>Sample</th>
<th>Total Cost (k£)</th>
<th>Interruption Cost (k£)</th>
<th>Generation Cost (k£)</th>
<th>Standard Dev. (k£)</th>
<th>σ / µ [%]</th>
<th>Best Scenario</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>69.5</td>
<td>-4.5</td>
<td>74.0</td>
<td>35.3</td>
<td>50.8</td>
<td>No Fawley</td>
</tr>
<tr>
<td>2</td>
<td>50.3</td>
<td>-22.6</td>
<td>72.9</td>
<td>25.6</td>
<td>50.9</td>
<td>No Fawley</td>
</tr>
<tr>
<td>3</td>
<td>68.8</td>
<td>-4.3</td>
<td>73.1</td>
<td>35.1</td>
<td>51.0</td>
<td>No Fawley</td>
</tr>
<tr>
<td>4</td>
<td>49.8</td>
<td>-23.1</td>
<td>72.9</td>
<td>25.3</td>
<td>50.8</td>
<td>No Fawley</td>
</tr>
<tr>
<td>5</td>
<td>72.0</td>
<td>-1.3</td>
<td>73.3</td>
<td>1.5</td>
<td>2.1</td>
<td>No Fawley</td>
</tr>
<tr>
<td>6</td>
<td>56.3</td>
<td>-17.0</td>
<td>73.3</td>
<td>26.9</td>
<td>47.8</td>
<td>No Fawley</td>
</tr>
<tr>
<td>7</td>
<td>84.8</td>
<td>11.8</td>
<td>73.0</td>
<td>16.1</td>
<td>19.0</td>
<td>No Fawley</td>
</tr>
<tr>
<td>8</td>
<td>264.1</td>
<td>192.5</td>
<td>71.6</td>
<td>121.8</td>
<td>46.1</td>
<td>No Fawley</td>
</tr>
<tr>
<td>Total</td>
<td>73.0</td>
<td>-0.1</td>
<td>73.1</td>
<td></td>
<td></td>
<td>No Fawley</td>
</tr>
</tbody>
</table>

### Table 2.18 Case 4 SW System – Computation of Value of Security - CASE 4- SCENARIO NO FAWLEY - Variance Reduction Methods Application

<table>
<thead>
<tr>
<th>Sample</th>
<th>Trials</th>
<th>Total Cost (k£)</th>
<th>Interruption Cost (k£)</th>
<th>Generation Cost (k£)</th>
<th>Standard Dev. (k£)</th>
<th>σ / µ [%]</th>
<th>CPU Time [min]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Adaptive Strat.</td>
<td>13001</td>
<td>4813</td>
<td>1798</td>
<td>3015</td>
<td>107</td>
<td>2.22</td>
<td>162.7</td>
</tr>
<tr>
<td>Adaptive Strat.</td>
<td>13493</td>
<td>4808</td>
<td>1793</td>
<td>3016</td>
<td>105</td>
<td>2.18</td>
<td>161.5</td>
</tr>
<tr>
<td>Adaptive Strat.</td>
<td>3022</td>
<td>4065</td>
<td>1047</td>
<td>3018</td>
<td>99</td>
<td>2.44</td>
<td>36.1</td>
</tr>
<tr>
<td>Adaptive Strat.</td>
<td>11875</td>
<td>4442</td>
<td>1426</td>
<td>3016</td>
<td>116</td>
<td>2.61</td>
<td>132.8</td>
</tr>
<tr>
<td>Adaptive Strat.</td>
<td>1775</td>
<td>3928</td>
<td>911</td>
<td>3017</td>
<td>97</td>
<td>2.47</td>
<td>17.1</td>
</tr>
<tr>
<td>Total</td>
<td>43166</td>
<td>4621</td>
<td>1605</td>
<td>3016</td>
<td>56</td>
<td>1.22</td>
<td></td>
</tr>
</tbody>
</table>

1- The maximum number of trials was 100000
2- Convergence criterion 95% degree of confidence and 5% confidence interval
2.5 Case 5

This case considers the following conditions:

- VOLL is a function of the duration of interruptions as defined in Case 2.
- Average weather condition hold during the full 24 hours period.
- Cascade and sympathetic tripping are not simulated.
- The simulation extends over 24 hours
- The failure rate of DIDC3A, which is equal to the Fawley’s failure rate in previous cases, is equal to DIDC2A’s failure rate.

As in case 4, the analysis consists of two steps: the determination of the best scenario using correlated sampling and the computation of the value of security for this scenario.

The selection of the best scenario step by correlated sampling (Table 2.19) determines that the No-Fawley scenario is the best. In this case, none of the samples satisfies the convergence criterion needed to determine the value of security.

The second step relies on the adaptive stratified sampling method because this method requires smallest number of trials for computing the value of security in the South-Western system. Table 2.20 shows the results of simulations for this case. The value of security interval is [4486, 4704] in k£.

Comparison with the total cost obtained in study case 2 (adaptive sampling from Table 2.11 and total cost interval from Table 2.14) shows that an increase in the failure rate of Didcot3A provokes an increase in the interruption and total costs. This is a logical and expected result.
Table 2.19 Case 5 SW System – Correlation Sampling – Selection of Best Scenario

<table>
<thead>
<tr>
<th>Sample</th>
<th>Trials</th>
<th>Total Cost (k£)</th>
<th>Interruption Cost (k£)</th>
<th>Generation Cost (k£)</th>
<th>Standard Dev. (k£)</th>
<th>σ / µ [%]</th>
<th>CPU Time [min]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1132</td>
<td>4107</td>
<td>1017</td>
<td>3090</td>
<td>311</td>
<td>7.56</td>
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</tr>
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<td>2</td>
<td>300</td>
<td>4099</td>
<td>1009</td>
<td>3090</td>
<td>394</td>
<td>9.61</td>
<td>7.8</td>
</tr>
<tr>
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<td>574</td>
<td>3860</td>
<td>770</td>
<td>3090</td>
<td>202</td>
<td>5.22</td>
<td>14.0</td>
</tr>
<tr>
<td>4</td>
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<td>4203</td>
<td>1112</td>
<td>3091</td>
<td>330</td>
<td>7.85</td>
<td>10.0</td>
</tr>
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<td>300</td>
<td>3929</td>
<td>840</td>
<td>3090</td>
<td>394</td>
<td>10.03</td>
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<td>6</td>
<td>300</td>
<td>4010</td>
<td>919</td>
<td>3091</td>
<td>342</td>
<td>8.52</td>
<td>4.8</td>
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<tr>
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<td>300</td>
<td>4629</td>
<td>1543</td>
<td>3086</td>
<td>1160</td>
<td>25.06</td>
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<td>8</td>
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<td>4210</td>
<td>1117</td>
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<td>13.0</td>
</tr>
<tr>
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<td>4115</td>
<td>1025</td>
<td>3090</td>
<td>148</td>
<td>3.60</td>
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</tr>
</tbody>
</table>

1- The maximum number of trials was 100000
2- CPU Time in this case is the total time used to simulate the two scenarios

DIFFERENCE : Fawley Scenario - No Fawley Scenario

<table>
<thead>
<tr>
<th>Sample</th>
<th>Total Cost (k£)</th>
<th>Interruption Cost (k£)</th>
<th>Generation Cost (k£)</th>
<th>Standard Dev. (k£)</th>
<th>σ / µ [%]</th>
<th>Best Scenario</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>46.1</td>
<td>-26.6</td>
<td>72.7</td>
<td>23.5</td>
<td>51.0</td>
<td>No Fawley</td>
</tr>
<tr>
<td>2</td>
<td>91.1</td>
<td>18.6</td>
<td>72.5</td>
<td>18.6</td>
<td>20.4</td>
<td>No Fawley</td>
</tr>
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<td>3</td>
<td>176.0</td>
<td>103.6</td>
<td>72.4</td>
<td>89.6</td>
<td>50.9</td>
<td>No Fawley</td>
</tr>
<tr>
<td>4</td>
<td>143.3</td>
<td>70.3</td>
<td>73.0</td>
<td>72.9</td>
<td>50.9</td>
<td>No Fawley</td>
</tr>
<tr>
<td>5</td>
<td>65.4</td>
<td>-6.9</td>
<td>72.3</td>
<td>5.5</td>
<td>8.4</td>
<td>No Fawley</td>
</tr>
<tr>
<td>6</td>
<td>69.6</td>
<td>-3.4</td>
<td>73.0</td>
<td>2.4</td>
<td>3.4</td>
<td>No Fawley</td>
</tr>
<tr>
<td>7</td>
<td>82.9</td>
<td>10.7</td>
<td>72.2</td>
<td>9.2</td>
<td>11.1</td>
<td>No Fawley</td>
</tr>
<tr>
<td>8</td>
<td>51.5</td>
<td>-21.9</td>
<td>73.4</td>
<td>26.3</td>
<td>51.1</td>
<td>No Fawley</td>
</tr>
<tr>
<td>Total</td>
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<td>72.7</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 2.20 Case 5 SW System – Computation of Value of Security -

<table>
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<tr>
<th>Sample</th>
<th>Trials</th>
<th>Total Cost (k£)</th>
<th>Interruption Cost (k£)</th>
<th>Generation Cost (k£)</th>
<th>Standard Dev. (k£)</th>
<th>σ / µ [%]</th>
<th>CPU Time [min]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Adaptive Strat.</td>
<td>18358</td>
<td>4580</td>
<td>1564</td>
<td>3016</td>
<td>116</td>
<td>2.53</td>
<td>219.9</td>
</tr>
<tr>
<td>Adaptive Strat.</td>
<td>2808</td>
<td>4232</td>
<td>1214</td>
<td>3018</td>
<td>105</td>
<td>2.49</td>
<td>34.3</td>
</tr>
<tr>
<td>Adaptive Strat.</td>
<td>5001</td>
<td>4514</td>
<td>1496</td>
<td>3018</td>
<td>106</td>
<td>2.34</td>
<td>59.5</td>
</tr>
<tr>
<td>Adaptive Strat.</td>
<td>13001</td>
<td>4514</td>
<td>1497</td>
<td>3017</td>
<td>114</td>
<td>2.52</td>
<td>145.8</td>
</tr>
<tr>
<td>Adaptive Strat.</td>
<td>15111</td>
<td>4777</td>
<td>1760</td>
<td>3017</td>
<td>94</td>
<td>1.96</td>
<td>165.4</td>
</tr>
<tr>
<td>Total</td>
<td>54279</td>
<td>4595</td>
<td>1578</td>
<td>3017</td>
<td>55</td>
<td>1.21</td>
<td></td>
</tr>
</tbody>
</table>

1- The maximum number of trials was 100000
2- Convergence criterion 95% degree of confidence and 5% confidence interval
3 SETTING SIMULATION PARAMETERS – USING A LARGE POWER SYSTEM

As the Value of Security Assessor uses a Monte Carlo probabilistic method for the computation of the cost of outages, it needs the definition of some parameters in order to give confidence to the results. These parameters are:

- The convergence criterion
- The minimum number of trials

Decisions about these parameters affect not only the confidence in the results but also the computation time.

3.1 Defining the Convergence Criterion

The Assessor uses the following equation as convergence criterion

\[ \frac{\alpha \sigma}{\mu} \leq x\% \]  

(3.1)

Where the value of \( \alpha \) depends of the degree of confidence required and it is 2.567 and 1.956 for a 99% and 95% confidence degree respectively. \( x \) is the convergence parameter.

In the tables that follow, the confidence that can be associated with the results is given in terms of the ratio of the standard deviation to the mean value of the total cost of value of security (\( \sigma/\mu \)). Table 2.2 gives the value of this ratio associated with some combinations of degrees of confidence and confidence interval.

The confidence interval is defined as a function of the mean (\( \mu \)) and standard deviation (\( \sigma \)) values and the degree of confidence as in equation (2.1). \( \alpha \) in equation (2.1) is equal to 1.96 for a 95% degree of confidence and 2.57 for a 99% degree of confidence.

