Reliability and Availability Analysis Methodology for Power System Protection Schemes

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Abstract—A new methodology is presented, allowing to evaluate protection systems reliability and availability indexes, taking into account equipment failure and repair rates. The protection scheme is translated into a reliability graph, enabling to identify all possible logical occurrences in the system, either meaning failure or successful operation. Evaluation of the system reliability and availability indexes is achieved by Monte Carlo simulation. The methodology is applied to a typical transmission line protection bay, for different time to repair scenarios, and conclusions on asset management options are drawn.

Keywords—power system protection, automation, reliability, availability, reliability graph, Monte Carlo simulation.

I. INTRODUCTION

Reliability and availability of power systems is of strategic importance for defining power utilities’ CAPEX and OPEX policies. Furthermore, regulators are requiring that utilities comply with objectives in power system design and operation, towards fulfillment of a specified Adequate Level of Reliability for the bulk power system [1] to [3]. Consequently, utilities are facing new challenges in redefining equipment life cycles, establishing reliability-centered and condition-based maintenance programs, downsizing operational maintenance teams, outsourcing maintenance, reducing spare part storage, and redesigning cost effective protection and automation schemes. These are some of the utilities concerns that urge for a reliability and availability analysis approach.

Reliability and availability analysis of power system protection schemes is usually addressed by means of fault tree and Markov analysis [4] to [8]. In the present paper, an alternative methodology, based on complex system description by means of reliability graphs and solution by Monte Carlo simulation, is described and applied to a line bay protection system.

II. PROPOSED METHODOLOGY

A. System Description

Complex systems are composed by numerous units operating in series, parallel, standby, or a combination of those. The system working principle is represented by a reliability block diagram, and the corresponding reliability graph. For illustration, a very simple example is presented in figure 1.

In the reliability graph, each unit is represented by a directed branch, whereas nodes represent unit connections. The system success is described by any path connecting cause to effect. Redundancy will result into alternative paths; therefore, system success does not depend on the success of all its units.

The reliability of a given unit, \( R(t) \), is defined as the probability of failure-free operation up to time \( t \). Unit performance is also described by a failure rate function \( z(t) \), related to the time rate of unit survival, \( n(t) \):

\[
z(t) = -\frac{1}{n(t)} \frac{dn(t)}{dt}
\]

\[
R(t) = \exp \left[ - \int_0^t z(t) \, dt \right]
\]

Successful operation of series-connected units naturally requires that all units operate successfully. Considering that the defined units do not interact with each other, system reliability is given by:

\[
R_{sys}(t) = R_{U1}(t) \cdot R_{U2}(t) \cdots R_{Un}(t)
\]

In a parallel configuration, the system success occurs if any of the units succeeds, the system reliability being:

\[
R_{sys}(t) = R_{U1}(t) + R_{U2}(t) + \cdots + R_{Un}(t)
\]

The mean time to fail MTTF is a key performance index commonly used to describe the system reliability:

\[
MTTF = \int_0^\infty R(t) \, dt
\]

Another important system index is its availability. The availability function \( A(t) \) is defined as the probability that the
Reliability of the respective equivalent units is given by
\[ \lambda(t) = \exp \left( - \sum_{i=1}^{n} Z_i(t) \right) \]  
(7)

where \( Z_i(t) = \int_0^t z(t) \, dt \).

From an operational point of view, merging is recommended only for units with common repair processes.

### C. Solution Algorithm

Reliability graph analysis allows identifying all possible logical occurrences in the system, as well as the subset corresponding to system successful operation. Each successful event, commonly named tie-set [9], corresponds to a set of rightly oriented branches connecting cause and effect. A tie-set is said minimal when no node is traversed more than once.

The set of all minimum tie-sets defines the reliability of the overall system. Considering a system with \( i \) minimum tie-sets \((T_1, T_2, ..., T_i)\), the system reliability is given by:
\[ R_{sys}(t) = R_{T_1}(t) + R_{T_2}(t) + \cdots + R_{T_i}(t) \]  
(9)

For the system being used as illustration (figure 1), two minimum tie-sets exist and:
\[ R_{T_1}(t) = R_{U1}(t)R_{U2}(t) \]  
(10)
\[ R_{T_2}(t) = R_{U3}(t) \]  
(11)

These tie-sets are described as rows in Table 1, where the columns correspond to the reliability graph branches. The probability of occurrence of a tie-set is simply the product of probabilities of success of each dotted branch.

