Review of the Swedish Network Performance Assessment Model

Lina Bertling, Mats B. O. Larsson and Carl Johan Wallnerström

Abstract— *The Swedish energy agency (STEM), has developed a new regulatory model to supervise the revenues of the Distribution System Operators (DSO), referred to as the Network Performance Assessment Model (NPAM). The fundamental idea of the NPAM is that the electrical distribution system provides customer values, and the DSO is allowed to collect revenue corresponding to these values. The NPAM calculates customer values for a fictive electrical distribution system, with a total cost referred to as the Network Performance Assessment (NPA). The allowed debiting rate for a DSO is defined by the quotient of the revenue and the NPA. If the debiting rate is higher than a certain value, defined by the Energy Market Inspection (EMI) at STEM, the DSO is placed under review and could be forced to pay back revenue to customers. A lawsuit is currently in progress on this use of the NPAM, which has highlighted drawbacks in the model. This paper provides a comprehensive presentation of the NPAM. It describes in detail the different input data for the model, the steps in the calculations and the resulting cost factors. The paper also presents for the first time details on the theory underlying the calculations..*

Index Terms—Electrical Distribution System, Regulatory model, Network Performance Assessment Model, NPAM, Customer value, Outage cost, Probability, Performance-based regulation, Redundancy, Reference networks, Monte Carlo simulation and Reliability.

I. INTRODUCTION

The electrical power system is one of the fundamental infrastructures in a modern society. Its overarching aims are to produce, and provide customers with, electrical energy of a certain voltage quality and level of reliability, at a *reasonable cost* and with regard for the environment. The issues of cost and environment first came into focus at the end of the last century. A paradigm shift took place when market conditions for the electrical power systems were introduced, and Sweden was one of the first countries to start de-regulation. In 1996, the Swedish electricity market was re-regulated and in 1998 a new regulating authority, the Swedish energy agency (STEM), was established.

Following market conditions, the subscribers of electrical energy were to pay a price for delivery corresponding to the customer value. Different customers, industrial or household, would have different values for energy not supplied. Consequently, there would be different sets of prices for power supply from a customer point of view. However, from the perspective of the distribution system operators (DSOs), there are costs for operation and maintenance to balance against the requirements for system reliability and the profit for the stakeholders. In a perfect market environment, a balance would be reached when customers select the DSO with the best price for the required customer value. However, the infrastructure for the electrical distribution system is a natural monopoly. For a DSO, this monopoly typically means being responsible for all electrical distribution in a geographically well-defined area, offering all customers a connection, and setting network tariffs. It is the task of the authorities to judge if this tariff is reasonable. To cope with this situation, the authorities apply different regulatory tools. In Sweden, a regulatory tool has been introduced by STEM, referred to as the Network Performance Assessment Model (NPAM) [1]-[4].

The use of the NPAM has met with several difficulties, and an ongoing law suit is expected to provide guidance on how the model could be used [5]. The fact that it is an ex-post model implies that the regulation is carried out the following year. Consequently, the model includes the experienced rather than the predicted reliability performance, which is the case in an ex-ante model. Work is in progress to explore ways of developing the NPAM into an ex-ante model. The documentation was improved by a comprehensive presentation of the model [3]. However, this provides not a complete presentation on the theoretical underpinnings of the model. Some of the theory is presented in [1], and there are several publications studying the model e.g. [6]-[14] ([15] studying a law working parallel with the NPAM), but no stringent description of the complete model is available. This paper aims to fill this gap by providing an overall picture of the NPAM including hitherto unpublished details on underlying theory. This could hopefully inspire and give a reference when developing regulations in different countries in the future; both by learning from novel theory as well as learning from mistakes done in Sweden. This paper complements paper [2] which present results from an investigation of the robustness of the model.

Manuscript received March 5, 2008.

L. Bertling (e-mail: lina.bertling@ee.kth.se) and C. J. Wallnerström (e-mail: cjw@kth.se) are with the Royal Institute of Technology (KTH) in Stockholm, Sweden. Mats B. O. Larsson (e-mail: mats@mml.se) MML Åhus, Sweden.

II. OVERALL PICTURE OF THE NPAM

A. Background to NPAM

In 1998, STEM called for a new regulating model. It was to be based on self-regulation and provide incentives to the DSOs to increase cost-efficiency, and to keep a high level of reliability. No existing regulation model was found to fulfill requirements, and it was decided to develop a new model. The primary drawback found in the existing models was, that they were based on the existing electrical distribution systems, with no regard for their efficiency [1].

The proposed regulation model, NPAM, is a performance-based regulation, implying a change in perspective from a company to a customer focus. The customer perspective focuses attention on the performance provided to the customers, rather than the expenses incurred by the DSO in managing the electrical distribution system. As a result of this new customer perspective, the legislation was changed [16].

The model was first implemented in 2003, and is being used by STEM to regulate the network tariffs. A special department at STEM has been appointed to use the NPAM for regulating the tariffs: the Energy Market Inspection (EMI). However, several DSOs have lodged an appeal [5] against the EMI for not agreeing to pay back revenues based on results from the NPAM, and the future for the model is unknown.