The Assessor has the facility to use as mean value (\( \mu \)) either the outage cost or the total cost of operation of the system. The outage cost is defined as the load interruption cost plus the generation rescheduling cost. The total cost is defined as the outage cost plus the cost associated with the original generation schedule.

Therefore, the Assessor requires the definition of:

- Confidence degree
- Convergence parameter or confidence interval degree (equation 2.1)
- Partial blackout reference cost (see equations 3.7 to 3.10)

The following discussion will be based on a sample test of the NGC system 1996/97 under normal weather conditions. A total of 30000 trials were simulated. Partial results were recorded each 100 trials in order to see the evolution of both the mean value of the outage and total costs and of the standard deviation (\( \sigma \)).
3.1.1 Outage and Total Cost

Figure 3.1 shows the evolution of the mean value of the outage cost. It also shows some mean values. These values are before and after a large variation in the outage cost mean value occurs.

This strong variation indicates that a big outage (total or partial blackout) caused by some contingency (or contingencies) was present in this interval of trials. Obviously, other outage cases were presented in other trials of this sample, but with a small impact on the mean value.

The interesting point about these three severe outages is that their costs are very close. Table 3.1 shows a comparison of the outage cost for the 100 trials interval where the severe contingency occurs.

![Outage Cost Evolution of Mean Value](image)

Table 3.1 Outage Cost Severe Outages intervals

<table>
<thead>
<tr>
<th>Severe contingency’s interval</th>
<th>Outage Cost (k£) of the 100 Trials interval</th>
</tr>
</thead>
<tbody>
<tr>
<td>2100 – 2200</td>
<td>632200</td>
</tr>
<tr>
<td>8000 – 8100</td>
<td>631840</td>
</tr>
<tr>
<td>28900 – 29000</td>
<td>630860</td>
</tr>
</tbody>
</table>

The effect of a new severe outage on the mean value of the outage cost will be smaller outwards of the 30000 trials. This means that there are enough trials to “ensure” that, if one of the new trials results in a major incident, the effect of the interruption cost of this incident will not affect “too much” the values of the mean and the standard deviation.

As the total cost is equal to the outage cost plus a constant value (6876.8 k£), the evolution of this variable is similar to the evolution of the outage cost.

3.1.2 Standard Deviation Evolution and Convergence Criterion

The standard deviation evolves in a very similar manner as the mean value (Figure 3.2) with large variations due to the severe outages.
Since, $\alpha$ is a constant value, equation (3.1) can be written as:

$$\frac{\sigma}{\mu} \leq y\%$$  \hspace{1cm} (3.2)

As $\mu$ can be either the total cost or the outage cost, two different patterns are possible for the $\sigma/\mu$ ratio. Figure 3.3 shows the evolution of this ratio when the total cost is used. A convergence criterion of 99% confidence degree and 1% confidence interval means that $y$ in (3.2) is 0.39%. Based on Figure 3.3, it is clear that the simulation will be stopped before the first severe contingency. The ratio $\sigma$/Total Cost is smaller than 0.39% from interval 200-300 trials until interval 2000-2100 trials. So, if the minimum number of trials is lower than 2000 (in this sample) the simulation stops at the minimum number with results that do not include severe shocks to the system.

On the other hand, if the minimum number of trials is set larger than 2100 the simulation will require more than 30000 trials.
Table 3.2 shows an estimate of the number of trials to satisfy different convergence criteria based on the $\sigma/\mu$ ratio ($\mu$ of the Total Cost). As it is shown, the confidence interval is more significant than the confidence degree for determining the number of trials. On the other hand, the convergence is not reached before 26000 or 27000 trials (from Figure 3.3).

Therefore, an appropriate convergence criterion on $\sigma$/Total Cost ratio is 95%-1% using a larger minimum number of trials.

### Table 3.2 Estimation of number of trials

<table>
<thead>
<tr>
<th>Confidence Degree</th>
<th>Confidence Interval</th>
<th>$y$ [%] Value</th>
<th>Estimated Number of Trials</th>
</tr>
</thead>
<tbody>
<tr>
<td>99 %</td>
<td>1 %</td>
<td>0.39 %</td>
<td>&gt; 30000</td>
</tr>
<tr>
<td>95 %</td>
<td>1 %</td>
<td>0.51 %</td>
<td>Around 30000</td>
</tr>
<tr>
<td>99 %</td>
<td>5 %</td>
<td>1.95 %</td>
<td>4600</td>
</tr>
<tr>
<td>95 %</td>
<td>5 %</td>
<td>2.56 %</td>
<td>3500</td>
</tr>
</tbody>
</table>

As was mentioned above, the $\sigma/\mu$ ratio could be computed using the mean value of the outage cost rather than the total cost. Figure 3.4 shows the evolution of this ratio for the $\mu$ of the Outage Cost.

As the cost associated with the original scheduled generation (constant value) is not included here, the interruption cost is not masked by the total cost of operation. However, setting of the convergence criterion is a problem.

If $\mu$ and $\sigma$ are respectively the mean value and the standard deviation of the outage cost and $\alpha$ is the parameter associated with the confidence degree, the interval of confidence of the value of security is given by:

$$[\mu - \alpha \sigma, \mu + \alpha \sigma]$$  \hspace{1cm} (3.3)

![Evolution of $\sigma$/Outage Cost](image)

**Figure 3.4 Evolution $\sigma$ / $\mu$ (Outage Cost)**

If $y$ is defined as:
Then, the interval of (3.3) is re-defined as:

\[
\left[ \mu (1 - \alpha y), \mu (1 + \alpha y) \right]
\]

(3.5)

Since the simulation contains at least one trial with load interruption, the outage cost value is non-zero. Hence, \( y \) must satisfy:

\[
y < \frac{1}{\alpha}
\]

(3.6)

So, \( y \) is 38.9\% and 51.1\% for a confidence degree of 99\% and 95\% respectively. Based on this constraint and Figure 3.4, the test simulation requires more than 30000 trials for a 99\% degree of confidence and 19000 trials for a 95\% degree of confidence. A confidence degree of 99\% is recommended when an \( \sigma/\text{Outage cost} \) ratio is used.

3.1.3 A new constraint

The cost of a blackout (\( C_{\text{blackout}} \)) can be computed a-priori based on the load restoration model, the load demand and the VOLL function. Assume that the simulation stops at trial \( i \).

The impact of a major outage on the mean value at the next trial (i.e. \( i+1 \)) is lower than the impact produced by a blackout and is given by:

\[
\mu_{i+1} = \frac{i \mu_i + C_{\text{blackout}}}{i+1}
\]

(3.7)

Dividing by \( \mu_i \), when \( i \) is large, equation (3.7) is approximated by

\[
\frac{\mu_{i+1}}{\mu_i} \approx 1 + \frac{C_{\text{blackout}}}{i \mu_i}
\]

(3.8)

On the other hand, the confidence interval gives the interval with certain probability where the true value of the outage cost is. If it is assumed that the confidence interval for trial \( i \) includes all major incidents, the following equation must be satisfied

\[
\mu_i + \alpha \sigma_i \geq \mu_i + \frac{C_{\text{major incident}}}{i}
\]

(3.9)

where \( C_{\text{major incident}} \) is the cost associated with a major incident (for example a blackout). So, a minimum value of standard deviation as function of the number of trials that gives a confidence interval including major incidents is defined as:

\[
\sigma_{\text{min}}(i) = \frac{C_{\text{major incident}}}{\alpha} \frac{1}{i}
\]

(3.10)
Figure 3.5 Minimal Standard Deviation

Figure 3.5 shows a comparison of $\sigma$ and $\sigma_{\text{min}}$ for the test used. The blackout cost has been used as the cost of the major incident. As the figure shows the first 2100 trials do not satisfy this constraint. This constraint could be moved depending on the value of the cost of the major incident that is took to define it.

### 3.2 Setting the Minimum Number of Trials

One of the most important parameters to set for the simulation is the minimum number of trials. The last section suggests that a large number must be used for this parameter.

In the sample test used in section 3.1, it is clear that the minimum value for trials must be larger than 2100. But, how can it be defined before the simulation?

Assume that a new sample will be simulated and a convergence criterion on $\sigma/\mu$ ratio ($\mu$, Total Cost) of 95%-1% will be used. Let $x$ represent the minimum number of trials.

Simulation of these $x$ trials can give one of the following results:

1. A least one severe contingency was present and the convergence criterion is not satisfied at trial $x$. The simulation continues until the convergence criterion is satisfied. The calculated value of security will be reliable.

2. As in the previous case, severe outages are present but the convergence criterion is satisfied at trial $x$. The simulation stops and the results are reliable. This case is unlikely.

3. No severe outages occur before trial $x$ and the convergence criterion is not satisfied. The simulation continues until the convergence criterion is satisfied. This case is improbable.

4. No severe outages occurred before trial $x$ and the convergence criterion is satisfied. Simulation stops. The results are unreliable.
Figure 3.6 shows the evolution of the $\sigma/\mu$ ratio (Total Cost) for a new sample of the test system. The convergence criterion is satisfied if the ratio is less than 0.51%. At trial 4000 (x), the simulation stops. None severe contingency was present. Note that the $\sigma$/Total Cost ratio is much smaller than ratio for satisfying the converge criterion (0.51%).

![Evolution of $\sigma$/Total Cost](image)

**Figure 3.6 Simulation Sample – Minimum number of trials = 4000 -**

Table 3.3 compares the outage cost and the standard deviation for the original test sample (sample 1) and the new sample (sample 2). The difference is clear.

<table>
<thead>
<tr>
<th>Sample</th>
<th>Outage Cost (k£)</th>
<th>$\sigma$ (k£)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>92.8</td>
<td>36.6</td>
</tr>
<tr>
<td>2</td>
<td>37.8</td>
<td>11.3</td>
</tr>
</tbody>
</table>

Sample 2 was run another time with the minimum number of trials set at 10000. A severe contingency occurs between trials 4500 and 4600. This suggests that a larger minimum value must be used.

The minimum number of trials can be set based on the initial test sample (sample 1) as the number of trials divided by the number of severe outages (30000/3). The problem of setting this parameter in this way is that it requires a large number of trials. On the other hand, in spite of setting a large number as the minimum number of trials (x), it is still possible that the simulation will stop at the minimum x with a small $\sigma$/Total Cost ratio.

It is therefore not enough a large value for setting the minimum number of trials. There is always a risk of getting non-reliable results.

One important characteristic: the $\sigma/\mu$ ($\mu$ is the total cost average) ratio is smaller than the convergence criterion ratio during almost all the simulation. As Figure 3.6 shows, the $\sigma/\mu$ ratio decreases quickly in the first trials (<1000). After that, it remains very small.
So, a method for automatically adjusting the minimum number of trials has been developed. It is based on the concept of minimum standard deviation presented before and works as follow:

1. Choose values for the initial minimum number of trials $x$ and its increment $\Delta x$. Assume that the required $\sigma_{\text{min}}$ is a low percentage ($z\%$) of the scheduled generation cost. As the cost of the reference major incident ($C_{\text{major incident}}$) is known a priori and the confidence degree defines the $\alpha$ value, the $x$ value is computed from equation (2.11) as:

$$x = \frac{C_{\text{major incident}}}{\alpha \sigma_{\text{min}}}$$  \hspace{1cm} (3.11)

Define $\Delta x$ as a percentage of $x$ (e.g. 10%).

2. Simulate until the minimum number of trials $x$ is reached.

3. Compare $\sigma$ to $\sigma_{\text{min}}(x)$. If $\sigma$ is smaller than $\sigma_{\text{min}}(x)$, increase $x$ to $x + \Delta x$ and go to step 2.

4. Continue the simulation without a new adjustment of the minimum number of trials.

At the last point, the $\sigma/\mu$ ratio is compared to the ratio given by the convergence criteria. If the $\sigma/\mu$ ratio is smaller than the convergence criteria (0.51%) the simulation stops. In the other case (i.e. it is higher than 0.51%), the simulation continues until it satisfies the convergence criteria.
4 TESTING THE ASSESSOR OF VALUE OF SECURITY ON A LARGE POWER SYSTEM - THE NGC SYSTEM

A model of the NGC transmission system for 1996/97 has been used for testing the Value of Security Assessor program on a large power system. This model has 700 nodes, 1464 branches (lines, transformers and shunt compensation equipment) and 82 available generators. The load demand is at the minimum: 34484 MW.

