

MAINTENANCE OPTIMIZATION OF RELIABILITY CENTERED ASSET MANAGEMENT FOR POWER SYSTEMS

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RISK- OCH
TILLFÖRLITLIGHETSANALYS



Maintenance Optimization of Reliability Centered Asset Management for Power Systems

Implementation Roadmap

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Förord

Fortsättningsprojektet *Reability optimization in power system – stage I* är nyskapande och intressant för att det tillämpar en tidigare framtagna metod för optimal implementering av sannolikhetsbaserad tillgångsförvaltning för kraftsystem med komplexa topologier.

Projektet ingår i programmet Risk- och tillförlitlighetsanalys och det bygger vidare på resultatet från en mer teoretisk postdoktorandstudie, 2017:444 *Optimal Implementation of Reliability Centered Asset Management for Power Systems*.

Projektet har initierats och utförts inledningsvis av Ebrahim Shayesteh med Patrik Hilber som projektledare vid QED Asset Management-forskningsgruppen, KTH. Stora delar av projektet genomfördes och även avslutades av Jan Henning Jürgensen, som också tillhör Patrik Hilbers grupp på KTH. Referensgruppen som har följt och väglett projektet består av Erik Lejerskog, Kjell Oberger, Fadi Safou, Ulf Jansson, Malin Wihlén och Lars Enarsson från Ellevio. Fredrik Carlsson, Annalilly Brodersson, Ying He, Johan Öckerman, Andrew Kitimbo från Vattenfall. Tommie Lindquist, Milan Radosavljevic från Svk. Robert Saers, Nilanga Abeywickrama, Lena Meltzer från ABB. Matz Tapper från Energiföretagen Sverige, Erik Jenelius från KTH och Thomas Welte från Sintef.

Stort tack till programstyrelsen för stort engagemang och initiativ till att upplåta eget elnät och data för projektgenomförande:

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- Kenny Granath, Mälarenergi Elnät
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- Ola Löfgren, FIE
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- Carl Johan Wallnerström, Energimarknadsinspektionen

Följande bolag har varit involverade som intressenter. Ett stort tack för värdefulla insatser.

- | | |
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| • Ellevio AB, | • Skellefteå Kraft Elnät AB, |
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Sammanfattning

Reliability Centered Asset Management (RCAM) är en effektiv strategi för beslutsfattande som beaktar både de ekonomiska och tekniska aspekterna av kraftsystem. Detta projekt är en fortsättning på Energiforsk-studien "Optimal Implementation of Reliability Centered Asset Management for Power Systems " och beskriver den praktiska implementeringen av algoritmen i ett verktyg. Det inledande projektet har utförts av Ebrahim Shayesteh med Patrik Hilber som projektledare vid QED Asset Management-forskningsgruppen, School of Electrical Engineering, KTH Royal Institute of Technology, Stockholm.

Det föregående projektet utvecklade en strukturerad metod för optimal implementering av RCAM-metoden för kraftsystem. Det har dock testats på ett relativt litet svenskt distributionssystem och beaktar följaktligen inte utmaningarna med stora och komplexa kraftsystemtopologier. Därför är det huvudsakliga målet med projektets fortsättning en 'Roadmap' för implementering som beskriver utmaningar och möjligheter för en implementering för större elkraftsystem.

Dessutom tillhandahåller detta projekt en mer praktiskt tillämplig version av den utvecklade metoden i form av ett verktyg som kan användas av Göteborgs Energi Nät AB, andra svenska system-operatörer och svenska elkraftmyndigheter.

Summary

Reliability Centered Asset Management (RCAM) is an effective strategy for decision-making that considers both the economic and technical aspects of power systems. This project is the continuation of the Energiforsk study “Optimal Implementation of Reliability Centered Asset Management for Power Systems” and describes the practical implementation of the algorithm in a utility. The initial project has been performed by Ebrahim Shayesteh with Patrik Hilber as project manager at the QED Asset Management research group, School of Electrical Engineering, KTH Royal Institute of Technology, Stockholm. The previous project developed a structured method for optimal implementation of the RCAM approach for power systems. However, it has been tested on a relatively small Swedish distribution system and consequently does not consider the challenges of large and complex power system topologies. Therefore, the main goal of this project continuation is an implementation roadmap that describes the challenges and opportunities of an implementation for larger power system. Moreover, this project provides a more practically applicable version of the developed method in the form of a toolbox that can be used by the project collaborate Göteborg Energi Nät AB, and other Swedish system operators, and Swedish electric power authorities.

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1 Introduction

This report is prepared based on the postdoctoral research performed by Ebrahim Shayesteh (first part) and Jan Henning Jürgensen (second part) at QED Asset Management research group, School of Electrical Engineering, KTH Royal Institute of Technology in Stockholm. The project duration was from July 2018 to October 2019.