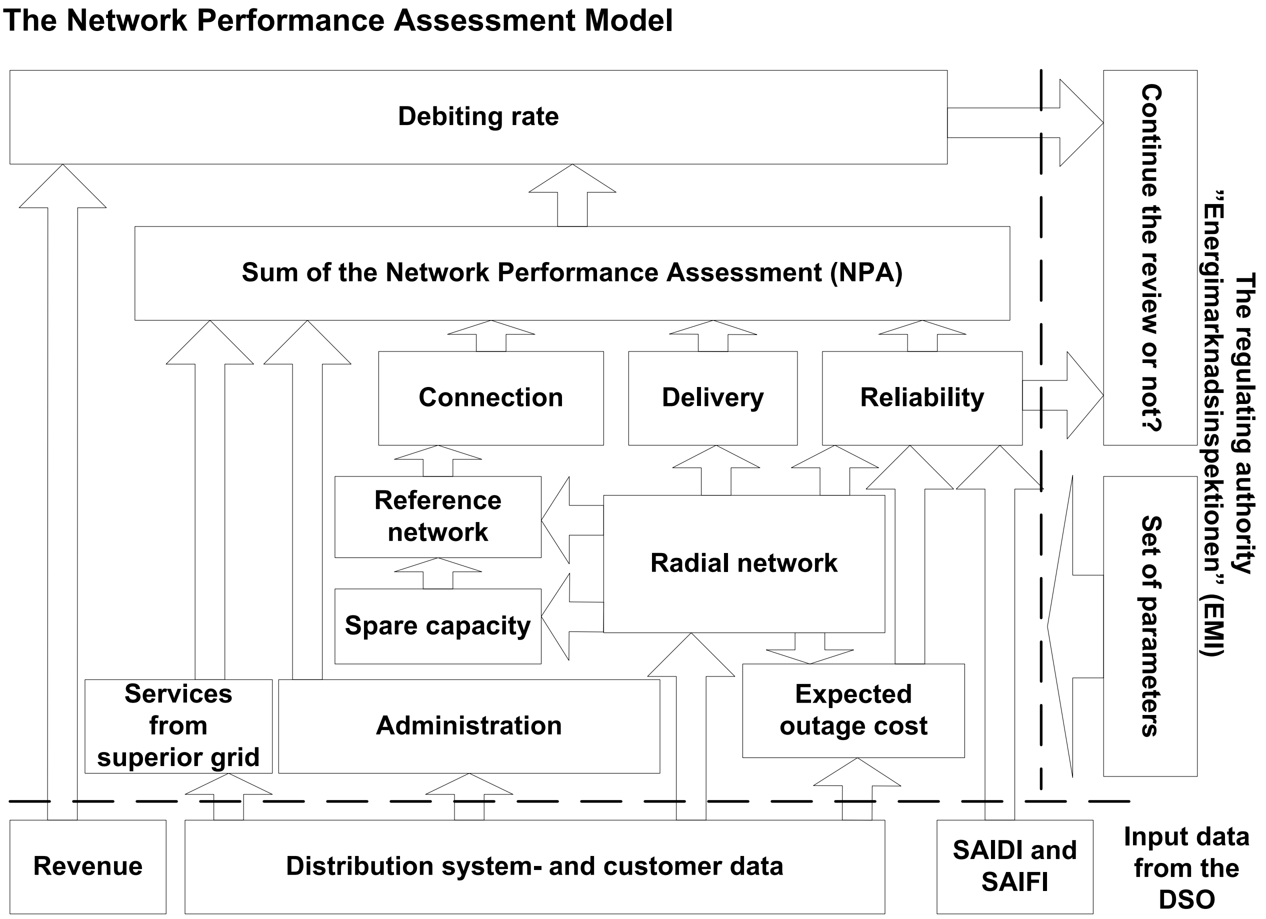

Figure 1 – A review of the NPAM and the calculation of the debiting rate with required cost factors and input data.

B. Summary presentation of the NPAM

Figure 1 provides an overview of the NPAM The NPAM builds up a radial fictive reference network, based on annual reported data. The fictive network is based on information in the customer or production nodes. In a pure radial network, each component failure would result in system outage. Consequently, electrical distribution systems often include component redundancy to improve system reliability. To capture this effect in the NPAM, a spare capacity feature has been included. The amount of spare capacity, i.e. component redundancy, corresponds to what the customers are willing to pay for. The model estimates this amount and the resulting required investment cost. This cost is then added to the estimated cost of the radial reference network, resulting in a *reference network*. Other costs for operation and maintenance are added. Finally, this total cost can be reduced, but what is known as *reliability cost*, if the performance of the electrical distribution system is better than expected, in terms of customer outage cost. The resulting total cost is referred to as the Network Performance Assessment (NPA).

The NPA is an assessment of the customer values of an electrical distribution system. The fundamental idea of the NPAM is that DSO will be allowed to collect *revenue* that corresponds to these customer values. The allowed *debiting rate* for a DSO is defined by the quotient of the revenue and the NPA, as shown in Equation 1. The results from NPAM are considered to be the primary tool for the regulating authority to judge the level of tariffs, and to decide if a DSO should be monitored for further review [5].

$$Debiting\ Rate = \frac{Revenue}{NPA}$$

Equation 1: Calculation of the debiting rate by the NPAM

The model implies that for an electrical distribution system area with a resulting performance that equals the revenue collected by the DSO (i.e. corresponding to the tariffs), the *debiting rate* is 1. Experience to date shows that most of the DSOs have a debiting rate over 1. For the first year that the model was used in practice, 1.3 was considered an accepted performance, and for the following year this value was decreased to 1.2.