<table>
<thead>
<tr>
<th></th>
<th>U1</th>
<th>U2</th>
<th>U3</th>
</tr>
</thead>
<tbody>
<tr>
<td>T1</td>
<td>•</td>
<td></td>
<td></td>
</tr>
<tr>
<td>T2</td>
<td></td>
<td>•</td>
<td></td>
</tr>
</tbody>
</table>

Table 1: Tie-sets of system composed of a unit in series with two parallel units.

Evaluation of the system reliability and availability indexes is achieved by Monte Carlo simulation [10]. A stochastic process, which describes the operation of large number of systems operating during a long period, is simulated. System failures, survivals and repairs are registered as if they were the result of one single experiment.

The simulation time span is divided into an equal number of time intervals (trials), such as a second, an hour, or a year. At each trial, a set of random numbers is generated according to a uniform distribution over the interval \([0, 1]\). The generated numbers are compared with the corresponding unit failure probability, \( F(t) = 1 - R(t) \), or repair \( C(t) \), during the trial. If the unit is in operation at the trial beginning, and the generated random number is higher than its failure probability, the unit will fail. If the unit is on a fail state and the generated random number is higher than its repair probability, the unit will be repaired.

The simulation starts with all units in operation and, as the simulation evolves, the units’ state will change according to their fail/repair cycles. Trial results are used at the end of the simulation to compute \( R(t) \), \( A(t) \) and \( z(t) \).

### D. Unit Hazard Model

A unit hazard model describes its failure and repair rates. One of the most commonly adopted failure rate models is the constant failure rate. Available field data suggest that this is a good assumption for power system equipment [11]. The same applies to equipment repair rates. The corresponding reliability and repair functions are written as:
\[ R(t) = e^{-\lambda t} \]  
(12)
\[ C(t) = e^{-\mu t} \]  
(13)

where \( \lambda \) and \( \mu \) denote the failure and repair rates.

### E. Statistical analysis

The reliability and availability indexes cannot truly be determined from a single Monte Carlo simulation. However, when repeated \( N \) times, with different random seeds, the simulations yields a set of values for reliability and availability indexes. For each set one can calculate statistical parameters such as the average \( E(X) \), the standard deviation \( V(X) \) or a two side confidence intervals \( CI \) on \( E(X) \):
\[ E(X) = \frac{1}{N} \sum_{n=1}^{N} x_n f(x) \]  
(14)
\[ V(X) = \frac{1}{N} \sum_{n=1}^{N} x_n^2 f(x) - E(X)^2 \]  
(15)
\[ CI = \left[ E(X) - z_{a/2} \frac{V(X)}{\sqrt{N}} ; E(X) + z_{a/2} \frac{V(X)}{\sqrt{N}} \right] \]  
(16)

where \( f(x) \) is the frequency of occurrence, and \( z_{a/2} \) is the standard normal random variable corresponding to \( 100(1 - \alpha)\% \) CI.

### F. Algorithm Validation

A system composed of two redundant units was considered for validation of the proposed algorithm. The units are characterized by constant failure and repair rates, \( \lambda = 105 \times 10^{-6} \) failures/hour, \( \mu = 10.4 \times 10^{-3} \) repairs/hour.

\[ MTTR = \int_0^t C(t) \, dt \]  
(6)

### B. System Reduction

Problem complexity can be reduced by reducing the number of branches required to describe the system working principle. Considering equations (3) and (4), equivalent units can be defined by merging series and parallel connected units. Reliability of the respective equivalent units is given by \( R_s(t) \) and \( R_p(t) \) [9]:
\[ R_s(t) = \exp \left( - \sum_{i=1}^{n} Z_i(t) \right) \]  
(7)
\[ R_p(t) = 1 - \left[ \prod_{i=1}^{n} \left( 1 - \exp(-Z_i(t)) \right) \right] \]  
(8)

where \( Z_i(t) = \int_0^t z(t) \, dt \).

The simulation time span is divided into an equal number of time intervals (trials), such as a second, an hour, or a year. At each trial, a set of random numbers is generated according to a uniform distribution over the interval \([0, 1]\). The generated numbers are compared with the corresponding unit failure probability, \( F(t) = 1 - R(t) \), or repair \( C(t) \), during the trial. If the unit is in operation at the trial beginning, and the generated random number is higher than its failure probability, the unit will fail. If the unit is on a fail state and the generated random number is higher than its repair probability, the unit will be repaired.