QED Asset Management research group is managed by Docent Patrik Hilber and involves researcher and several PhD students with particular focus on power system risk and reliability topics.

1.1 BACKGROUND

The method proposed in [1] is an algorithm for optimal maintenance decision-making for power systems using the Reliability Centered Asset Management (RCAM) approach. The subject of the reliability chain has been presented and utilized to develop an optimization-based approach for implementing RCAM. This approach considers and assesses the conditions of all system components to evaluate the system reliability. Afterwards, all asset management actions with their associated costs and potential impact on component reliability are listed for each component of the system. A mixed-integer linear program is applied to determine the most appropriate asset management action for each component of the system. The proposed program also provides the best time for implementing the optimal asset management action determined for each component. Another feature of the optimization algorithm is the consideration of the component reliability variations and power system reliability into account. A simplified overview of the optimization algorithm is illustrated in Figure 1.

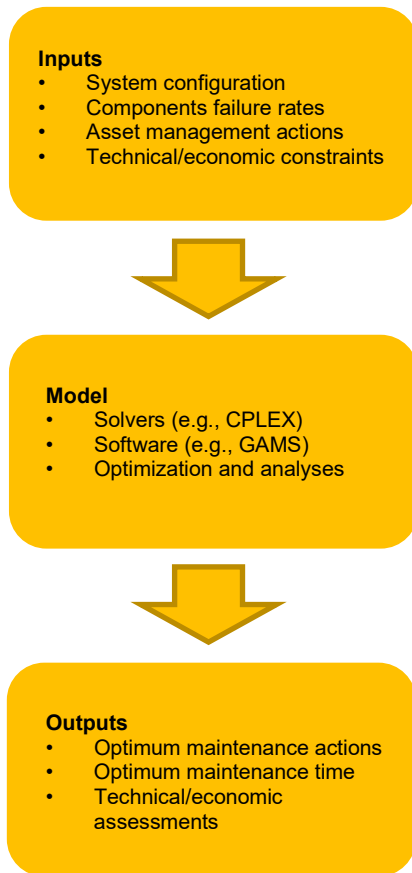


Figure 1: Abstract overview of the optimization algorithm with inputs and outputs

1.2 OBJECTIVES

The main objective is to provide a practical version of the maintenance optimization method in the form of a software or toolbox, which could be used by different researchers and industries. Three different approaches have been identified to reach the goal of the implementation phase:

1. Toolbox under GAMS: A generalization of the method + a graphical user interface (GUI) + some modifications in GAMS code + link it to Excel/MATLAB.
2. Toolbox under PSS/E: The first option + a new model based on defined programming languages, e.g. python script code for PSS/E + C# for advanced GUI.
3. Specific software developed: Implementing the developed method as an executable program (EXE file), i.e. not dependent on any software. To do so, the developed model is used as a core model using C++ and merged in a GUI with some input files (e.g., Excel files) and an executable binary file (EXE) is extracted.

1.3 PROJECT DELIVERABLES

The project has the following two major outcomes:

1. Prepare the fundamentals for implementing the theoretical method for practical usage by Swedish researchers and industries:
 - Operational beta tool for maintenance optimization
 - Initiate the development of the required graphical user interface (GUI)
 - Outline of prerequisites for running the optimization
 - Start collecting base failure and repair times and how they develop over time
 - Initial testing of the developed tool using small systems
 - Strong collaboration between KTH and Swedish industries is initiated for application in the industry.
2. Implementation and assessment of the theoretical method into a useable tool:
 - Finalizing the graphical user interface (GUI) based on the software available at Göteborg Energi Nät AB (GENAB)
 - Running the optimization on the software available at GENAB
 - Collecting the base failure and repair times and how they develop over time
 - Actual testing of the developed tool through applying to real systems
 - The initiated collaboration between KTH and Swedish industries is completed through the proposed exchange research project (6 months at GENAB).
 - The expected research results will be published during the second part of the project.

2 Maintenance Optimization toolbox

The recommended solution consist of a generalization of the method developed in [1] based on a GAMS optimization algorithm which can be adapted to the power system structure of interest. The first proposed solution, a toolbox under GAMS, has been implemented. A graphical user interface (GUI) has been programmed in EXCEL 2016 to access the model and set the necessary input parameter.

2.1 PROPOSED SOLUTION

A general flow chart of the software solution is presented in Figure 2. First, the GUI in EXCEL needs to be opened and the input data such as

- Component failure rates,
- Components repair rates,
- Asset management actions and costs,
- Number of customers at each defined load point,
- Power at each defined load point
- Interruption costs at each defined load point,
- As well as the cost constant k and c needs to be set.

If the system structure has been described in reliability equations in the GAMS model, the optimization can be started. After the optimization has found a solution, the results must be loaded from another EXCEL file and can be viewed in the GUI.