The data on reliability of transmission equipment provided by [1] has been used as typical data for this system. Failure rates of transmission lines have been computed using their length (See appendix B of [2]). Failure rates of generators have been computed from forced outage rates (FOR) provided in [3] and assuming mean time to repair (MTTR) values given by [4]. The generation prices associated with each generator are given in appendix D of [2].

The same load restoration process has been assumed in all cases. Each step was given a duration of 20 minutes. The simulation therefore involves 3 subintervals for each hour.

The system has been divided into 8 areas for the weather modelling. These areas are:

1- Scotland
2- Northwest
3- Northeast
4- Yorkshire
5- West Midlands
6- East Anglia
7- London including the Thames Estuary, Inner and Outer London, and the Southeast coast
8- Southwest and South of Wales

4.1 Scenarios

Three scenarios have been defined for testing the Assessor:

- Scenario 1 is the base scenario. The reserve margin is 2342 MW. Units 1 and 2 of DIDCOT are running. Units 1 to 4 at West Burton are running.

- Scenario 2. Units 1, 3 and 4 of DIDCOT are running. Units 1 to 4 of West Burton are running but reduced total generated power. The difference with scenario 1 is the replacement of generation from West Burton by generation from Didcot and the commitment of one more unit replacement at Didcot. The reserve margin is 2843 MW.

- Scenario 3. Units 1, 3 and 4 of DIDCOT are running. Units 1, 3 and 4 of West Burton are running. The difference with scenario 1 is the replacement of generation from West Burton by generation from Didcot without changing the reserve margin
of the system. The reserve margin is 2349 MW, almost equal to the scenario 1’s reserve margin.

4.2 Computation of Value of Security by Naïve Monte Carlo

As an initial step for testing the Value of Security Assessor program with a large power system, naïve Monte Carlo simulations were run for each scenario. Three different cases are used. Their main characteristics are:

- **Case 1**: No weather effect is considered, i.e. the failure rates for average weather conditions are used. Cascade and sympathetic tripping are not simulated.
- **Case 2**: No weather effect is considered. Cascade and sympathetic tripping are simulated.
- **Case 3**: Adverse weather conditions are applied to the south of the system (areas 6, 7, 8), i.e. the area around Didcot. Cascade and sympathetic tripping are simulated.

Simulations of each case use the following:

- **VOLL** is a function of the duration of interruption (Data from [5]). A consumer distribution of 35% residential consumers, 27% commercial consumers, 34% industrial consumers and 4% large users is assumed. The load factor is assumed to be 0.65 at each node.
- The simulation extends over 1 hour using 3 intervals of 20 minutes.
- A convergence criterion of 95% confidence degree and 1% confidence interval, as it is recommended in section 3.1. The total cost is used for computation of the convergence criterion, i.e. the expected value of $y$ (equation 3.2) is 0.51.
- The minimum number of trials is computed by the auto-adjustable method. The initial minimum number of trials is 4860. The incremental value is 10%.

4.2.1 Case 1

Table 4.1 presents the results obtained for case 1 for the three scenarios. Two samples were run for each scenario.

These samples are stopped by the specified criterion. Some simulations have required the adjustment of the minimum number of trials in order to satisfy equation 3.10. In this way, the confidence in the results is guaranteed. Note that each sample includes at least one severe outage in the system.

Fulfilment of the minimum standard deviation criterion (equation 3.10) makes the results reliable but requires a lot of time due to the increase in the number of trials required.
Table 4.1 Case 1 NGC System – Naïve Monte Carlo Simulation -

<table>
<thead>
<tr>
<th>Sample</th>
<th>Trials ¹</th>
<th>Final Adjusted Minimum</th>
<th>Total Cost (k£)</th>
<th>Interruption Cost (k£)</th>
<th>Reschedule Generation Cost (k£)</th>
<th>Standard Dev. σ (k£)</th>
<th>σ / µ [%]</th>
<th>CPU Time</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
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<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>12502</td>
<td>5346</td>
<td>6938.4</td>
<td>62.5</td>
<td>-0.9</td>
<td>35.4</td>
<td>0.51</td>
<td>339' 23&quot;</td>
</tr>
<tr>
<td>2</td>
<td>25234</td>
<td>4860</td>
<td>6955.1</td>
<td>79.3</td>
<td>-1.0</td>
<td>35.5</td>
<td>0.51</td>
<td>596' 12&quot;</td>
</tr>
<tr>
<td>Total</td>
<td>37736</td>
<td></td>
<td>6949.6</td>
<td>73.7</td>
<td>-1.0</td>
<td>26.5</td>
<td>0.38</td>
<td></td>
</tr>
</tbody>
</table>

CASE 1- SCENARIO 2 - System NGC 1996/97

<table>
<thead>
<tr>
<th>Sample</th>
<th>Trials ¹</th>
<th>Final Adjusted Minimum</th>
<th>Total Cost (k£)</th>
<th>Interruption Cost (k£)</th>
<th>Reschedule Generation Cost (k£)</th>
<th>Standard Dev. σ (k£)</th>
<th>σ / µ [%]</th>
<th>CPU Time</th>
</tr>
</thead>
<tbody>
<tr>
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<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>25216</td>
<td>5346</td>
<td>6947.4</td>
<td>71.0</td>
<td>-0.4</td>
<td>35.4</td>
<td>0.51</td>
<td>665' 37&quot;</td>
</tr>
<tr>
<td>2</td>
<td>30824</td>
<td>11664</td>
<td>6955.6</td>
<td>79.4</td>
<td>-0.6</td>
<td>35.5</td>
<td>0.51</td>
<td>799' 1&quot;</td>
</tr>
<tr>
<td>Total</td>
<td>56040</td>
<td></td>
<td>6951.9</td>
<td>75.6</td>
<td>-0.5</td>
<td>25.2</td>
<td>0.36</td>
<td></td>
</tr>
</tbody>
</table>

CASE 1- SCENARIO 3 - System NGC 1996/97

<table>
<thead>
<tr>
<th>Sample</th>
<th>Trials ¹</th>
<th>Final Adjusted Minimum</th>
<th>Total Cost (k£)</th>
<th>Interruption Cost (k£)</th>
<th>Reschedule Generation Cost (k£)</th>
<th>Standard Dev. σ (k£)</th>
<th>σ / µ [%]</th>
<th>CPU Time</th>
</tr>
</thead>
<tbody>
<tr>
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<td></td>
</tr>
<tr>
<td>1</td>
<td>7578</td>
<td>4860</td>
<td>6930.1</td>
<td>54.0</td>
<td>-0.7</td>
<td>35.5</td>
<td>0.51</td>
<td>184' 34&quot;</td>
</tr>
<tr>
<td>2</td>
<td>30918</td>
<td>4860</td>
<td>6976.0</td>
<td>100.4</td>
<td>-1.2</td>
<td>29.4</td>
<td>0.42</td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>38496</td>
<td></td>
<td>6967.0</td>
<td>91.3</td>
<td>-1.1</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

1- Maximum number of trials = 100000.
Minimum number of trials = 4860 (auto-adjustable).
Convergence criterion of 95% of degree of confidence and 1% of confidence interval

4.2.2 Case 2

Table 4.2 Case 2 NGC System – Naïve Monte Carlo Simulation -

<table>
<thead>
<tr>
<th>Sample</th>
<th>Trials ¹</th>
<th>Final Adjusted Minimum</th>
<th>Total Cost (k£)</th>
<th>Interruption Cost (k£)</th>
<th>Reschedule Generation Cost (k£)</th>
<th>Standard Dev. σ (k£)</th>
<th>σ / µ [%]</th>
<th>CPU Time</th>
</tr>
</thead>
<tbody>
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<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>18468</td>
<td>18468</td>
<td>6948.2</td>
<td>72.4</td>
<td>-1.0</td>
<td>34.5</td>
<td>0.50</td>
<td>429' 11&quot;</td>
</tr>
<tr>
<td>2</td>
<td>18373</td>
<td>5346</td>
<td>6958.6</td>
<td>82.8</td>
<td>-1.0</td>
<td>35.5</td>
<td>0.51</td>
<td>490' 32&quot;</td>
</tr>
<tr>
<td>Total</td>
<td>36841</td>
<td></td>
<td>6953.4</td>
<td>77.6</td>
<td>-1.0</td>
<td>24.7</td>
<td>0.36</td>
<td></td>
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CASE 2- SCENARIO 2 - System NGC 1996/97

<table>
<thead>
<tr>
<th>Sample</th>
<th>Trials ¹</th>
<th>Final Adjusted Minimum</th>
<th>Total Cost (k£)</th>
<th>Interruption Cost (k£)</th>
<th>Reschedule Generation Cost (k£)</th>
<th>Standard Dev. σ (k£)</th>
<th>σ / µ [%]</th>
<th>CPU Time</th>
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<td></td>
</tr>
<tr>
<td>1</td>
<td>47628</td>
<td>47628</td>
<td>6903.7</td>
<td>26.9</td>
<td>0.0</td>
<td>3.4</td>
<td>0.05</td>
<td>1470' 01&quot;</td>
</tr>
<tr>
<td>2</td>
<td>18025</td>
<td>17982</td>
<td>6939.0</td>
<td>62.6</td>
<td>-0.4</td>
<td>35.4</td>
<td>0.51</td>
<td>489' 31&quot;</td>
</tr>
<tr>
<td>Total</td>
<td>65653</td>
<td></td>
<td>6913.4</td>
<td>36.7</td>
<td>-0.1</td>
<td>10.0</td>
<td>0.15</td>
<td></td>
</tr>
</tbody>
</table>

CASE 2- SCENARIO 3 - System NGC 1996/97

<table>
<thead>
<tr>
<th>Sample</th>
<th>Trials ¹</th>
<th>Final Adjusted Minimum</th>
<th>Total Cost (k£)</th>
<th>Interruption Cost (k£)</th>
<th>Reschedule Generation Cost (k£)</th>
<th>Standard Dev. σ (k£)</th>
<th>σ / µ [%]</th>
<th>CPU Time</th>
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<td></td>
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<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>7020</td>
<td>7020</td>
<td>6942.4</td>
<td>66.4</td>
<td>-0.8</td>
<td>33.8</td>
<td>0.49</td>
<td>156' 55&quot;</td>
</tr>
<tr>
<td>2</td>
<td>17900</td>
<td>4680</td>
<td>6942.9</td>
<td>67.0</td>
<td>-0.9</td>
<td>35.4</td>
<td>0.51</td>
<td>426' 54&quot;</td>
</tr>
<tr>
<td>Total</td>
<td>24920</td>
<td></td>
<td>6942.8</td>
<td>66.8</td>
<td>-0.9</td>
<td>27.2</td>
<td>0.39</td>
<td></td>
</tr>
</tbody>
</table>

1- Maximum number of trials = 100000.
Minimum number of trials = 4860 (auto-adjustable).
Convergence criterion of 95% of degree of confidence and 1% of confidence interval
Table 4.2 presents the results obtained for case 2 for the three scenarios. Two samples were run for each scenario. These samples are stopped by the specified criterion.

Only 1 sample has not required the adjustment of the minimum value of trials in order to satisfy equation 3.10. 4 samples have required many adjustments to the minimum such as the final minimum number of trials is very close to the required number of trials. In some cases, these values are the same (sample 1 of each scenario). Sample 1 in scenario 2 has required a lot of simulations to satisfy equation 3.10 criterion. Severe outages are not present in this sample, that is the reason of the small value of the standard deviation.

On the other hand, the outage costs are similar to those obtained in case 1. Note that the system is operating at a low load level, so the effect of cascade or sympathetic tripping could be diminished.

4.2.3 Case 3

Table 4.3 presents the results obtained for case 3 for the three scenarios. The adverse weather increases the number of contingencies and, hence, the number of trials to be analysed. Results show that the interruption cost increases as expected.