Moreover, the model resulted in a higher performance value to customers than requested, i.e. NPA larger than the revenue will not be compensated, but, on the other hand, a lower value will result in less accepted revenue. Another aspect to consider is that, since the NPAM studies fictive networks, the customer is not affected by the history of the DSOs or by poor efficiency.

C. Overall picture of the NPAM

Figure 1 illustrates how the *debiting rate* is calculated based on different cost factors and required input data. The bottom of the figure shows the three types of input data from the DSOs. It is seen that the Network Performance Assessment (NPA) is the total of five different cost factors, e.g. *Connection* which in turn depends on the *reference network* including both *spare capacity* and a *radial network*

D. Calculation of the Network Performance Assessment

The unit used in NPA is Swedish crowns [SEK], where 9 SEK is approx. € 1. It is calculated annually for each electrical distribution system area (a DSO can own several electrical distribution system areas).

NPA expresses the different customer values in terms of five different costs as follows:

1. The *cost of the connection*, $C_{Connect}$, corresponds to capital for the fictive reference network, which has up to four voltage levels, referred to as *Net Levels* (defined in chapter III.). This cost includes the cost of the *radial network*, C_{Radial}, and additional cost representing investments in component redundancy, referred to as *the cost of the spare capacity*, C_{Spare}. The *cost of the connection* represents the cost of an electrical distribution system built with new technology and efficient solutions. Thus, the model takes into account the fact that a newly built electrical distribution system in Sweden would, if possible, be based on investment in underground cables rather than overhead lines (to minimize the effect of weather). E.g. Net Level 3 and 4 have 50% underground cables and 50% overhead lines in the NPAM. Consequently, the investment cost for the *radial network* has several built-in assumptions of how an electrical distribution system is built. Chapter III. provides more details on how the cost of the *radial network* and the cost of the *spare capacity* are calculated. The *cost of the connection* is expressed by

$$C_{Connect} = C_{Spare} + C_{Radial}$$

Equation 2: Cost of the connection in the NPAM

2. The *cost of the administratio*n, $C_{Ad\min}$ includes an administrative cost for each customer, which depends partly on the net level of the reference network. These costs are given as input data from EMI.
3. The *cost of the delivery*, C_{Deliv}, is the energy loss in the system. It depends on the subscriber density, which in turn depends on the *radial network.* Note that the price of electricity is determined by period prices on the Nordic Energy Market, Nord pool.
4. The *cost of the services,* $C_{Service}$, are costs from superior grids. These are actual costs reported by the DSO, such as costs for compensation to local producers. Note that some expenses, like government fees, are not included in this cost, but are instead factored in by reducing the *revenue*.
5. The *cost of reliability*, $C_{\mathrm{Re}l}$, provides a means for the DSO to reduce the allowed revenue by reducing the expected cost for the reference network by a maximum of the calculated cost for spare capacity that is worth investing in. Section C. provides more details on how this cost is calculated in NPAM.

The summary presentation of NPA results in the following equation:

$$NPA = C_{Connect} + C_{Admin} + C_{Deliv} + C_{Service} - C_{Rel}$$

Equation 3: NPA as a sum of cost factors

From the above presentation of the five cost factors, it is known that some of the cost factors depend on the reference network and/or its performance, i.e. $C_{Connect}, C_{Deliv}, C_{Rel}$ and some are defined by input parameters $C_{Ad\min}, C_{Service}$. This paper attempts to throw light on how the first group of cost factors is calculated by the NPAM.

*E. **Results from tests with NPAM***

Comprehensive tests of the NPAM were made during the development phase. The largest of these, called pilot tests, involved 114 DSOs and 2.7 million customers, (to be compared with the total number of DSOs in Sweden of around 260 with approx. 5.3 million customers).

The results shows on a debiting rate of 1.19 [1][6]. These studies also presented the resulting costs divided into the different cost factors, summarized in Table I. The results show that the major cost factor is $C_{Connect} = 58\%$ where the greatest contribution to the cost is from the *radial network*.

This seems a reasonably representative cost for an electrical distribution system. Furthermore, the reduction in cost due to investments in spare components is shown to be 5%, which is a more questionable result. The level of investments in component redundancy is highly dependent on where the electrical distribution system is located – e.g. in urban or rural areas--, which is an aspect the model does not take into account.

TABLE 1

RESULTS FROM TESTS OF NPAM FOR REAL SYSTEMS

NPAM cost factors	**Cost [SEK]**	**% of NPA**
Connection; Radial network	1 297	46 %
Connection; Spare Capacity	336	12 %
Administration	341	12 %
Delivery	170	6 %
Reliability	-129	- 5 %
Services from superior grid	826	29 %
Total customer values (NPA)	2 841	100 %
Revenue	3 389	119 %
Debiting rate = Revenue/NPA	**1.19**	**19%**

(SEK 1 ~9€)

F. *Input data to NPAM*

EMI performs an annual review of the revenues of the DSOs using the NPAM. The input data are therefore annually updated with data from EMI and the DSOs. All the input data are entered using a computer program, Netben, which creates the *reference network* and gives the resulting output data from the model expressed as the debiting rate, or NPA, or different cost factors in NPA.

The input data from EMI are a set of parameters, some of which are revised each year. They include constants used is the calculation algorithms and the price of electricity. The total number of parameters can vary from year to year and is approximately 50 for each Net Level, i.e. an approximate total of 200 parameters. For a complete and updated presentation of the parameters, see the home page at www.energimarknadsinspektionen.se.