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(12)
\[ C(t) = e^{-\mu t} \]  
(13)

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(14)
\[ V(X) = \frac{1}{N} \sum_{n=1}^{N} x_n^2 f(x) - E(X)^2 \]  
(15)
\[ CI = \left[ E(X) - z_{a/2} \frac{V(X)}{\sqrt{N}} ; E(X) + z_{a/2} \frac{V(X)}{\sqrt{N}} \right] \]  
(16)

where \( f(x) \) is the frequency of occurrence, and \( z_{a/2} \) is the standard normal random variable corresponding to \( 100(1 - \alpha)\% \) CI.

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Performed algorithm validation encompasses checking the computed reliability and availability values, and also checking the adequacy of Monte Carlo simulation to describe the reliability of a single unit.

On one hand, as regards availability, for such simple system, it can be theoretically calculated by [9]:

$$ A = \frac{\mu}{\lambda + \mu} \quad (17) $$

Therefore, for the considered system, $A = 99.99\%$. On the other hand, no closed form exists allowing direct calculation of the reliability. Validation is carried out by comparison with results obtained by Markov Chain approach.

Using the developed methodology, the system reliability index was calculated by simulating $N=300$ systems operating during 40000 hours. Trials are made on an hourly basis and the obtained number of system failures and survivals, are presented in table 2, for each 4000 hours.

System reliability values, at the end of each time interval, shown in figure 2, are calculated as the corresponding number of survivals, divided by the number of simulated systems.

Table 2: FAILURES AND SURVIVALS from a Monte Carlo simulation of 300 systems operating during 40000 hours.

<table>
<thead>
<tr>
<th>Time interval (Hour)</th>
<th>Failures in the interval</th>
<th>Number of survivals</th>
</tr>
</thead>
<tbody>
<tr>
<td>0-4000</td>
<td>32</td>
<td>268</td>
</tr>
<tr>
<td>4000-8000</td>
<td>60</td>
<td>208</td>
</tr>
<tr>
<td>8000-12000</td>
<td>63</td>
<td>145</td>
</tr>
<tr>
<td>12000-16000</td>
<td>49</td>
<td>96</td>
</tr>
<tr>
<td>16000-20000</td>
<td>30</td>
<td>66</td>
</tr>
<tr>
<td>20000-24000</td>
<td>26</td>
<td>40</td>
</tr>
<tr>
<td>24000-28000</td>
<td>7</td>
<td>33</td>
</tr>
<tr>
<td>28000-32000</td>
<td>11</td>
<td>22</td>
</tr>
<tr>
<td>32000-36000</td>
<td>7</td>
<td>15</td>
</tr>
<tr>
<td>36000-40000</td>
<td>3</td>
<td>12</td>
</tr>
</tbody>
</table>

Using a Markov Chain approach, the system reliability and availability indexes are evaluated by solving $m$ first order differential equations, $m$ being the number of system states [9]. Even if only two states (success/fail) are possible for each of the $n$ units in the system, $m = 2^n$. This indicates that, although being a very powerful method, the Markov Chain approach rapidly explodes in complexity as soon as the number of units and states increases. For the simple system being considered, only 4 equations are solved. Obtained results are presented in figure 2, and their matching with results from Monte Carlo simulation is clear.

In order to calculate the system availability index, unit repair is now taken into account. This index is calculated at the end of the simulated time span, as the percentage of system successful operation time. The simulated time span ranged from $10^6$ to $18 \times 10^6$ hours. Each simulation is repeated 40 times, and statistical analysis of all results is carried out to assess system availability. Figure 3 presents the calculated availability, its average and the corresponding 95% and 98% confidence intervals, as function of the simulated time. Results clearly show that simulation time span must be defined in accordance to the required confidence interval.

Using the results from Table 2, the corresponding failure rate was calculated using equation (18).
\[
z(t) \approx \frac{1}{n(t)} \frac{n(t) - n(t + \Delta t)}{\Delta t}
\]

where \(n\) denotes the number of survivals in the interval. The corresponding histogram is presented in figure 4. It shows that the simulation data, while still showing some randomness, respects the unit fault rate.

III. FAILURE RATE OF BASIC COMPONENTS

A. Adopted Description Format

The failure rate data of the main components of a line bay protection system has been collected from several sources. Unfortunately, the failure rate data do not share a common format and, in order to combined all these data on the same study, it is necessary to adopt a unique failure rate format. In the present study, the adopted failure rate index is the number of failures per year.

A thoughtful bibliographical survey on reliability data for the relevant protection system components was conducted and data were processed in order to fit the adopted description format.