2.2 TECHNICAL ENVIRONMENT

2.2.1 Software requirements

Software requirements:

- Excel 2016
- GAMS Base Module plus CPLEX solver

Total Costs of the GAMS software package:

GAMS Basic 3200 USD +CPLEX Solver 9600 USD (August 2019)

Total = 12 800 USD ~ 121 300 SEK one time fee plus an optional 20% (24260 SEK) of total as annual fee for Maintenance & Support

2.2.2 Operating System

Windows 10 is the preferred operating system.

2.2.3 Data requirements

The following data is required to run the maintenance optimization algorithm.

Component Data

- Failure rates and repair times: power transformers, bus bar, circuit breakers, and disconnectors
- Determining the component conditions to estimate failure rate
- Determining cost of maintenance tasks
 - Condition monitoring
 - Minor preventive maintenance
 - Major preventive maintenance
 - Component replacement

Load Point Data

- Load point number
- Number of customers at each load point
- Interruption costs at each load point
- Power at each load point
- Cost constant k and c at each load point

System Reliability Topology

- Reliability structure and equations of the system:

2.2.4 Database

The database for all required input data is implemented in the excel file with the graphical user interface.

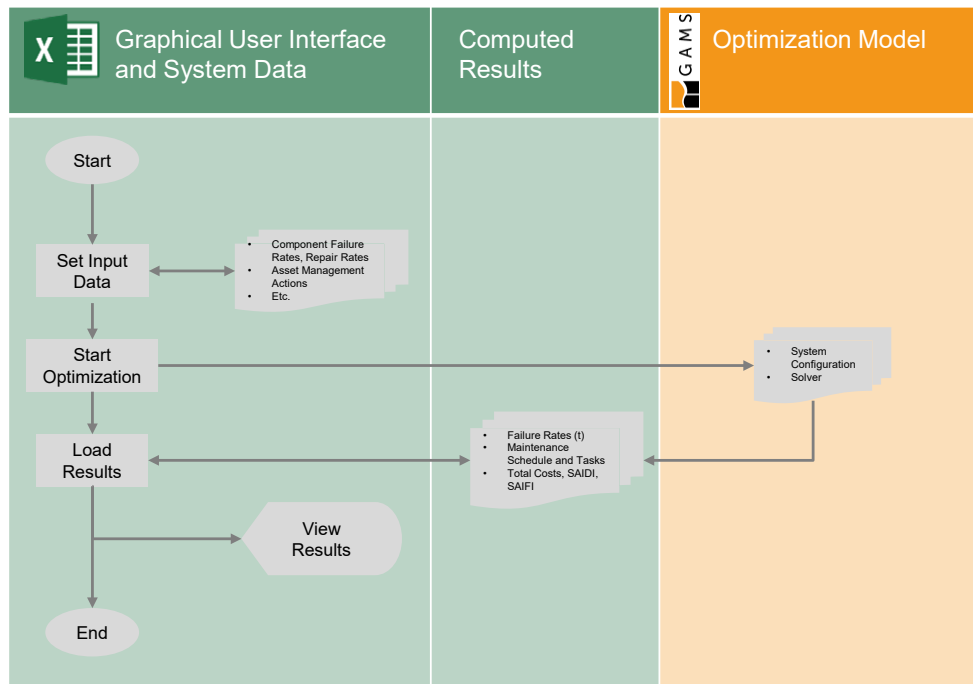


Figure 2: Proposed solution of the maintenance optimization algorithm

2.3 GENERAL DESCRIPTION OF TOOLBOX

The architecture in Figure 2 is described with a fictional substation called “Goete_2019”. The GUI and database is included in the EXCEL workbook “Graphical User Interface and System Data”. Here, the optimization can be started and the results loaded from another excel workbook “Computed Results”. Currently, the additional EXCEL workbook “Computed Results” with the results from the maintenance optimization algorithm is required because GAMS cannot write the results into an open EXCEL workbook. Therefore, the results must be loaded separately. The EXCEL workbook “Graphical User Interface and System Data” includes the following worksheets:

- **Main:** The GAMS parameter directory and model must be set, the optimization can be started, and the results loaded. It also shows the date of the last optimization and the key output results such as System Average Interruption Frequency Index (SAIFI), total interruption costs, total correction cost, total preventive costs, total costs, and total profit. The reference value is “to do nothing”, in fact to do no maintenance at all under the study time period.
- **MaintenanceSchedule:** This worksheet presents the maintenance actions results of the algorithm. It shows in detail which maintenance actions on a monthly basis needs to be undertaken with a time horizon of 10 years.
- **FailureRate_Results:** In this worksheet, the failure rate of each component is shown over a 10 year horizon. All failure rates are shown in a graph when no particular components are selected. A component filter makes it possible to select only particular components, for example, by component type or ID.