The input data to NPAM from the DSOs are of three types:

1. The total *revenue*. The revenue is the sum of all reported customer tariffs during the year plus revenues from connection and changing fees, with a reduction for the annual government fee. Some other reductions of the revenue can be made if allowed by EMI.
2. The performance data expressed as annual system reliability indices, including both advertised and unadvertised interruptions, during the year in question which are
    - **a.** The System Average Interruption Frequency Index (SAIFI), defined as the average number of interruptions per year and customer,
    - **b.** The System Average Interruption Duration Index (SAIDI), defined as the average outage duration (minutes) per year and customer.
3. The system and component data for the actual electrical distribution system with customer data, and a list of nodes. These data are also referred to as *objective data*. The nodes must be listed within four categories: low-voltage customers, high-voltage customers, border feed points, and local supply points. For every node, the following data must always be reported: a unique number, its category, and two coordinates of the location, the sum of electrical consumption minus the electrical supply, revenue (which can be zero), and cost (which can be zero). For all nodes, except the low-voltage customers, the subscribed electrical power must be reported. The electrical power of the low-voltage customers is assumed by the NPAM to be the individual annual electrical consumption divided by 1900 hours, i.e. load factor function. Some other data, such as individual outage data, for the nodes are possible to report, but are not mandatory or used by the current version of the NPAM.

The system and component data to the NPAM for a specific electrical distribution system area, will result in a *reference network* including different voltage levels, which has different subscriber density for different feeders. Together with the performance data the NPAM calculates the different sets of cost factors. The subsequent chapters will provide some underlying theory showing how these calculations have been performed.

III. THE REFERENCE NETWORK AND RELIABILITY ASSESSMENT IN THE NPAM

This chapter summarizes how the assessment of reliability is treated by the NPAM. (This part of the model is also called the quality function. However, it does not address aspects of voltage quality.) The chapter aims to show, how the cost functions $C_{Connect}$ and $C_{\mathrm{Re}l}$ are calculated by the NPAM. The first cost factor concerns the reference network and the calculated spare capacity (i.e. the motivated investment in redundancy). The second cost factor concerns the reliability performance for the reference network based on system reliability indices, reported by the DSOs. Consequently, both the cost factors depend on the reference networks in the NPAM and on the underlying theory on developing these. This chapter will therefore begin by clarifying the background for developing the reference network.

A. The radial reference network in the NPAM

A radial fictive network is built by the NPAM for an electrical distribution system area based on yearly reported data from a DSO. The input data for the network includes the subscribers, boundary nodes, and production nodes.

Therefore, the model does not take into account the actual electrical distribution system, but only its nodes and its performance.

The radial reference network is used when calculating several of the cost factors in the NPAM. Specifically, the subscriber density of this radial reference network, i.e., the meter fictive radial line per customer, is input for several calculations in the model.

The radial reference network has four voltage levels, as follows [6]:

1. *Net Level 1* (NL1) [0.4 kV] for nodes between 0.0 and 1.0 kV
2. *Net Level 2* (NL2) [10 kV] for nodes between 1.1 and 25.0 kV.
3. *Net Level 3 (NL3)* [40 kV] for nodes between 25.1 and 60.0 kV.
4. *Net Level 4* (NL4) [135 kV] for nodes above 60.0 kV.

These levels are a simplification of the way in which the Swedish electrical distribution system is built; for instance, two common operating levels are 11 kV and 22 kV, which with the NPAM corresponds to the same Net Level. It has, however, been decided to use these two levels in the model, and it is important to note that it could significantly affects .the cost functions when different investment alternatives are calculated, in that it would mean a different price invested in a spare component at different voltage levels.

Figure 2 illustrates a radial reference network presented in the NPAM tool, Netben. This figure corresponds to a fictive radial reference network that is based on input data to NPAM for an electrical distribution system area.

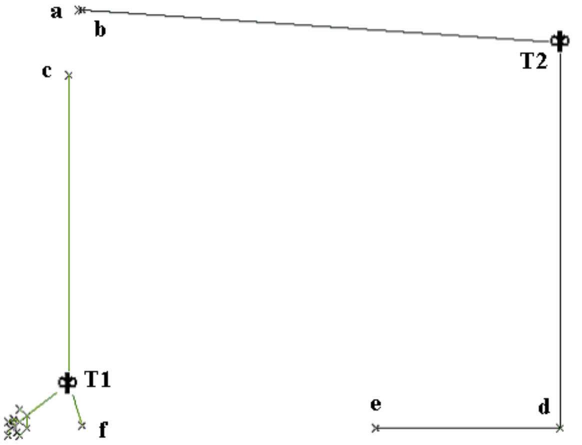

Figure 2 – *Example of two radial networks at Net Level 1 presented in Netben. (The right system has three feeders: one to node a and b, one to node d, and one to node e, and also one transformer, T2, to the network at Net Level 2)*

The resulting cost of the radial network, C_{Radial}, is the calculated investment cost for a radial network derived by the NPAM. The result depends on input parameter values from EMI for costs of transformers and feeders, and from the system and component input data, in accordance with previous presentations of input data, from the DSO.

B. Incremental cost

The fundamental idea of the NPAM is to calculate customer values corresponding to the performance of the reference network. The model represents these customer values in terms of costs. For the reliability factor, this implies that the model assumes a customer interruption cost. Investments for a radial network by adding redundant components would improve the availability of the network and consequently lower the customer interruption cost. This could be expressed as a marginal reliability benefit ΔR at a marginal cost, ΔC. The incremental cost, i.e. $\Delta C / \Delta R$, is often used to decide if an investment in the system is worthwhile [19].