B. Circuit Breaker

Data published in CIGRE TB 510 [12], resulting from a worldwide survey, were selected. It includes both Major and Minor Failures. The circuit breaker components were grouped into two categories: i) the components at service voltage, and the operating mechanism; ii) the electric control and auxiliary circuits. This classification was adopted, resulting into two separate tables, Tables 4 and 5. Presented data correspond to all Major Failures in which a fail to open occurred after a fault clearing command.

C. Measuring Transformers

Measurement transformers reliability data was collected from the CIGRE brochure TB 512 [13], also resulting from a worldwide survey.

The transformer components are divided in two categories regarding their physical connection to the power system: i) primary components and ii) secondary components. This classification was adopted and the corresponding failures/year were evaluated. Results are shown in Tables 6 and 7.

D. Communication System

Regarding reliability of communication systems, the objective values proposed in the Communications Systems Performance Guide for Protective Relaying Applications were considered. This guide was prepared jointly by the WSCC Telecommunications and IEEE PSRC Relay Work Groups [14]. The communication systems are classified according to the importance of the bulk power system element which they are applied to. The failure rates were evaluated considering the target values for availability proposed in [9], and for different MTTR.

<table>
<thead>
<tr>
<th>Kind of service</th>
<th>(failures/year (10^{-6}))</th>
</tr>
</thead>
<tbody>
<tr>
<td>Overhead line</td>
<td>46  39  5  6</td>
</tr>
<tr>
<td>Transformer</td>
<td>41  47  3  4</td>
</tr>
<tr>
<td>Cable</td>
<td>17  47  3  2</td>
</tr>
<tr>
<td>Shunt reactor</td>
<td>456 729 49 35</td>
</tr>
<tr>
<td>Capacitor</td>
<td>193 211 16 3</td>
</tr>
<tr>
<td>Bus coupler</td>
<td>61  56  6  7</td>
</tr>
</tbody>
</table>

Table 4: CB FAILURE RATE - Components at service voltage and operating mechanism.

<table>
<thead>
<tr>
<th>Kind of service</th>
<th>(failures/year (10^{-6}))</th>
</tr>
</thead>
<tbody>
<tr>
<td>Overhead line</td>
<td>20  17  2  2</td>
</tr>
<tr>
<td>Transformer</td>
<td>17  20  1  2</td>
</tr>
<tr>
<td>Cable</td>
<td>7  20  1  1</td>
</tr>
<tr>
<td>Shunt reactor</td>
<td>196 313 21 15</td>
</tr>
<tr>
<td>Capacitor</td>
<td>83  90  7  1</td>
</tr>
<tr>
<td>Bus coupler</td>
<td>26  24  3  3</td>
</tr>
</tbody>
</table>

Table 5: CB FAILURE RATE - electric control and auxiliary circuits.

<table>
<thead>
<tr>
<th>Rated Voltage</th>
<th>AIS</th>
<th>CVT</th>
<th>CCVT</th>
<th>CT</th>
<th>VT</th>
<th>CT</th>
</tr>
</thead>
<tbody>
<tr>
<td>60&lt;=V&lt;110kV</td>
<td>58  18</td>
<td>90  29</td>
<td>93  93</td>
<td>0</td>
<td></td>
<td></td>
</tr>
<tr>
<td>100&lt;=V&lt;200kV</td>
<td>355 452</td>
<td>116 438</td>
<td>25  3</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>200&lt;=V&lt;300kV</td>
<td>772 718</td>
<td>290 372</td>
<td>72  17</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>300&lt;=V&lt;500kV</td>
<td>931 699</td>
<td>716 308</td>
<td>109 15</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>500&lt;=V&lt;700kV</td>
<td>181 126</td>
<td>129 80</td>
<td>0  0</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>&gt;=700kV</td>
<td>0  0  0</td>
<td>12329 0</td>
<td>0</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 6: MEASURING TRANSFORMERS FAILURE RATE - primary components.

<table>
<thead>
<tr>
<th>Rated Voltage</th>
<th>AIS</th>
<th>CVT</th>
<th>CCVT</th>
<th>CT</th>
<th>VT</th>
<th>CT</th>
</tr>
</thead>
<tbody>
<tr>
<td>60&lt;=V&lt;110kV</td>
<td>11  3</td>
<td>16  5</td>
<td>18  11</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>100&lt;=V&lt;200kV</td>
<td>69  82</td>
<td>21  76</td>
<td>5  69</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>200&lt;=V&lt;300kV</td>
<td>150 129</td>
<td>52  65</td>
<td>14  150</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>300&lt;=V&lt;500kV</td>
<td>181 126</td>
<td>129 54</td>
<td>21  181</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>500&lt;=V&lt;700kV</td>
<td>0  23</td>
<td>0  14</td>
<td>0  0</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>&gt;=700kV</td>
<td>0  0  0</td>
<td>2147 0</td>
<td>0</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 7: MEASURING TRANSFORMERS FAILURE RATE - secondary components.
Computed values for the three communication system classes are shown in Table 8.