<table>
<thead>
<tr>
<th>Sample</th>
<th>Trials</th>
<th>Final Adjusted Minimum</th>
<th>Total Cost (k£)</th>
<th>Interruption Cost (k£)</th>
<th>Reschedule Generation Cost (k£)</th>
<th>Standard Dev. σ (k£)</th>
<th>σ / μ [%]</th>
<th>CPU Time [min]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>5346</td>
<td>5346</td>
<td>7100.8</td>
<td>226.3</td>
<td>-2.3</td>
<td>34.5</td>
<td>0.49</td>
<td>505' 59&quot;</td>
</tr>
<tr>
<td>2</td>
<td>25127</td>
<td>18468</td>
<td>7045.1</td>
<td>170.2</td>
<td>-1.9</td>
<td>35.5</td>
<td>0.50</td>
<td>2155' 22&quot;</td>
</tr>
<tr>
<td>Total</td>
<td>30473</td>
<td></td>
<td>7054.9</td>
<td>180.0</td>
<td>-2.0</td>
<td>29.9</td>
<td>0.42</td>
<td></td>
</tr>
</tbody>
</table>

CASE 3- SCENARIO 2 - System NGC 1996/97

<table>
<thead>
<tr>
<th>Sample</th>
<th>Trials</th>
<th>Final Adjusted Minimum</th>
<th>Total Cost (k£)</th>
<th>Interruption Cost (k£)</th>
<th>Reschedule Generation Cost (k£)</th>
<th>Standard Dev. σ (k£)</th>
<th>σ / μ [%]</th>
<th>CPU Time [min]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>21951</td>
<td>4860</td>
<td>7098.6</td>
<td>223.6</td>
<td>-1.8</td>
<td>36.2</td>
<td>0.51</td>
<td>2448' 30&quot;</td>
</tr>
<tr>
<td>2</td>
<td>22356</td>
<td>22356</td>
<td>7007.2</td>
<td>131.3</td>
<td>-0.9</td>
<td>28.7</td>
<td>0.41</td>
<td>2494' 32&quot;</td>
</tr>
<tr>
<td>Total</td>
<td>44307</td>
<td></td>
<td>7052.5</td>
<td>177.0</td>
<td>-1.3</td>
<td>23.1</td>
<td>0.33</td>
<td></td>
</tr>
</tbody>
</table>

CASE 3- SCENARIO 3 - System NGC 1996/97

<table>
<thead>
<tr>
<th>Sample</th>
<th>Trials</th>
<th>Final Adjusted Minimum</th>
<th>Total Cost (k£)</th>
<th>Interruption Cost (k£)</th>
<th>Reschedule Generation Cost (k£)</th>
<th>Standard Dev. σ (k£)</th>
<th>σ / μ [%]</th>
<th>CPU Time [min]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>65728</td>
<td>7488</td>
<td>7212.0</td>
<td>338.6</td>
<td>-3.4</td>
<td>36.8</td>
<td>0.51</td>
<td>6570' 1&quot;</td>
</tr>
</tbody>
</table>

1- Maximum number of trials = 100000.
Minimum number of trials = 4860 (auto-adjustable).
Convergence criterion of 95% of degree of confidence and 1% of confidence interval

On the other hand, the simulation time increases dramatically. Almost all the samples have required the adjustment of the minimum number of trials. In some cases, the required number of trials is equal to the adjusted minimum.
4.3 Correlated Sampling

Reference [12] has shown that correlated sampling is a good method for selecting the best scenario. Section 4.2 shows the results of the computation of the value of security for three scenarios under and three cases. However, the computation of the value of security intervals does not allow the selection of the best scenario in a direct way. The correlated sampling is used here to select the best scenario in each case (the cases are defined in section 4.2).

4.3.1 Case 1

The comparison of the three scenarios is realised in two steps: first two scenarios are compared (scenario 1 vs. scenario 2) and then the best of them is compared with the third scenario (scenario 3).

Table 4.4 Case 1 NGC System – Scenario 1 vs. Scenario 2 - Correlated Sampling

<table>
<thead>
<tr>
<th>Sample</th>
<th>Trials 1</th>
<th>Total Cost (k£)</th>
<th>Interruption Cost (k£)</th>
<th>Generation Cost (k£)</th>
<th>Standard Dev. σ (k£)</th>
<th>σ / µ [%]</th>
<th>CPU Time [min] 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1995</td>
<td>6908.2</td>
<td>31.9</td>
<td>6876.3</td>
<td>12.1</td>
<td>0.18</td>
<td>191' 33&quot;</td>
</tr>
<tr>
<td>2</td>
<td>1000</td>
<td>6881.6</td>
<td>5.0</td>
<td>6876.6</td>
<td>3.2</td>
<td>0.05</td>
<td>61' 53&quot;</td>
</tr>
<tr>
<td>3</td>
<td>5783</td>
<td>6914.2</td>
<td>38.0</td>
<td>6876.2</td>
<td>13.4</td>
<td>0.19</td>
<td>226' 54&quot;</td>
</tr>
<tr>
<td>4</td>
<td>1941</td>
<td>6897.2</td>
<td>20.8</td>
<td>6876.4</td>
<td>7.5</td>
<td>0.11</td>
<td>84' 17&quot;</td>
</tr>
<tr>
<td>5</td>
<td>4113</td>
<td>7053.3</td>
<td>177.5</td>
<td>6875.8</td>
<td>147.1</td>
<td>2.09</td>
<td>185' 45&quot;</td>
</tr>
<tr>
<td>Total</td>
<td>14832</td>
<td>6947.5</td>
<td>71.4</td>
<td>6876.2</td>
<td>41.2</td>
<td>0.59</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Sample</th>
<th>Trials 1</th>
<th>Total Cost (k£)</th>
<th>Interruption Cost (k£)</th>
<th>Generation Cost (k£)</th>
<th>Standard Dev. σ (k£)</th>
<th>σ / µ [%]</th>
<th>CPU Time [min] 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1995</td>
<td>6894.5</td>
<td>17.6</td>
<td>6879.6</td>
<td>7.3</td>
<td>0.11</td>
<td>191' 33&quot;</td>
</tr>
<tr>
<td>2</td>
<td>1000</td>
<td>6882.0</td>
<td>5.0</td>
<td>6877.0</td>
<td>3.2</td>
<td>0.05</td>
<td>61' 53&quot;</td>
</tr>
<tr>
<td>3</td>
<td>5783</td>
<td>6909.8</td>
<td>33.1</td>
<td>6876.7</td>
<td>0.4</td>
<td>0.01</td>
<td>226' 54&quot;</td>
</tr>
<tr>
<td>4</td>
<td>1941</td>
<td>6884.6</td>
<td>7.6</td>
<td>6877.0</td>
<td>2.9</td>
<td>0.04</td>
<td>84' 17&quot;</td>
</tr>
<tr>
<td>5</td>
<td>4113</td>
<td>7045.1</td>
<td>168.7</td>
<td>6876.4</td>
<td>147.2</td>
<td>2.09</td>
<td>185' 45&quot;</td>
</tr>
<tr>
<td>Total</td>
<td>14832</td>
<td>6940.1</td>
<td>63.4</td>
<td>6876.7</td>
<td>40.8</td>
<td>0.59</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Sample</th>
<th>Total Cost (k£)</th>
<th>Interruption Cost (k£)</th>
<th>Generation Cost (k£)</th>
<th>Standard Dev. σ (k£)</th>
<th>σ / µ [%]</th>
<th>Best Scenario</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>13.7</td>
<td>14.3</td>
<td>-0.6</td>
<td>6.3</td>
<td>46.0</td>
<td>Scenario 2</td>
</tr>
<tr>
<td>2</td>
<td>-0.4</td>
<td>0.0</td>
<td>-0.4</td>
<td>0.0</td>
<td>0.08</td>
<td>Scenario 1</td>
</tr>
<tr>
<td>3</td>
<td>4.4</td>
<td>4.9</td>
<td>-0.5</td>
<td>2.2</td>
<td>50.0</td>
<td>Scenario 2</td>
</tr>
<tr>
<td>4</td>
<td>12.6</td>
<td>13.2</td>
<td>-0.6</td>
<td>6.4</td>
<td>50.8</td>
<td>Scenario 2</td>
</tr>
<tr>
<td>5</td>
<td>8.2</td>
<td>8.8</td>
<td>-0.6</td>
<td>3.9</td>
<td>47.6</td>
<td>Scenario 2</td>
</tr>
<tr>
<td>Total</td>
<td>7.5</td>
<td>8.0</td>
<td>-0.5</td>
<td></td>
<td></td>
<td>Scenario 2</td>
</tr>
</tbody>
</table>

1- Maximum number of trials = 100000. Minimum number of trials = 1000.
Convergence criterion of 95% of degree of confidence
2- CPU Time in this case is the total time used to simulate the two scenarios.
Table 4.5 Case 1 NGC System – Scenario 2 vs. Scenario 3 – Correlated Sampling

<table>
<thead>
<tr>
<th>Sample</th>
<th>Trials ¹</th>
<th>Total Cost (k£)</th>
<th>Interruption Cost (k£)</th>
<th>Generation Cost (k£)</th>
<th>Standard Dev. σ (k£)</th>
<th>σ / µ [%]</th>
<th>CPU Time [min] ²</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1000</td>
<td>6877.7</td>
<td>0.6</td>
<td>6877.1</td>
<td>0.5</td>
<td>0.01</td>
<td>102' 33&quot;</td>
</tr>
<tr>
<td>2</td>
<td>1527</td>
<td>6896.2</td>
<td>19.3</td>
<td>6876.9</td>
<td>7.3</td>
<td>0.11</td>
<td>84' 55&quot;</td>
</tr>
<tr>
<td>3</td>
<td>2921</td>
<td>6899.3</td>
<td>22.4</td>
<td>6876.9</td>
<td>11.6</td>
<td>0.17</td>
<td>188' 24&quot;</td>
</tr>
<tr>
<td>4</td>
<td>3366</td>
<td>6910.1</td>
<td>33.3</td>
<td>6876.8</td>
<td>15.2</td>
<td>0.22</td>
<td>140' 28&quot;</td>
</tr>
<tr>
<td>5</td>
<td>5281</td>
<td>7011.0</td>
<td>134.5</td>
<td>6876.5</td>
<td>114.7</td>
<td>1.64</td>
<td>320' 54&quot;</td>
</tr>
<tr>
<td>Total</td>
<td>14095</td>
<td>6941.9</td>
<td>65.1</td>
<td>6876.7</td>
<td>43.2</td>
<td>0.62</td>
<td></td>
</tr>
</tbody>
</table>

1- Maximum number of trials = 100000. Minimum number of trials = 1000.
Convergence criterion of 95% of degree of confidence

2- CPU Time in this case is the total time used to simulate the two scenarios.

Table 4.4 compares scenarios 1 and 2 using correlated sampling. Four of the 5 samples choose scenario 2 as the best. The second sample converges at the minimum number of trials and gives almost identical cost for both scenarios. Conclusions from this sample are not reliable.

Table 4.5 compares scenario 2 (the best from the previous stage) and scenario 3. As in the previous case, four of five samples indicate scenario 2 as the best one. Sample 1 gives costs so close that the difference between them is almost zero.

Both tables show that a relatively small number of trials is required to get a reliable answer about the best scenario. Presence of major incidents (partial or total blackouts) is not necessary to draw conclusions from the correlated sampling comparison. Sample 5 in Table 4.4 is the only one that includes the simulation of a major incident in the system.
4.3.2 Case 2

Two samples are obtained for each step of scenarios comparison (scenario 1 vs. scenario 2 and the best vs. scenario 3).