The NPAM uses the incremental cost analysis to evaluate the worth of different alternative investments in spare components. The approach in NPAM was to (1) calculate the incremental cost of different alternative investments in the radial reference network, (2) list the results and implement the solution with the highest incremental cost, (3) calculate the incremental cost of different alternative investments in the new system as a result of (2), and continue until there are no more solutions with an incremental cost over 1. The total cost of spare capacity resulting from the incremental cost analysis is therefore the maximum number of profitable spare components to include in the radial reference network, and is referred to as C_{Max}. A presentation of the approach to deriving the spare capacity is found in e.g. [1][3][9].

C. Spare capacity in the reference network

The resulting reference network in the NPAM implies that the radial network is added component redundancy, by the amount that increases the customer value corresponding to the required investment cost. This section will shed light on how this amount, called the spare capacity for the reference network, has been derived.

The calculations of spare capacity for the reference networks in the NPAM were made during the development phase. The calculations were repeated for numerous electrical distribution system areas. The resulting spare capacity is the calculated optimal value for investment in redundant components that provides an incremental improvement in reliability performance for customers. (Section B. presents more details.) The results from these assessments were then transformed into functions that vary with the subscriber density and Net Level. Graphs of these functions can be found in [1] and [3]. From these graphs, a given set of subscriber density and *Net Level* gives a value for the cost of the spare capacity. This cost can involve investment costs for either spare transformers or additional feeder length. For example, a feeder at *Net Level 2* results in around 25 % (10 % *Net Level 1*) for urban systems and around 18 % (1 % *Net Level 1*) for rural systems in extra feeder length [1].

The resulting cost of the spare capacity, C_{Spare}, is thus a cost for investment in the amount of spare capacity, which the NPAM has defined as the optimal solution. This gives that

$$C_{Spare} = C_{Max}$$

Equation 4: Cost of spare capacity equals the maximum possible reduction in the NPAM

D. Customer outage cost

The *Customer outage cost* in the NPAM represents the cost that the customer sees. (This cost is also referred to as attained cost.) The *Customer outage cost* depends on delivered electrical energy, system reliability indices, and customer interruption costs. The customer interruption costs depend on the subscriber density, and have been calculated based on a customer survey made by the association of Swedish DSOs, Svensk Energi (SwedEnergy) in 1993 [18], including updated data in 2003 [1] The *Customer outage cost* is calculated both for advertised , i.e. planned events, and unadvertised interruptions, i.e. stochastic events. Table 2 gives examples of functions for the customer interruption cost in the NPAM. As seen from the table, the interruption costs decrease with increased density. Hence, for the NPAM it follows that customers in an urban distribution system, with typically few meters per customer, receive more compensation than customers in a rural distribution system, with typically many meters per customer.

Table 2 –Example of values for the interruption costs in the NPAM

Density [m/cust.]	[1] 2] Fixed cost x_i, [SEK/kW,int.]		Non fixed cost y_i, [SEK/kWh,int.]	
	planned (x_1)	stochastic (x_2)	planned (y_1)	stochastic (y_2)
10	5	22	81	117
50	4	20	62	91
100	2	18	50	72
300	2	18	48	71

(Data from [6][14], €1~ SEK 9, \$1 ≈ SEK7 .)

Equation 5 summarizes the calculation of the *Customer outage cost* in NPAM [SEK/year]:

$$C_{Outage} = \frac{E}{8760} \cdot \sum_{i=a,b} \left(x_i \cdot SAIFI_i + y_i \cdot SAIDI_i \right)$$

Equation 5: Calculation of the Customer outage cost

where

- E is delivered electrical energy for an electrical distribution system area [kWh/yr],
- 8760 is the total number of hours per year [h/yr],
- the index i indicates if the interruptions are planned events, with a, or stochastic, with b,
- $SAIFI_i$ [int/yr] and $SAIDI_i$ [h/yr] are system reliability indices,
- x_i [SEK/kW, int.] and y_i [SEK/kWh] are customer interruption costs.

From Equation 5 it can be seen that the actual undelivered energy is not included in the calculation of the customer outage cost. This implies the simplification that every customer are considered to consume a mean value with respect to the total annual delivered electrical energy E, i.e. the NPAM does not take into account the different loads for the individual customers when calculating the outage cost.

E. Expected outage cost

The *Expected outage cost,* C_{Expect} , in the NPAM is the expected outage cost that the reference network would incur. The cost is calculated by algorithms in the NPAM, and the output depends on subscriber density, *Net Level* and the total amount of delivered kWh per year. Table 3 shows examples of expected outage costs in the NPAM. The expected outage cost is clearly higher, with higher density per subscriber, and for lower *Net Level.* Both these results are as expected for a real electrical distribution system.

Table 3 – Examples of values for the expected outage costs in the NPAM.