<table>
<thead>
<tr>
<th>Class</th>
<th>A (%)</th>
<th>MTTR=24h</th>
<th>MTTR=48h</th>
<th>MTTR=72h</th>
<th>MTTR=168h</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>99.95</td>
<td>0.18</td>
<td>0.09</td>
<td>0.06</td>
<td>0.03</td>
</tr>
<tr>
<td>2</td>
<td>99.5</td>
<td>1.83</td>
<td>0.91</td>
<td>0.61</td>
<td>0.26</td>
</tr>
<tr>
<td>3</td>
<td>95</td>
<td>18.25</td>
<td>9.13</td>
<td>6.08</td>
<td>2.61</td>
</tr>
</tbody>
</table>

### E Protection Relays

It is understood that reliability of power system protection schemes encompasses the ability to operate whenever required (dependability) and the ability not to operate if not required (security).

Reliability and availability data for protection relays are not common in the literature. These are very much dependent on the utility philosophy towards: maintenance practices; availability and treatment of substation SCADA alarms; relay type and manufacturer. Even so, field data on availability can be found for different relay technologies [15] [5].

For failure rate computation, a MTTR value of 2.5 years was considered for electromechanical and static technologies. It is commonly accepted that this corresponds to a utility practice of a 5-year time-based maintenance program. For the digital technology, self-supervision was assumed, and a 1-week MTTR was considered. Results are presented in Table 9.

### F DC Power Supply

The 99.9994% availability value was considered for the DC Power Supply, resulting from field data published by Schweitzer [5]. This number, although very high, does not seem too far from reality, given the substation auxiliary power supply system architecture. Indeed, the DC power supply has multiple redundancy, most of the cases delivered from tertiary windings of alternative power transformers, backup batteries and a diesel generator.

Computed results shown in Table 10 correspond to considering different values of MTTR, ranging from 1 day to 1 week.

### IV. CASE STUDY - RELIABILITY AND AVAILABILITY OF A LINE BAY PROTECTION SYSTEM

A typical transmission line bay protection system is considered, with full redundancy of most of its components: main protection relays, current transformer cores, voltage transformer secondary circuits, circuit breaker tripping coils, and auxiliary power supply. The study is intended to provide guidance on asset management policy based on protection system availability requirements.

Taken from section III, reliability data of the relevant line bay elements are shown in Table 11, corresponding to maximum and minimum failure rate values.

![Fig. 5: Line bay protection system a). Reliability graph b) reduced model c).](image-url)
Reliability indices of the equivalent units in the reduced model are given by:

\[ R_{U1} = R_{VT5}R_{CT5}R_{CB1} \]  
\[ R_{U2} = R_{VT6}R_{CT6}R_{CB2}R_{M1}R_{DCPS1} \]  
\[ R_{U3} = R_{VT7}R_{CT7}R_{CB3}R_{M2}R_{DCPS2} \]  

The corresponding computed values are presented in Table 12. Tie-sets are identified in Table 13. Given the unit failure rates \( \lambda_{U1} \), \( \lambda_{U2} \), and \( \lambda_{U3} \), the system reliability is evaluated according to:

\[ R(t) = e^{-\lambda_{U1}t} \left( 1 - e^{-\lambda_{U2}t} \right) \left( 1 - e^{-\lambda_{U3}t} \right) \]  

Results shown in Table 14 correspond to 2, 5 and 10 years of system operation. They are compared with the reliability of the main protection relay. These results are useful to define equipment warranties and stocking.

In order to evaluate the system availability, the proposed Monte Carlo solution algorithm was applied. Several scenarios, characterized by a combination of different primary and secondary systems MTTR values, were considered: 1 to 6 months, in steps of 1 month, for the secondary system; and 1, 2 and 3 days, for the primary system. The simulations were carried out considering 40 systems operating simultaneously over \( 2 \times 10^6 \) hours. Each scenario was simulated 80 times. The corresponding system availability was evaluated. Statistical analysis of the results was carried out.