Table 4.6 Case 2 NGC System – Scenario 1 vs. Scenario 2 – Correlated Sampling

<table>
<thead>
<tr>
<th>Sample</th>
<th>Trials</th>
<th>Total Cost (k£)</th>
<th>Interruption Cost (k£)</th>
<th>Generation Cost (k£)</th>
<th>Standard Dev. (k£)</th>
<th>σ / µ [%]</th>
<th>CPU Time [min]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>5436</td>
<td>6903.4</td>
<td>27.1</td>
<td>6876.3</td>
<td>9.9</td>
<td>0.14</td>
<td>252' 50&quot;</td>
</tr>
<tr>
<td>2</td>
<td>1498</td>
<td>6905.8</td>
<td>29.5</td>
<td>6876.3</td>
<td>11.9</td>
<td>0.17</td>
<td>78' 33&quot;</td>
</tr>
<tr>
<td>Total</td>
<td>6934</td>
<td>6903.9</td>
<td>27.6</td>
<td>6876.3</td>
<td>8.2</td>
<td>0.12</td>
<td></td>
</tr>
</tbody>
</table>

1- Minimum number of trials = 1000. Convergence criterion of 95% of degree of confidence
2- CPU Time in this case is the total time used to simulate the two scenarios

DIFFERENCE : Scenario 1 - Scenario 2

<table>
<thead>
<tr>
<th>Sample</th>
<th>Total Cost (k£)</th>
<th>Interruption Cost (k£)</th>
<th>Generation Cost (k£)</th>
<th>Standard Dev. (k£)</th>
<th>σ / µ [%]</th>
<th>Best Scenario</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>5.6</td>
<td>2.7</td>
<td>-0.6</td>
<td>2.7</td>
<td>48.2</td>
<td>Scenario 2</td>
</tr>
<tr>
<td>2</td>
<td>16.7</td>
<td>6.1</td>
<td>-0.7</td>
<td>8.1</td>
<td>48.5</td>
<td>Scenario 2</td>
</tr>
<tr>
<td>Total</td>
<td>8.0</td>
<td>8.6</td>
<td>-0.6</td>
<td></td>
<td></td>
<td>Scenario 2</td>
</tr>
</tbody>
</table>

Table 4.7 Case 2 NGC System – Scenario 2 vs. Scenario 3 – Correlated Sampling

<table>
<thead>
<tr>
<th>Sample</th>
<th>Trials</th>
<th>Total Cost (k£)</th>
<th>Interruption Cost (k£)</th>
<th>Generation Cost (k£)</th>
<th>Standard Dev. (k£)</th>
<th>σ / µ [%]</th>
<th>CPU Time [min]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1349</td>
<td>6892.4</td>
<td>15.5</td>
<td>6876.9</td>
<td>5.8</td>
<td>0.08</td>
<td>69' 37&quot;</td>
</tr>
<tr>
<td>2</td>
<td>1282</td>
<td>6891.0</td>
<td>14.1</td>
<td>6876.9</td>
<td>7.7</td>
<td>0.11</td>
<td>78' 38&quot;</td>
</tr>
<tr>
<td>Total</td>
<td>2631</td>
<td>6891.7</td>
<td>14.8</td>
<td>6876.9</td>
<td>4.8</td>
<td>0.07</td>
<td></td>
</tr>
</tbody>
</table>

1- Minimum number of trials = 1000. Convergence criterion of 95% of degree of confidence
2- CPU Time in this case is the total time used to simulate the two scenarios

DIFFERENCE : Scenario 2 - Scenario 3

<table>
<thead>
<tr>
<th>Sample</th>
<th>Total Cost (k£)</th>
<th>Interruption Cost (k£)</th>
<th>Generation Cost (k£)</th>
<th>Standard Dev. (k£)</th>
<th>σ / µ [%]</th>
<th>Best Scenario</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>-20.2</td>
<td>-20.8</td>
<td>0.6</td>
<td>9.7</td>
<td>48.0</td>
<td>Scenario 2</td>
</tr>
<tr>
<td>2</td>
<td>-22.0</td>
<td>-22.6</td>
<td>0.6</td>
<td>10.1</td>
<td>45.9</td>
<td>Scenario 2</td>
</tr>
<tr>
<td>Total</td>
<td>-21.1</td>
<td>-21.7</td>
<td>0.6</td>
<td></td>
<td></td>
<td>Scenario 2</td>
</tr>
</tbody>
</table>
Table 4.6 compares scenario 1 and scenario 2, while Table 4.7 compares scenario 2, the best in the previous step and scenario 3. The general conclusion is that scenario 2 is the best. As the difference between scenarios, in each comparison, is remarkable the sample simulation requires a relative small number of trials. Of preference, the required number of trials must be higher than the minimum value fixed. When the convergence criterion stops simulation at the minimum number of trials, the results are not very confident, requiring an increase of the minimum.

4.3.3 Case 3

Three samples are obtained for each step of the comparison of scenarios (scenario 1 vs. scenario 2 and the best vs. scenario 3).

Table 4.8 compares scenario 1 and scenario 2, while Table 4.9 compares scenario 2 (the best in the previous comparison) and scenario 3. Scenario 2 is again selected as the best one. Since adverse weather is modelled in 3 areas of the system, the failure rates of lines in these areas increase. The number of analysed trials also increases; hence the CPU time increases dramatically. For this reason, the maximum number of trials was set at 5000.

Table 4.8 Case 3 NGC System – Scenario 1 vs. Scenario 2 – Correlated Sampling

<table>
<thead>
<tr>
<th>Sample</th>
<th>Trials</th>
<th>Total Cost (k£)</th>
<th>Interruption Cost (k£)</th>
<th>Generation Cost (k£)</th>
<th>Standard Dev. σ (k£)</th>
<th>σ / µ [%]</th>
<th>CPU Time [min]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1136</td>
<td>7083.3</td>
<td>208.7</td>
<td>6874.6</td>
<td>46.8</td>
<td>0.66</td>
<td>235' 57&quot;</td>
</tr>
<tr>
<td>2</td>
<td>5000</td>
<td>7186.7</td>
<td>313.3</td>
<td>6873.4</td>
<td>135.8</td>
<td>1.89</td>
<td>977' 32&quot;</td>
</tr>
<tr>
<td>3</td>
<td>2155</td>
<td>7071.4</td>
<td>196.7</td>
<td>6874.7</td>
<td>36.9</td>
<td>0.52</td>
<td>408' 10&quot;</td>
</tr>
<tr>
<td>Total</td>
<td>8291</td>
<td>7142.6</td>
<td>267.8</td>
<td>6873.9</td>
<td>82.7</td>
<td>1.16</td>
<td></td>
</tr>
</tbody>
</table>

Table 4.9 Case 3 NGC System – Scenario 2 vs. Scenario 3 – Correlated Sampling

<table>
<thead>
<tr>
<th>Sample</th>
<th>Trials</th>
<th>Total Cost (k£)</th>
<th>Interruption Cost (k£)</th>
<th>Generation Cost (k£)</th>
<th>Standard Dev. σ (k£)</th>
<th>σ / µ [%]</th>
<th>CPU Time [min]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1136</td>
<td>7015.2</td>
<td>139.4</td>
<td>6875.8</td>
<td>30.7</td>
<td>0.44</td>
<td>235' 57&quot;</td>
</tr>
<tr>
<td>2</td>
<td>5000</td>
<td>7039.5</td>
<td>163.9</td>
<td>6875.6</td>
<td>19.8</td>
<td>0.28</td>
<td>977' 32&quot;</td>
</tr>
<tr>
<td>3</td>
<td>2155</td>
<td>7043.2</td>
<td>167.6</td>
<td>6875.6</td>
<td>32.8</td>
<td>0.47</td>
<td>408' 10&quot;</td>
</tr>
<tr>
<td>Total</td>
<td>8291</td>
<td>7037.1</td>
<td>161.5</td>
<td>6875.6</td>
<td>15.3</td>
<td>0.22</td>
<td></td>
</tr>
</tbody>
</table>

1- Maximum number of trials = 5000. Minimum number of trials = 1000.
2- CPU Time in this case is the total time used to simulate the two scenarios

DIFFERENCE : Scenario 1 - Scenario 2

<table>
<thead>
<tr>
<th>Sample</th>
<th>Total Cost (k£)</th>
<th>Interruption Cost (k£)</th>
<th>Generation Cost (k£)</th>
<th>Standard Dev. σ (k£)</th>
<th>σ / µ [%]</th>
<th>Best Scenario</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>68.1</td>
<td>69.3</td>
<td>-1.2</td>
<td>34.5</td>
<td>50.7</td>
<td>Scenario 2</td>
</tr>
<tr>
<td>2</td>
<td>147.2</td>
<td>149.4</td>
<td>-2.2</td>
<td>130.3</td>
<td>88.5</td>
<td>Scenario 2</td>
</tr>
<tr>
<td>3</td>
<td>28.2</td>
<td>29.1</td>
<td>-0.9</td>
<td>14.2</td>
<td>50.4</td>
<td>Scenario 2</td>
</tr>
<tr>
<td>Total</td>
<td>105.4</td>
<td>107.2</td>
<td>-1.7</td>
<td></td>
<td></td>
<td>Scenario 2</td>
</tr>
</tbody>
</table>

Sample 2 in Table 4.8 reached the maximum number of trials without satisfying the convergence criterion (see σ/µ ratio in the difference section is higher than 51%). However, the difference between scenarios is enough to conclude that scenario 2 is the best. An even larger number of trials would be required to confirm this selection.
The last comment also applies to all the samples in Table 4.9. Note that for sample 2 the conclusion is that the best scenario is the third.

Table 4.9 Case 3 NGC System – Scenario 2 vs. Scenario 3 – Correlated Sampling

<table>
<thead>
<tr>
<th>Sample</th>
<th>Trials</th>
<th>Total Cost (k£)</th>
<th>Interruption Cost (k£)</th>
<th>Generation Cost (k£)</th>
<th>Standard Dev. σ (k£)</th>
<th>σ / µ [%]</th>
<th>CPU Time [min]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>5000</td>
<td>7151.7</td>
<td>277.3</td>
<td>6874.4</td>
<td>127.1</td>
<td>1.78</td>
<td>16 hr 30'</td>
</tr>
<tr>
<td>2</td>
<td>5000</td>
<td>7101.5</td>
<td>226.5</td>
<td>6875.0</td>
<td>48.8</td>
<td>0.69</td>
<td>16 hr 30'</td>
</tr>
<tr>
<td>3</td>
<td>5000</td>
<td>7089.5</td>
<td>214.4</td>
<td>6875.1</td>
<td>33.3</td>
<td>0.47</td>
<td>16 hr 30'</td>
</tr>
<tr>
<td>Total</td>
<td>15000</td>
<td>7114.2</td>
<td>239.4</td>
<td>6874.8</td>
<td>46.7</td>
<td>0.66</td>
<td></td>
</tr>
</tbody>
</table>

**Case 3- Scenario 3 - System NGC 1996/97**

<table>
<thead>
<tr>
<th>Sample</th>
<th>Trials</th>
<th>Total Cost (k£)</th>
<th>Interruption Cost (k£)</th>
<th>Generation Cost (k£)</th>
<th>Standard Dev. σ (k£)</th>
<th>σ / µ [%]</th>
<th>CPU Time [min]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>5000</td>
<td>7184.8</td>
<td>311.4</td>
<td>6873.4</td>
<td>136.0</td>
<td>1.89</td>
<td>16 hr 30'</td>
</tr>
<tr>
<td>2</td>
<td>5000</td>
<td>7061.3</td>
<td>186.5</td>
<td>6874.8</td>
<td>23.1</td>
<td>0.33</td>
<td>16 hr 30'</td>
</tr>
<tr>
<td>3</td>
<td>5000</td>
<td>7169.2</td>
<td>294.7</td>
<td>6874.5</td>
<td>123.0</td>
<td>1.72</td>
<td>16 hr 30'</td>
</tr>
<tr>
<td>Total</td>
<td>15000</td>
<td>7138.4</td>
<td>264.2</td>
<td>6874.2</td>
<td>61.6</td>
<td>0.86</td>
<td></td>
</tr>
</tbody>
</table>

1- Maximum number of trials = 5000. Minimum number of trials = 1000.
Convergence criterion of 95% of degree of confidence
2- Estimated CPU Time in this case is the total time used to simulate the two scenarios

<table>
<thead>
<tr>
<th>Sample</th>
<th>Total Cost (k£)</th>
<th>Interruption Cost (k£)</th>
<th>Generation Cost (k£)</th>
<th>Standard Dev. σ (k£)</th>
<th>σ / µ [%]</th>
<th>Best Scenario</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>-33.1</td>
<td>-34.1</td>
<td>1.0</td>
<td>44.1</td>
<td>133.2</td>
<td>Scenario 2</td>
</tr>
<tr>
<td>2</td>
<td>40.2</td>
<td>40.0</td>
<td>0.2</td>
<td>40.2</td>
<td>100.0</td>
<td>Scenario 3</td>
</tr>
<tr>
<td>3</td>
<td>-79.7</td>
<td>-80.3</td>
<td>0.6</td>
<td>121.6</td>
<td>152.6</td>
<td>Scenario 2</td>
</tr>
<tr>
<td>Total</td>
<td>-24.2</td>
<td>-24.8</td>
<td>0.6</td>
<td></td>
<td></td>
<td>Scenario 2</td>
</tr>
</tbody>
</table>
5 CONSIDERATION OF SEVERE OUTAGES

The computation of the value of security must take into consideration the consequences of severe contingencies. As test of the Value of Security Assessor program (“Assessor”) on the NGC systems shows, severe outages have a great impact on the final statistics of Value of Security.