Density [m/cust.]	Net Level 1 [öre/kWh]	Net Level 2 [öre/kWh]	Net Level 3 and 4 [öre/kWh]
1	0.30	0.11	0.00
100	0.32	0.17	0.00

(Data from [6][14], SEK 1 = 100 öre)

F. The reliability function in the NPAM

The reliability cost, $C_{\mathrm{Re}l}$, provides a means to reduce the revenue that the DSO is allowed to collect, by reducing the expected cost for the reference network. This reduction is made with a maximum of the calculated cost for spare capacity, C_{Max}. This maximum value equals the calculated optimal solution for investment in component redundancy, C_{Spare} . The reduction is made if the resulting system reliability performance, C_{Outage} , is higher than the expected reliability performance, C_{Expect} , for the reference network. The equation for the reliability cost is summarized as follows:

$$C_{\mathrm{Re}l} = \begin{cases} 0 & if\ C_{Outage} - C_{Expect} \le 0 \\ C_{Outage} - C_{Expect} & if\ 0 \le C_{Outage} - C_{Expect} \le C_{Max} \\ C_{Max} \Leftrightarrow C_{Spare} & if\ C_{Outage} - C_{Expect} \ge C_{Max} \end{cases}$$

Equation 6: Calculation of the reliability cost

IV. UNDERLYING THEORY FOR THE NPAM

The previous chapter has presented the different cost factors included in the assessment using the NPAM. The NPAM model uses a set of so called *template functions* to assess these cost functions. The template functions were defined during the development phase, and they stem from a set of simulation studies. This chapter will present for the first time details of how these simulations were made. It is, however, not necessary to understand this underlying theory to apply the NPAM.

A. The subscriber density in the NPAM

All template functions have one variable, the subscriber density x, i.e. number of feeder meters per customer. This is the density of the radial reference network that the NPAM derives, and is consequently a result during assessment with the model. Since there are four net levels in the model, each electrical distribution system area has four functions for x. Note particularly that x is the local subscriber density of each line, and not a mean value of subscriber density, which is presented by Netben as an output from the NPAM.

B. The template functions in the NPAM

The general approach to defining the template functions in the NPAM is as follows:

1. Sequential Monte Carlo Simulations (MCS) are performed, for the radial network, for example, using the incremental cost theory to define an optimal investment alternative.
2. The MCSs are repeated numerous times for different sets of electrical distribution system areas.
3. The result from the MCS studies is expressed as a function of the subscriber density, x.
4. The results are plotted and a curve is fitted to the plot using the function $ModTanh(x)$, Equation 7. This function has five parameters $k_0,\cdots,k_4$, which define the shape of the curve (which could also be a constant function). The function has been used because it could represent a general function with different characteristics depending on the parameter values [1].
5. Based on the results, pilot studies are made, and the parameter values are adjusted.

$$ModTanh(x)=\left(k_1+k_2\cdot\tanh\left(k_3\left(x-k_4\right)\right)\right)^{k_0}$$

Equation 7: Function used for calculating template functions in the NPAM [6]

where

- x is the subscriber density at the actual net level and for a specific line [meter/customer],
- k_0 defines the sharpness of the curve,
- k_1 defines the horizontal position of the curve,
- k_2 determines the rake of the curve,
- k_3 stretches the curve vertically,
- k_4 defines the vertical position of the curve.

C. The Approach for deriving the template functions of the reference network in the NPAM

1) A summary of the approach, divided into five steps

The *reference network* for the NPAM has been calculated in five steps as follows:

1. The *customer outage cost,* C_{Outage}, is calculated from data reported to the DSO (See Equation 5).
2. A fictive radial network is created based on input data to the NPAM. The sequential Monte Carlo simulation approach is used to simulate the expected behavior of the system. The generally known Weibull distribution has been used to model failure occurrences for components in the system. Components are in one of three states: operation, service or failure. The simulation includes the effect of component failures with both planned and stochastic events. A resulting outage cost is evaluated for the radial network.
3. The incremental cost approach is used to investigate different alternatives for component redundancy, i.e. feeders, for the radial network. (See also Section A.) MCS studies are used to evaluate the resulting outage costs for the different investment alternatives. From a resulting list of possible redundancy solutions, the first profitable one is selected, i.e. where the gain in outage costs is higher than the required annual cost for investment in component redundancy. This results in C_{Spare}.
4. The radial network is simulated, including failure occurrences for transformers, and possible solutions for redundancy of transformers. The resulting outage cost is compared with the required annual investment cost.
5. MCSs are made for the resulting redundant *reference network* system including possible redundancy for feeders and transformers. Events are simulated as for the radial network. The resulting C_{Expect} is calculated.

2) A summary of assumptions

The NPAM models a complex system, and as such involves many simplifications. A few of those that show limitations in modeling the electrical distribution system ,have been identified by the authors as important, and are as follows:

- Isolation of component failures, i.e. feeders or transformers, is assumed to be perfect and occur momentarily, i.e. the breaker components are assumed to work with a probability of 100%.
- Only single failure is considered, i.e. simultaneous failures are neglected.
- No load flow analysis is made for dimensioning of the spare capacity defined for the feeders. This implies that the resulting reference network could have feeders that are not dimensioned to deliver the energy requested by the customers and modeled by the NPAM.

D. Summary of the Monte Carlo simulations during the developing phase of the NPAM

In summary, four different types of simulation studies were made during the development phase of the NPAM. They all used the sequential Monte Carlo simulation approach. Note that the studies were made for all *net levels*. For NL4, the result early indicates of using a constant template function, whose value, to a great degree, was chosen based on discussions with the industry [1]. The third simulation study is described in more detail in this paper, and Figure 3 shows the underlying logic of this MCS. The other simulations have similar and simpler algorithms.