Results presented in figures 6 (a), (b) and (c) correspond to the worst case scenarios regarding reliability data (maximum failure rate values in Table 11). The average value and the corresponding 95% and 98% confidence intervals of the protection system availability are shown. Each figure corresponds to a given primary system MTTR, and the system availability is represented as a function of the secondary system MTTR.

Figure 6 shows that an increase on the primary or secondary system MTTR impacts negatively on the system availability, this impact being higher as regards the primary system. This is expected given the redundant design of the secondary system. The proposed methodology allows the quantification of these impacts, thus providing guidance on system design, while accounting for maintenance strategies.

### Table 12: Maximum and Minimum Failure Rates of the Equivalent Units

<table>
<thead>
<tr>
<th></th>
<th>min</th>
<th>max</th>
</tr>
</thead>
<tbody>
<tr>
<td>U1</td>
<td>2109</td>
<td>4470</td>
</tr>
<tr>
<td>U2</td>
<td>10624</td>
<td>21125</td>
</tr>
<tr>
<td>U3</td>
<td>10624</td>
<td>21125</td>
</tr>
</tbody>
</table>

### Table 13: Tie-sets of the Line Bay Protection System Reduced Model

<table>
<thead>
<tr>
<th></th>
<th>U1</th>
<th>U2</th>
<th>U3</th>
</tr>
</thead>
<tbody>
<tr>
<td>T1</td>
<td>•</td>
<td>•</td>
<td></td>
</tr>
<tr>
<td>T2</td>
<td>•</td>
<td></td>
<td>•</td>
</tr>
</tbody>
</table>

### Table 14: Reliability of Line Bay Protection System and Main Protection, after 2, 5 and 10 years of Operation

<table>
<thead>
<tr>
<th></th>
<th>Reliability (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Protection System</td>
<td>2 years</td>
</tr>
<tr>
<td>Max</td>
<td>99.94</td>
</tr>
<tr>
<td>Min</td>
<td>98.94</td>
</tr>
<tr>
<td>Main Protection Relays</td>
<td>2 years</td>
</tr>
<tr>
<td>Max</td>
<td>98.02</td>
</tr>
<tr>
<td>Min</td>
<td>96.43</td>
</tr>
</tbody>
</table>
V. DISCUSSION ON ASSET MANAGEMENT

Regarding asset management, several conclusions can be drawn from Table 14:

- After 10 years of operation, the reliability of the main protection drops to a value between 90.48% to 83.36%. This means that if 100 systems are placed in service, it is expected that 11 to 17 units will fail after 10 years in service. Under these circumstances, it is reasonable to accept a 10-year warranty period for the equipment if the price increment is less than 17% of the price without warranty.

- If no warranty is purchased and a 10-year equipment depreciation period is defined, it is reasonable to establish a spare parts stock in the range of 11% to 17% of the total installed units.

- Mixed strategies can also be analyzed. Considering a purchase of 100 main protection units, with 5-year warranty and 10-year depreciation periods, the main protection price should not be higher than 8% of the price without warranty, in order to cover the expected number of failures during the first 5 years of operation. Indeed, for the last 5 years of operation, it is expected that 5 to 8 units will fail. Therefore, this is a reasonable number for spare parts stocking.

Results depicted in figure 6 allow the following conclusions:

- The secondary system MTTR ranging from 1 to 6 months does not significantly impact the availability of the protection system. Therefore, spare parts stocking may be avoided, if the manufacturers are engaged with a time to repair and replace of a failed element in the considered time range.

- 99.95% availability is a reasonable minimum objective value for the line bay protection system. This value could be used as an indicator in a regulatory framework, although higher values may be internally targeted by utilities.

VI. CONCLUSION

The paper presents a numerical methodology applied to protection systems based on complex system description by means of reliability graphs and solution by Monte Carlo simulation. The protection system is divided into numerous individual components, and the corresponding reliability graph is built according to its operating principle. Monte Carlo simulation is used to compute system reliability and availability indices, which can be used for decision making with regard to utmost important utility policies, such as equipment warranty requirements, spare part quantification and mean time to repair specification.

An extensive survey on existing data was carried out, resulting into specification of typical and realistic reliability indices for each protection and automation system component: circuit breaker, current and voltage transformers, auxiliary power supply and protection relay.

The developed methodology is a valuable tool on tracking the operational performance of different protection and automation schemes, thus enhancing system reliability-centered and condition-based maintenance programs, as well as supporting life cycle assessment and refurbishment decisions.

REFERENCES