On the other hand, the computation of this impact imposes additional constraints on the Assessor (minimal standard deviation, equation 3.10) that ensure that this impact is included in the simulation.

The following has been observed from the Assessor’s test on the NGC system:

- Load outages can be grouped in two distinct categories: small outages and large outages.
- Major load outages are associated with partial or total blackouts. A sample simulation requires a huge number of trials to include a major outage and to satisfy the convergence criteria. A sample simulation will normally include at least one major incident.
- If a major incident is not included in a sample simulation, the minimal standard deviation constraint results in a number of trials so large that a major incident will not affect the statistics obtained from this simulation.
- Statistics for small outages can be obtained using a small number of trials. However, the Assessor has to analyse a lot of small outages for every large outage that is simulated. The simulation time required therefore increases dramatically if large outages are to be included in the simulation.

This document examines some ideas on how to compute the Value of Security taking into account the effect of major and minor incidents separately.

5.1 Some Facts

The following facts must be noted before the analysis of large and small outages:

- The outage cost associated with a total or partial blackout can be computed analytically (“a priori”). Indeed, the duration of the interruption is calculated from the total lost load and based on a model of the restoration process. As the VOLL depends on the duration of the interruption, the outage cost can be easily computed.
- Major outages (total or partial blackouts) have a very small probability. For example, 1 major incident occurs for every 17000 trials in the NGC system tests.

5.2 Assumptions

The following assumptions are formulated from the analyses of previous simulations on the NGC system:
A major incident will be defined as an incident whose outage cost is higher than a predefined value. Let $C_{\text{blackout}}$ be the outage cost for a total blackout. Outages whose cost is less than the predefined value $C_{\text{bound}}$ (see section 5.6) will be considered minor.

The outage costs of major incidents will be modelled by a probabilistic distribution function (pdf), for example a uniform distribution between $C_{\text{bound}}$ and $C_{\text{blackout}}$. Hence, the mean value ($\mu_1$) and variance of the population ($\text{var}_1$) are given by:

$$
\mu_1 = \frac{C_{\text{blackout}} + C_{\text{bound}}}{2}
$$

$$
\text{var}_1 = \frac{(C_{\text{blackout}} - C_{\text{bound}})^2}{12}
$$

The assessor will be used to compute the mean value ($\mu_2$) and the standard deviation of the estimator ($\sigma_2$) for incidents below the boundary cost, i.e. it does not take into account trials whose outage costs are higher than $C_{\text{bound}}$. The variance of the population of these incidents is given by:

$$
\text{var}_2 = n_2 \sigma_2^2
$$

where $n_2$ is the number of trials (of small incidents).

The probability of major incident ($p_1$) is uncertain and very low.

### 5.3 A Theoretical Analysis

The impact of large and small outages on the VS can be analysed using the basic theory of stratified sampling. Let us define two strata based on the outage costs: small outages and large outages. In this way, a simple estimator of the mean ($\mu$) of the value of the security is given by [13]:

$$
\mu = p_1 \mu_1 + p_2 \mu_2
$$

Subscripts 1 and 2 refer to the large and small incident strata respectively. The variance of the stratified estimator is given by [13]:

$$
\sigma^2 = \sum_{k=1}^{2} p_k^2 \frac{\text{var}_k}{n_k}
$$

where $n_k$ is the number of trials in strata $k$, and $\text{var}_k$ is the population variance in the strata (it is not the variance of the estimator).

As

$$
p_2 = \frac{n_2}{n_2 + n_1} \quad \text{and} \quad p_1 = \frac{n_1}{n_2 + n_1}
$$

Equation (5.5) becomes
\[ \sigma^2 = \frac{n_1}{(n_1 + n_2)^2} \text{var}_1 + \frac{n_2}{(n_1 + n_2)^2} \text{var}_2 \]  

(5.7)

As \( n_1 \ll n_2 \). Equation (5.5) can be approximated by:

\[ \sigma^2 = \frac{n_1 \text{var}_1}{n_2^2} + \frac{\text{var}_2}{n_2} = \frac{n_1 \text{var}_1}{n_2^2} + \sigma_2^2 \]  

(5.8)

The variance of the estimator can be computed from the variance of the estimator for small incidents obtained by the Assessor (assumption 3) and the population variance for large impacts (assumption 2). The variance of the estimator is a function of the number of trials. But this number is approximately equal to the inverse of the probability of large outages, i.e.

\[ \sigma^2(p_1) = \sigma_2^2 + p_1^2 \left( \frac{C_{\text{blackout}} - C_{\text{bound}}}{12} \right)^2 \]  

(5.9)

Consequently, the Assessor is used to compute the statistics for the small impact outages, the final statistics of the Value of Security can be obtained from equations (5.4) and (5.9). The last one is expressed as a function of the probability of major incidents.

5.4 Example

A previous simulation of scenario 1 for the system NGC 1996/97 system is used in this example. Table 5.1 shows the value of the parameters associated with the assumptions on the impact of large incidents. This table also gives the statistics results produced by the Assessor for small incidents.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Blackout Cost (k£)</td>
<td>637000</td>
</tr>
<tr>
<td>Boundary Cost (k£)</td>
<td>318500</td>
</tr>
<tr>
<td>Mean Value Large Impacts (k£)</td>
<td>477750</td>
</tr>
<tr>
<td>Population Variance Large Impacts</td>
<td>8453520833</td>
</tr>
<tr>
<td>Mean Value Small Incidents (k£)</td>
<td>Assessor- 38</td>
</tr>
<tr>
<td>Standard Deviation Estimator – Assessor -</td>
<td>11</td>
</tr>
</tbody>
</table>

Table 5.1 Example Data

Figure 5.1 shows the effect of the major impacts on the mean value and the confidence intervals (inferior border and superior border). The mean value of the Value of Security computed by Assessor for small (and frequent) incidents and the bounds of the confidence interval are independent of the probability of major incidents. Major incidents increase the mean value as well as the bounds of the confidence interval, the impact is higher if the probability of occurrence of major incidents is higher (left side in the figure).

In the NGC test (scenario 1), one major incident has been observed for almost 17000 trials. This value will be assumed to be equal to the inverse of the probability of major incidents. Figure 5.1 presents the mean value and the limits of the confidence interval for this case.
If the Assessor is used to analyse simultaneously both small and major incidents (i.e. taking into account the constraint on minimum standard deviation), the mean value of the outage cost is 79.3 k£ and the confidence interval is [9.9, 148.7]. The proposed technique therefore very significantly reduces the size of the confidence interval.

If the probability of major incidents is very small, the impact will be very small (right hand side of the figure).

5.5 Sensitivity Analysis

5.5.1 Boundary Cost

The sensitivity analysis shown in Table 5.2 illustrates the effect of moving the boundary cost (equations 5.1 and 5.2). A lower boundary value ($C_{\text{bound}}$) implies a smaller mean value for the cost of large incidents. This table shows that the variation in the statistics of the outage cost is small. The third row corresponds to the example case.

Table 5.2 Sensitivity on the Boundary Cost ($p_i^{-1} = 17000$)

<table>
<thead>
<tr>
<th>Boundary Cost (k£)</th>
<th>Estimator Mean Value (k£)</th>
<th>Inferior Border (k£)</th>
<th>Superior Border (k£)</th>
</tr>
</thead>
<tbody>
<tr>
<td>95550</td>
<td>60</td>
<td>32</td>
<td>80</td>
</tr>
<tr>
<td>159250</td>
<td>61</td>
<td>35</td>
<td>88</td>
</tr>
<tr>
<td>318500</td>
<td>66</td>
<td>42</td>
<td>90</td>
</tr>
<tr>
<td>477750</td>
<td>71</td>
<td>49</td>
<td>93</td>
</tr>
<tr>
<td>541450</td>
<td>73</td>
<td>51</td>
<td>94</td>
</tr>
</tbody>
</table>
5.5.2 Probability distribution function of major incidents

The sensitivity analysis shown Table 5.3 illustrates the effect of the choice of the pdf used to represent the major outages. This analysis uses a normal distribution function, whose mean value is equal to the average value used in Table 5.1 but whose standard deviation changes. The fourth line corresponds to a normal distribution whose standard deviation is equal to the standard deviation of the uniform distribution of the example (Table 5.1). The second column is the probability that the cost of a major incident is between the boundary cost and the blackout cost.

With a normal distribution with variance $\sigma^2_N$, equation (5.9) becomes

$$\sigma^2(p_i) = \sigma^2_2 + \rho_i^2 \sigma^2_N$$  \hspace{1cm} (5.10)

<table>
<thead>
<tr>
<th>Standard Dev. ((\sigma_N)) Major Impacts (k£)</th>
<th>Prob. %</th>
<th>Estimator Mean Value (k£)</th>
<th>Inferior Border (k£)</th>
<th>Superior Border (k£)</th>
</tr>
</thead>
<tbody>
<tr>
<td>36777</td>
<td>99.99</td>
<td>66</td>
<td>44</td>
<td>88</td>
</tr>
<tr>
<td>55166</td>
<td>99.61</td>
<td>66</td>
<td>44</td>
<td>89</td>
</tr>
<tr>
<td>73554</td>
<td>96.97</td>
<td>66</td>
<td>43</td>
<td>89</td>
</tr>
<tr>
<td>91943</td>
<td>91.67</td>
<td>66</td>
<td>42</td>
<td>90</td>
</tr>
</tbody>
</table>

As Table 5.3 shows, varying the standard deviation of the normal distribution while keeping constant the mean value does not affect the estimate of the outage cost and has a small impact on the confidence interval.

These two sensitivity analyses suggest that the most important parameter to fix is the boundary cost $C_{\text{bound}}$. On the other hand, a more detailed knowledge of the major incidents’ pdf is not necessary.

5.6 Boundary Cost

The computation of the outage cost for many severe outages allows the determination of a boundary cost. Some simulations have been carried out using artificially high failure rates in order to provoke severe outages. The failure rate of lines has been increased 100 times and the sympathetic tripping probability has been set at 20% (a very high value). Obviously, the contingencies model many elements out of service at the same time.
Figure 5.2 Frequency of outages – Artificial failure rates –

Figure 5.2 shows the distribution of failure rates from trials obtained using these artificial failure rates. A large outage includes blackouts whose lost of load is between 92% and 100% of the total load of the system. Small outages correspond to a loss of less than 25% of the total load of the system.

The boundary cost could be fixed at the lower limit of large outages. So, the boundary cost is set a 95% of the blackout cost for this case. The Table 5.1 and Figure 5.1 are updated using the uniform pdf between this new boundary cost and the total blackout cost (see Table 5.4 and Figure 5.3).

Table 5.5 summarises the differences between calculating the value of security using this approach and a Monte Carlo simulation that includes small and large outages.