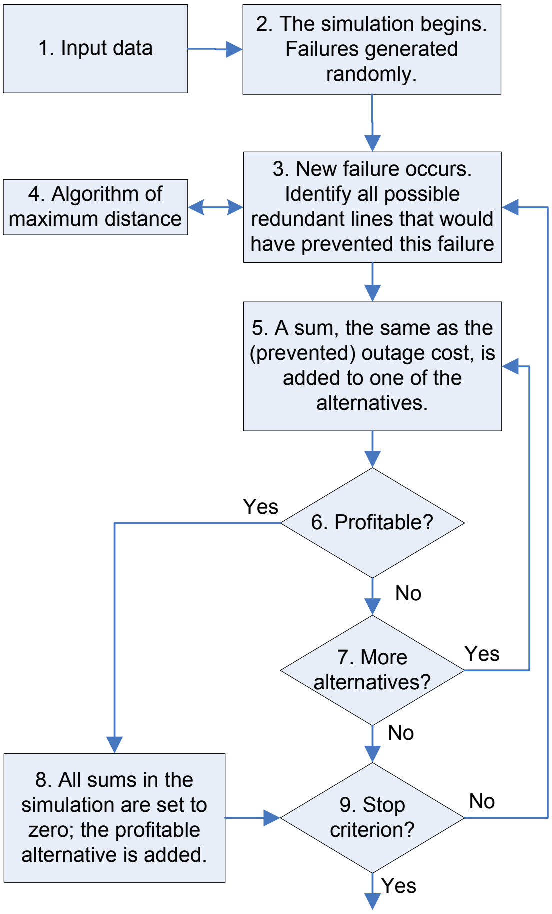

Figure 3 – The logic for MCSs to identify the optimal redundancy in feeder length for the NPAM.

1) Assessment of outage costs for the radial reference

Failure events were simulated, the generated outages were summarized, and a mean value was calculated. These simulations were input to calculation of the C_{Radial} , to be used in further development of the NPAM (and were not input to a template function used by the NPAM).

2) Assessment of redundancy in transformers

Simulations were made at each *Net Level* of the *radial reference network*. The resulting improvement in outage costs was compared with the required investment in redundancy for all transformers at the current *Net Level*. Consequently, the result from the simulations was either to have no redundant transformers for the *Net level* in question or to have redundancy for all transformers. The results provide input data for calculating the C_{Spare}

3) Assessment of the reference network – i.e. with feeder redundancy

This algorithm uses MCSs to identify an "optimal" (i.e first profitable) investment in additional feeder length for the radial network. The resulting *reference network* provides input for the study presented in simulation 4, and also provides input data for calculating the C_{Spare} .The algorithm for the MCS to identify component redundancy of feeders for the reference network is shown in Figure 3 and presented as follows:

0. The basic conditions :
    a. Every node in the system has a list with the alternative types of redundancy, together with two amounts each: a fixed sum corresponding to the cost of including the alternative in question, and a non-fixed sum which starts at zero.
    b. Some of the alternatives in the lists are connected to other nodes, because a redundant feeder can be used from both directions.
1. The input data includes customer experienced outage costs, the *radial reference network*, estimated costs of introducing the different redundancy alternatives, and reliability statistics on the components (failure rate and mean outage time).
2. The simulation begins, and failures are generated randomly for the radial reference network (including failure location and time to failure), based on reliability statistics. Not more than one failure is simulated at a time.
3. A new failure occurs and all alternatives, including redundant feeders that could have prevented the failure, are identified.
4. An algorithm investigates, and excludes from further calculation, redundant feeders with a length above a maximum value.
5. A sum corresponding to the hypothetical prevented outage cost is added to the non-fixed sum of one of the alternatives identified in step 3 and step 4.
6. For each addition, a comparison is made between the two sums of the alternative. If the non-fixed sum exceeds the fixed sum, go to step 8; else go to step 7. The two sums must be adjusted to the same time period.
7. If all alternatives identified in step 3 and step 4 have been reviewed, go to step 9; else go to step 5.
8. The alternative is introduced, and the simulation continues on the changed *reference network* (i.e. including the new alternative). All the non-fixed sums of the alternatives are set to zero.
9. The stop criterion is defined as follows: when the results begin to converge, i.e., there is a long time lapse between newly introduced alternatives, the simulation is stopped; else go to step 3.

4) Assessment of outage costs for the reference networks

The MCSs for the *reference network*, i.e. with redundancy, were made in a similar way as for 1, above. The result is a template function for the C_{Expect} .

V. CONCLUSIONS

This paper provides the first overall presentation of the NPAM. It presents in detail the different input data for the model, the steps in the calculations and the resulting output. The paper has also presented the underlying theory for calculating cost factors in the model based on simulation studies, for example, of how redundancy is treated by the model, which is a fundamental aspect for the system reliability of the reference network and the resulting interruption costs. Even though the paper has provided insight into underlying calculations for the cost functions, it does not give a stringent definition of these functions, since such a definition does not exist.

The recent paradigm shift with market conditions will result in several different regulatory models. The regulatory model presented in this paper was created for one of the first de-regulated markets in the world. The learning from this model is an important part for future developments.

VI. ACKNOWLEDGEMENTS

The knowledge of the NPAM summarized in this paper is the result of studies performed by the authors at the Royal Institute of Technology (KTH) since 2003. The studies have involved numerous discussions and meetings with users (representing both the DSOs and EMI). The authors gratefully acknowledge several persons that have contributed during the studies with a special thanks to; Olle Hansson (Fortum Distribution)

VII. REFERENCES

[1] Larsson, M. B-O,"The Network Performance Assessment Model - A new framework of regulating the Electricity Network Companies", Licentiate Thesis, TRITA-ICS-0501, KTH School of Electrical Engineering, Sweden, 2005.