<table>
<thead>
<tr>
<th>Table 5.4 Updating Example</th>
</tr>
</thead>
<tbody>
<tr>
<td>Parameter Value</td>
</tr>
<tr>
<td>Blackout Cost (k£)</td>
</tr>
<tr>
<td>Boundary Cost (k£)</td>
</tr>
<tr>
<td>Mean Value Large Impacts (k£)</td>
</tr>
<tr>
<td>Population Variance Large Impacts</td>
</tr>
<tr>
<td>Mean Value Small Incidents (k£) – Assessor</td>
</tr>
<tr>
<td>Standard Deviation Estimator – Assessor</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Table 5.5 Comparison of two approaches to compute Value of Security</th>
</tr>
</thead>
<tbody>
<tr>
<td>Statistic</td>
</tr>
<tr>
<td>-----------</td>
</tr>
<tr>
<td>Mean Value</td>
</tr>
<tr>
<td>Confidence Interval</td>
</tr>
</tbody>
</table>
5.7 Comparing Scenarios

Comparison of scenarios based on the Value of Security computed using equations (5.4) and (5.9) (or the most general equation (5.10)) requires the knowledge of $p_1$ for these scenarios.

If we assume that we are comparing two scenarios, two cases are possible:

1. The probability of severe outages, i.e. total or partial blackouts, is equal for both scenarios. In this case the impact of major outages on the Value of Security will be equal for both scenarios. The difference will be equal to the difference of the Value of Security associated only with the small outages. So, knowledge of $p_1$ is not necessary.

2. The probability of severe outages is different for both scenarios. Figure 5.4 shows an example. Scenario 2 has a mean value of small outages 15% higher than the same value for scenario 1. $p_1$ is 1/17000 for scenario 1 and 1/50000 for scenario 2. The final outage cost indicates that scenario 2 is the best. So, the knowledge of $p_1$ is necessary in this case.

It should be noted that a comparison using correlated sampling determines the best scenario from a “small” number of trials, which may or may not include severe outages. In other words, a comparison by correlated sampling avoids the comparison based on the final values of the Value of Security and, hence, does not require the knowledge of $p_1$. 

---

**Figure 5.3** Update Value of Security Curves
5.8 Observations

- The Assessor can be employed to compute the Value of Security statistics of small outages (i.e. below $C_{\text{bound}}$).

- The impact of severe outages on the Value of Security can be shown as a function of the probability that a severe outage occurs (i.e. as a curve like Figure 5.3).

- Separation of “small” and “large” outages for comparing scenarios is not relevant when correlated sampling is used.
6 CONCLUSIONS

Volumes I of this final report has presented a probabilistic approach to the computation of the Value of Security of power systems in an operational timeframe based on Monte Carlo sequential simulations. The Monte Carlo simulations represent the operation of the system subject to random events, modelling of corrective actions taken by the system operators and the load restoration process.

The modelling of the operation of power systems incorporates also time-dependent phenomena, such as cascade and sympathetic tripping, using simple and fast models. The modelling includes also the weather effect on the computation of the Value of Security.

Based on this model, the Value of Security Assessor Program has been developed under the research project supported by the EPSRC/ERCOS, grant reference no. GR/K 80310.

The Value of Security Assessor program can be used in two ways:

- To compare different operating scenarios.
- To compute the value of security of the system.

Comparison of different scenarios can be realised using their computed total costs or using the correlated sampling method. The first approach consumes much more CPU time and depending on the system and scenarios, it may be inconclusive.

Correlated sampling is thus a better way of selecting the best operating scenario.

Computing an accurate value of the total cost or the cost of outages is justifiable only for the best scenario. The naïve Monte Carlo gives a reliable estimate of the value of security but requires a lot of CPU time.

Volume II has presented testing applications of the Assessor program on a small (South-West portion of England and Wales system) and on a large power system (NGC system). The modelling capabilities of the Value of Security Assessor program have been tested and have shown the expected behaviour. In particular:

- The effect of adverse weather is reflected in an increase in interruption costs and, hence, in total cost. The best scenario can change depending on the weather conditions.
- An increase in the failure rate of one or more components increases the interruption costs.
- Consideration of sympathetic tripping also increases the interruption and total costs.
- The variance reduction methods, different of correlated sampling, have shown a well performance for reducing the required number of trials in small power systems; however, their performance in large power systems is not good.
As Chapter 5 shows, applications of the concept of stratified sampling variance reduction method based on small and large outage strata could provide an effective way to reduce the computational effort involved in the naïve Monte Carlo simulations. The separation analysis between small and large outages must be researched in more detail; developing and strategy to compute the probability associated with the occurrence of large load outages in the system (i.e. probability of blackouts).
REFERENCES


8 APPENDIX A – SOUTH WEST ENGLAND-WALES SYSTEM DATA

This appendix presents in more detail the data of the south-west portion of the England and Wales system that is used for testing the Value of Security Assessor program. It comprises the 400 kV system extending from Dungeness in Kent, and Melksham in Wiltshire, to Indian Queens in Cornwall.

8.1 Transmission Network

The network topology must be the same for all considered scenarios.

- **Summary data and area names**

  It is assumed that there is only one area for this system. Therefore, any used weather condition applies to all the system in the same way. Table 2.1 gives the general data of the system: 1 area, 53 nodes, 115 branches, 25 generation units.

- **Bus data**

  Table 8.1 gives the bus data for No-Fawley scenario: load and generation for the maximum load condition, limits on reactive power generation and base voltage in kV.

  For the Fawley Scenario the generation is changed according to the schedule presented below (section 8.2).

- **Branch data**

  Table 8.2 gives the list of lines, transformers and compensation equipment installed in the south-west portion of the England-Wales system. This table provides the electric characteristics (in p.u.) using a base of 100 MVA. The MVA limit of each branch is also supplied. An equal number of transformers and generating units is installed in the generating stations, however only a HV and a LV busbar is used in each one. For example, there are 4 generators in Didcot and 4 transformers DIDC0-DIDC4 (20/400 kV).

- **Generation data**

  Table 8.3 shows generation data used in the load flow data file of the Value of Security Assessor for the scenario No-Fawley. For the Fawley scenario the changes correspond to the appropriate schedule. In this part, the supplied generation schedule corresponds to the peak load condition.
Table 8.1 Bus Data – No Fawley Scenario -

<table>
<thead>
<tr>
<th>Name</th>
<th>PI [MW]</th>
<th>Ql [MVAr]</th>
<th>Pg [MW]</th>
<th>Qg [MVAr]</th>
<th>Vbase [kV]</th>
<th>Qmax [MVAr]</th>
<th>Qmin [MVAr]</th>
</tr>
</thead>
<tbody>
<tr>
<td>DUNG4</td>
<td>0.00</td>
<td>0.00</td>
<td>2642.00</td>
<td>514.00</td>
<td>400.00</td>
<td>1946.00</td>
<td>-830.00</td>
</tr>
<tr>
<td>BRLE4</td>
<td>100.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>400.00</td>
<td>0.00</td>
<td>0.00</td>
</tr>
<tr>
<td>DIDC4</td>
<td>-500.00</td>
<td>100.00</td>
<td>0.00</td>
<td>0.00</td>
<td>400.00</td>
<td>0.00</td>
<td>0.00</td>
</tr>
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<td>MELK4</td>
<td>-500.00</td>
<td>100.00</td>
<td>0.00</td>
<td>0.00</td>
<td>400.00</td>
<td>0.00</td>
<td>0.00</td>
</tr>
<tr>
<td>HINP4</td>
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<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>400.00</td>
<td>0.00</td>
<td>0.00</td>
</tr>
<tr>
<td>FAWL4</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>400.00</td>
<td>0.00</td>
<td>0.00</td>
</tr>
<tr>
<td>EXET4</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>-47.26</td>
<td>400.00</td>
<td>95.00</td>
<td>-105.00</td>
</tr>
<tr>
<td>LOVE4</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>-38.63</td>
<td>400.00</td>
<td>95.00</td>
<td>-105.00</td>
</tr>
<tr>
<td>MANN4</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>-37.21</td>
<td>400.00</td>
<td>95.00</td>
<td>-105.00</td>
</tr>
<tr>
<td>NINF4</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>-38.74</td>
<td>400.00</td>
<td>95.00</td>
<td>-105.00</td>
</tr>
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8.2 Generation Schedules

The Value of Security Assessor program requires a generation schedule for each scenario. These schedules must include:

- The schedule for each generator for each period that will be included in the value of security evaluation (for example 24 hours).
- The set of all generators used by all the scenarios.
- Maximum Bid Price or SMP for each hour. The Assessor program uses these values for computing the generation cost.

Table 8.4 shows the schedule for the No-Fawley scenario, while Table 8.5 shows the schedule for the Fawley scenario. The last line of both tables gives the SMP value. Both scenarios use the same SMP. In the Fawley scenario, the generation cost associated with the Fawley generator is costed at its bid price (53.09 £/MWh – see Table 8.3).

The schedule construction has taken into account:

- A spinning reserve larger than the largest generator (635 MW).
- A merit order based on generators’ bid prices.
Table 8.4 Generation Schedule – No Fawley Scenario –

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<td>80</td>
</tr>
<tr>
<td>HINPA6</td>
<td>80</td>
<td>80</td>
<td>80</td>
<td>80</td>
<td>80</td>
<td>80</td>
<td>80</td>
<td>80</td>
<td>80</td>
<td>80</td>
<td>80</td>
<td>80</td>
</tr>
<tr>
<td>HINPB1</td>
<td>635</td>
<td>635</td>
<td>635</td>
<td>635</td>
<td>635</td>
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<td>635</td>
</tr>
<tr>
<td>HINPB2</td>
<td>635</td>
<td>635</td>
<td>635</td>
<td>635</td>
<td>635</td>
<td>635</td>
<td>635</td>
<td>635</td>
<td>635</td>
<td>635</td>
<td>635</td>
<td>635</td>
</tr>
<tr>
<td>COST</td>
<td>7.00</td>
<td>7.00</td>
<td>7.00</td>
<td>7.00</td>
<td>7.00</td>
<td>22.66</td>
<td>22.66</td>
<td>22.74</td>
<td>31.51</td>
<td>31.51</td>
<td>31.51</td>
<td>31.51</td>
</tr>
</tbody>
</table>

8.3 Probabilistic Data

The failures rates (λ) for the generators have been computed from the forced outage rates (FOR) of each generator provided in reference [3] and mean time to repair (MTTR) provided in reference [4]. The MTTR values were selected based on the generator type and generator size. For nuclear generators the available data is only for units with capacities greater than 400 MW, however the MTTR for these units was used for all nuclear units in this study.
The failure rate of unit DIDCA3 (Didcot) was assumed to be equal to the failure rate of FAWL3 (Fawley) for study purposes. In case 5, the DIDCA3’s $\lambda$ was set equal to the value of DIDCA2’s $\lambda$. Note that in the No-Fawley scenario the DIDCA3 generator replaces the generation at Fawley. The assumption above makes possible an evaluation of the impact of different locations of generation. The second case (different failure rates) evaluates the complex impact of location and reliability.

The failure rate of OCGT at Fawley is based on the average value of $\lambda$ for OCGT units in the NGC system. The original data was a FOR of 0.0 %. Table 8.6 shows the failure rates used in the SW test and the data used to compute them.