[2] Wallnerström C. J. and Bertling L., "Investigation of the Robustness of the Swedish Network Performance Assessment Model", Accepted to be published in IEEE Transactions on Power Systems, Nov. 2007.

[3] Larsson, M. B-O, "The Network Perfomance Assessment Model from the Inside, ("Nätnyttomodellen från insidan"), (in Swedish), Åhus, Sweden, 2004.

[4] Heden H. et al., "Regulation of the Swedish Distribution System Operators using the Network Performance Assessment Model", ("Energimyndighetens reglering av elföretagens tariffer med Nätnyttomodellen"), (In Swedish), The Swedish Energy Agency, Sweden, April 2004.

[5] Law suit 2076-05 to the county of Södermalms län, appeal against the Energy Market Inspection (EMI) handled by the law firm Advokatfirman Södermark.

[6] Gammelgård M. and Larsson M. B-O, "The challenge of regulating natural monopolies in electrical distribution, experiences from Sweden", Proceedings of CIRED 2003.

[7] Gammelgård M., "The Network Performance Assessment Model – Considering implications on IT-investments", Licentiate Thesis, TRITA-ICS-0401, KTH School of Electrical Engineering, Sweden, 2004.

[8] Wallnerström C. J., "A comparative study of reliability assessment models for electrical distribution systems and evaluation of the method in the Network Performance Assessment Model", ("En jämförande studie av tillförlitlighetsmodeller för elnät – en utvärdering av Nätnyttomodellens tillförlitlighetsmetod"), (In Swedish), Master's Thesis, KTH School of Electrical Engineering, Sweden, May 2005.

[9] Bertling L., M. B-O Larsson och Wallnerström C. J., "Evaluation of the customer value of component redundancy in electrical distribution systems", Proceedings of IEEE PowerTech St. Petersburg, Russia, June 2005.

[10] Solver, T. "Reliability in performance-based regulation", Licentiate Thesis, TRITA-ETS-0511, KTH School of Electrical Engineering, Sweden, August 2005.

[11] Wallnerström C. J. and Bertling L., "Sensitivity analysis of input data for the Network performance assessment model", ("Känslighetsanalys av Nätnyttomodellens indata"), (In Swedish), A-ETS/EEK-0506, KTH School of Electrical Engineering, Sweden, September 2005.

[12] SP Swedish National Testing and Research Institute, "Statistical analysis of results from the performance assessment model", Borås, 2006,

[13] Bertling L., Wallnerström C. J, "Evaluation of the reliability of the Network performance assessment model (NPAM)" ("Nätnyttomodellens tillförlitlighet med avseende på små förändringar i indata), (In Swedish), TRITA-EE 2006:056, KTH School of Electrical Engineering, Sweden, December 2006.

[14] Wallnerström C. J. and Bertling L., "A sensitivity study of the Swedish network performance assessment model investigating the effects of changes in input data", Accepted to be published at the 19th International Conference on Electricity Distribution (Cired), Vienna, 21-24 May 2007.

[15] Setréus J., Wallnerström C. J. and Bertling L., "A comparative study of regulation policies for interruption of supply of electrical distribution systems in Sweden and UK", Accepted to be published at the 19th International Conference on Electricity Distribution (Cired), Vienna, 21-24 May 2007.

[16] The Swedish Law for the Electric Power System, Chapter 4, ("Ellagen"), (In Swedish) (1997:857), Sweden, 2002.

[17] The Swedish Energy Agency, "Decisions on parameters for NPAM and the tariff year 2004", ("Beslut om parametrar för tariffåret 2004"), (In Swedish), (www.energimarknadsinspektionen.se), Sweden, March 14, 2005.

[18] Cigré Task Force 38-06-01, Methods to Consider Customer Interruption Costs in Power System Analysis, Paris, 2001

[19] Billinton R. and Allan R.N., *Reliability Evaluation of Power Systems*, New York, US (2nd Edition, Plenum) 1996.

VIII. BIOGRAPHIES

Lina Bertling (S'98-M'02) was born in Stockholm in 1973. She received her Ph.D in electric power systems in 2002 and M.Sc. in systems engineering in 1997, from KTH - the Royal Institute of Technology, Stockholm, Sweden.

She is engaged at KTH School of Electrical Engineering as Associated Professor, and is the leader of the research group on reliability-centered asset management (RCAM). She is also engaged at Svenska Kraftnät as Assistant Research Director from Sept. 2007. Her research interests are in power system reliability modeling and assessment and applications for maintenance optimization.

Mats B-O Larsson was born in Stockholm in 1953. He received the Tech. Lic. degree in electric power systems in 2005 and M.Sc. in engineering physics in 1980, from KTH - the Royal Institute of Technology, Stockholm, Sweden. He is working as a consultant within model construction and is the originator of the Network Performance Assessment Model.

Carl Johan Wallnerström (S´06) was born in Stockholm in December 1980. He received his M.Sc. in electrical engineering in 2005, from KTH - the Royal Institute of Technology, Stockholm, Sweden.

He has been working at KTH School of Electrical Engineering since 2005., first as a research engineer, and from 2006 as a PhD student with the research group on RCAM. He has worked with different projects evaluating the Network Performance Assessment Model, and the title of his PhD project is" Risks related to the introduction of reliability-centered asset management (RCAM) for electrical distribution systems and the effect of regulatory models".