### Table 8.6 Failure Rate of Generators SW System

<table>
<thead>
<tr>
<th>Generator</th>
<th>Node</th>
<th>Pmax [MW]</th>
<th>Type</th>
<th>Year</th>
<th>FOR</th>
<th>MTTR [hr]</th>
<th>$\lambda$ [fail/yr]</th>
</tr>
</thead>
<tbody>
<tr>
<td>DIDCA1</td>
<td>DIDC0</td>
<td>490</td>
<td>Large Coal</td>
<td>1972-1975</td>
<td>0.159</td>
<td>48.9</td>
<td>33.923</td>
</tr>
<tr>
<td>DIDCA2</td>
<td>DIDC0</td>
<td>490</td>
<td>Large Coal</td>
<td>1972-1975</td>
<td>0.159</td>
<td>48.9</td>
<td>33.902</td>
</tr>
<tr>
<td>DIDCA3</td>
<td>DIDC0</td>
<td>490</td>
<td>Large Coal</td>
<td>1972-1975</td>
<td>0.159</td>
<td>48.9</td>
<td>5.610</td>
</tr>
<tr>
<td>DIDCA4</td>
<td>DIDC0</td>
<td>490</td>
<td>Large Coal</td>
<td>1972-1975</td>
<td>0.159</td>
<td>48.9</td>
<td>33.904</td>
</tr>
<tr>
<td>DIDCA3G</td>
<td>DIDC0</td>
<td>25</td>
<td>OCGT</td>
<td>1968-1970</td>
<td>0.120</td>
<td>53.2</td>
<td>22.441</td>
</tr>
<tr>
<td>DIDCA4G</td>
<td>DIDC0</td>
<td>25</td>
<td>OCGT</td>
<td>1968-1970</td>
<td>0.120</td>
<td>53.2</td>
<td>22.441</td>
</tr>
<tr>
<td>DUNGA1</td>
<td>DUNG4</td>
<td>112</td>
<td>Magnox</td>
<td>1965</td>
<td>0.132</td>
<td>93.8</td>
<td>14.209</td>
</tr>
<tr>
<td>DUNGA2</td>
<td>DUNG4</td>
<td>112</td>
<td>Magnox</td>
<td>1965</td>
<td>0.132</td>
<td>93.8</td>
<td>14.209</td>
</tr>
<tr>
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<td>DUNG4</td>
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<td>Magnox</td>
<td>1965</td>
<td>0.132</td>
<td>93.8</td>
<td>14.203</td>
</tr>
<tr>
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<td>Magnox</td>
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<td>0.132</td>
<td>93.8</td>
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<tr>
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<td>Nuclear</td>
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<td>9.366</td>
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<tr>
<td>DUNGB22</td>
<td>DUNG4</td>
<td>600</td>
<td>Nuclear</td>
<td>1985-1989</td>
<td>0.093</td>
<td>93.8</td>
<td>9.565</td>
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<tr>
<td>FAWL3</td>
<td>FAWL0</td>
<td>484</td>
<td>Oil</td>
<td>1969-1970</td>
<td>0.041</td>
<td>67.5</td>
<td>5.610</td>
</tr>
<tr>
<td>FAWL1G</td>
<td>FAWL0</td>
<td>17</td>
<td>OCGT</td>
<td>1969-1970</td>
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<td>53.2</td>
<td>8.352</td>
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<tr>
<td>FAWL3G</td>
<td>FAWL0</td>
<td>17</td>
<td>OCGT</td>
<td>1969-1970</td>
<td>0.048</td>
<td>53.2</td>
<td>8.352</td>
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<td>FRANCE1</td>
<td>DUNG4</td>
<td>497</td>
<td>Interconnection</td>
<td>0.074</td>
<td>0.074</td>
<td>0.074</td>
<td>0.074</td>
</tr>
<tr>
<td>FRANCE2</td>
<td>DUNG4</td>
<td>497</td>
<td>Interconnection</td>
<td>0.074</td>
<td>0.074</td>
<td>0.074</td>
<td>0.074</td>
</tr>
<tr>
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<td>HINP0J</td>
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<td>Magnox</td>
<td>1965</td>
<td>0.082</td>
<td>93.8</td>
<td>8.360</td>
</tr>
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<td>HINPA2</td>
<td>HINP0J</td>
<td>80</td>
<td>Magnox</td>
<td>1965</td>
<td>0.082</td>
<td>93.8</td>
<td>8.360</td>
</tr>
<tr>
<td>HINPA3</td>
<td>HINP0J</td>
<td>80</td>
<td>Magnox</td>
<td>1965</td>
<td>0.082</td>
<td>93.8</td>
<td>8.360</td>
</tr>
<tr>
<td>HINPA4</td>
<td>HINP0K</td>
<td>80</td>
<td>Magnox</td>
<td>1965</td>
<td>0.078</td>
<td>93.8</td>
<td>7.898</td>
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<td>HINPA5</td>
<td>HINP0K</td>
<td>80</td>
<td>Magnox</td>
<td>1965</td>
<td>0.078</td>
<td>93.8</td>
<td>7.898</td>
</tr>
<tr>
<td>HINPA6</td>
<td>HINP0K</td>
<td>80</td>
<td>Magnox</td>
<td>1965</td>
<td>0.078</td>
<td>93.8</td>
<td>7.898</td>
</tr>
<tr>
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<td>HINP0</td>
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<td>Nuclear</td>
<td>1976-1978</td>
<td>0.073</td>
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<td>7.319</td>
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<td>HINPB2</td>
<td>HINP0</td>
<td>635</td>
<td>Nuclear</td>
<td>1976-1978</td>
<td>0.074</td>
<td>93.8</td>
<td>7.482</td>
</tr>
</tbody>
</table>

Data for Coal, Oil and OCGT is believed to be very accurate. NGC 93 Fawley OCGT Units using average rates from NGC 93 MTTR from CEA

Failure rates for lines were computed based on the length of the lines and the average values of $\lambda$, provided for the Canadian system [1], taking into account the line’s voltage level. Reference [1] also provides failure rate data for transformers and compensation equipment.

### 8.4 Weather Modelling

The Value of Security Assessor program has the capability to include weather effects on the failure rates of transmission equipment. Reference [7] explains the modelling
characteristics used in the program. The number of weather states defined depends on the study. A detailed modelling is not always necessary. The effect of adverse weather conditions is evaluated for testing purposes. In this way only two weather conditions are used: adverse weather and normal weather conditions. Table 8.7 gives the data used in these tests.

<table>
<thead>
<tr>
<th>Weather State</th>
<th>Duration Factor [%]</th>
<th>Proportion Factor of Failures [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Season (Winter)</td>
<td>Year</td>
</tr>
<tr>
<td>Adverse</td>
<td>2</td>
<td>1</td>
</tr>
<tr>
<td>Other Condition</td>
<td>98</td>
<td>99</td>
</tr>
</tbody>
</table>

These factors have been computed as follow:

- The proportion of failures factor in adverse weather was computed from data collected in the Canadian system for the period 1991-1995 [10]. 67% of permanent failures take place in adverse weather conditions at 300 kV to 400 kV for any type of supporting structures. The proportion factor is 68% for supporting structures in steel. 72% of 110-149 kV line failures occur in adverse weather.

- It is assumed that adverse weather conditions have an average duration of 5 hours and take place every 750 hours based on a yearly average and every 300 hours on a (winter) seasonal average.

8.5 VOLL Modelling

VOLL is a function of the duration of interruption computed from the sector customer damage functions (SCDF) provided in [11]. A consumer distribution of 35% residential consumers, 27% commercial consumers, 34% industrial consumers and 4% large users is assumed in order to compute the VOLL. The assumed busbar’s load factor is 0.65. Table 8.8 gives the VOLL function used in this study computed by the Value of Security Assessor program.

<table>
<thead>
<tr>
<th>Duration of interruption</th>
<th>VOLL [£/kWh]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 min</td>
<td>258.21</td>
</tr>
<tr>
<td>20 min</td>
<td>28.75</td>
</tr>
<tr>
<td>1 hr</td>
<td>18.37</td>
</tr>
<tr>
<td>4 hr</td>
<td>14.14</td>
</tr>
<tr>
<td>8 hr</td>
<td>12.55</td>
</tr>
<tr>
<td>24 hr</td>
<td>5.60</td>
</tr>
</tbody>
</table>

8.6 Load Restoration Modelling

The restoration model and data presented in reference [6] was used in this study. Table 8.9 gives the corresponding data.
Table 8.9 Load Restoration Rates - SW System

<table>
<thead>
<tr>
<th>Time Period [min]</th>
<th>Restoration Rate [MW/min]</th>
</tr>
</thead>
<tbody>
<tr>
<td>0 – 30</td>
<td>10.0</td>
</tr>
<tr>
<td>30 – 60</td>
<td>33.3</td>
</tr>
<tr>
<td>60 – 90</td>
<td>66.6</td>
</tr>
<tr>
<td>90 and more</td>
<td>83.3</td>
</tr>
</tbody>
</table>
This appendix presents some characteristics of the data employed with the NGC system 1996/97 system for testing the Value of Security Assessor program.

9.1 Probabilistic Data

The failure rates ($\lambda$) for the generators have been computed from the forced outage rates (FOR) of each generator provided in reference [3] and mean time to repair (MTTR) provided in reference [4]. The MTTR values were selected based on the generator type and generator size. For nuclear generators the available data is only for units with capacities greater than 400 MW, however the MTTR for these units was used for all nuclear units in this study. Table 9.1 shows the failure rates used in this study and the data used to compute them. Failure rates for lines were computed based on the length of the lines and the average values of $\lambda$, provided for the Canadian system [1], taking into account the line’s voltage level. Reference [1] also provides failure rate data for transformers and compensation equipment.

### Table 9.1 Failure Rate of Generators - NGC System

<table>
<thead>
<tr>
<th>Generator</th>
<th>Node</th>
<th>Pmax [MW]</th>
<th>Type</th>
<th>Year</th>
<th>FOR</th>
<th>MTTR [hr]</th>
<th>$\lambda$ [fail/yr]</th>
</tr>
</thead>
<tbody>
<tr>
<td>COCK</td>
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<td></td>
<td></td>
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<tr>
<td>HUER</td>
<td>GEN2</td>
<td></td>
<td></td>
<td></td>
<td></td>
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</tr>
<tr>
<td>KINC</td>
<td>GEN3</td>
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<td></td>
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<td>0.000</td>
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<td>LOAN</td>
<td>GEN4</td>
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<td>GEN6</td>
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<td></td>
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<td>ABTH-7</td>
<td>GEN7</td>
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<td>Large Coal</td>
<td>1976</td>
<td>0.126</td>
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<td>25.765</td>
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<td>ABTH-8</td>
<td>GEN8</td>
<td>485</td>
<td>Large Coal</td>
<td>1971</td>
<td>0.126</td>
<td>48.9</td>
<td>25.765</td>
</tr>
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<td>BLYT-8</td>
<td>GEN9</td>
<td>313</td>
<td>Medium Co</td>
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<td>Large Coal</td>
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<td>48.9</td>
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<td>Large Coal</td>
<td>1972-1975</td>
<td>0.159</td>
<td>48.9</td>
<td>33.923</td>
</tr>
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<td>13.743</td>
</tr>
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<td>9.366</td>
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<td>Node</td>
<td>Pmax [MW]</td>
<td>Type</td>
<td>Year</td>
<td>FOR [fail/yr]</td>
<td>MTTR [hr]</td>
<td>λ [fail/yr]</td>
</tr>
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<td>---------------</td>
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<td>1968</td>
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<td>48.9</td>
<td>12.661</td>
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<td>GEN32</td>
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<td>1968</td>
<td>0.066</td>
<td>48.9</td>
<td>12.648</td>
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<td>Large Coal</td>
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<td>0.066</td>
<td>48.9</td>
<td>12.656</td>
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<td>Large Coal</td>
<td>1969</td>
<td>0.066</td>
<td>48.9</td>
<td>12.656</td>
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9.2 Weather Modelling

The Value of Security Assessor program has the capability to include weather effects on the failure rates of transmission equipment. Reference [7] explains the modelling characteristics used in the program. The number of weather states defined depends on the study. A detailed modelling is not always necessary. The effect of adverse weather conditions is evaluated for testing purposes. In this way only two weather conditions are used for testing the NGC system 1996/97: adverse weather and normal weather conditions. The same modelling has been used in the SW system (section 8.4).

9.3 VOLL Modelling

VOLL is a function of the duration of interruption computed from the sector customer damage functions (SCDF) provided in [11]. A consumer distribution of 35% residential consumers, 27% commercial consumers, 34% industrial consumers and 4% large users is assumed in order to compute the VOLL. The assumed busbar’s load factor is 0.65. Table 8.8 gives the VOLL function used in this study computed by the Value of Security Assessor program.

9.4 Load Restoration Modelling

The restoration model and data presented in reference [6] was used in this study. Table 9.2 gives the corresponding data.

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