- Results_1, Results_2, Results_3: Here are the plain results of the previous described worksheets.
- FailureRate: All input failure rates, condition, and description of components
- RepairRate: All input repair rates and description of components
- ModelParameter: The model to convert the component conditions to failure rates is described here. This model is based on [2].
- PM_Cost: The costs for the different maintenance actions.
- Interruption_Cost: The interruption costs at each load point. Thus far, only customer costs included.
- Number_Customers: Number of customer at each load point
- Power_LoadPoint: The power at each load point.
- Cost_Constant_K: The cost per power in [SEK/kW] derived from [3], appendix 3 and table 16 for unplanned outages.
- Cost_Constant_C: The cost per energy in [SEK/kWh] derived from [3], appendix 3 and table 16 for unplanned outages.
- Visual: The reliability block diagram design of substation Goete_2019.

The GAMS optimization model includes the general optimization algorithm and the system reliability equations. The reliability equations for the maintenance optimization algorithm are derived with the following steps:

1. The electrical circuit diagram provides the information necessary to build a reliability block diagram.
2. This reliability block diagram can be used to formulate the reliability equations necessary for the algorithm. The method to formulate the equations can be found in several reliability textbooks, for example [8].

3 Implementation - Challenges and Opportunities

During the implementation period at GENAB some challenges but also opportunities in form of research questions and data availability have been encountered. These are described in the following.

3.1 CHALLENGES

3.1.1 Data quality and availability

To improve the results of the maintenance optimization algorithm, the input data needs to be accurate. Section 2.2.3 describes the required data for the optimization algorithm. One main objective of this project is the data acquisition to improve the input data. This section describes the challenges that have been encountered during the implementation from component to system level in the following.

Component data

Accurate failure rates and repair times require detailed information about the condition and other relevant risk factors of the components. This project focused on power transformer, circuit breaker, disconnectors, and bus bars during the implementation at GENAB. Condition monitoring information is available for power transformer and circuit breaker and could be extracted from pdf documents and the homepages of the service providers.

The first challenge is the translation of condition monitoring and inspection information into a failure rate. References [4] and [5] discuss different methods for failure rate modelling in the power system domain with particular focus on data availability. The general approach can be divided into two steps if not sufficient failure data is available in the utility: condition monitoring data to a health index (condition indicator) and in the next step from the health index to a failure rate. Here, the condition monitoring information is translated into a health index first before using the method in [2] to calculate a failure rate as a function of the observed condition. In this project, the health index method presented in [6] has been applied with some modifications due to the condition monitoring information available at GENAB. To do so, this health index tool has been implemented as an EXCEL 2016 workbook. Dividing the failure rate calculation into two steps has the advantage that the asset manager can assess the condition of the power transformers separately to gain a better overview about the power transformer fleet as well as to observe trends. Figure 3 shows a screenshot of the developed health index tool in EXCEL.

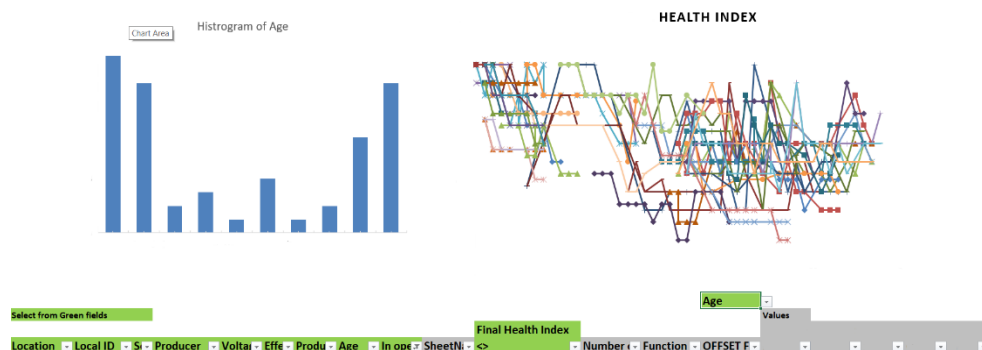


Figure 3: Screenshot of Health Index Tool in EXCEL

Based on the data availability and complexity more advance remaining useful life methods can be applied [7]. Expert systems are the method of choice if less complex methods are needed or failure and condition monitoring data is scarce. This approach showed good results in the power transformer case where sufficient experience in practise and literature exists. However, for circuit breaker and disconnector no actual rules to classify condition monitoring data have been established and sufficiently discussed yet. Consequently, even an rule based expert system is difficult to implement even though condition monitoring data is available.

Load point information

Load point data has been gathered through the utility's asset register and SCADA system. This has been a straightforward task without any particular actual challenges. Nevertheless, the load point information changes over time such as load, customer type and number, etc. Therefore, this procedure of data gathering should be automated in the future so that changes in the database of the asset register and SCADA system are automatically loaded into the maintenance optimization algorithm.

System Reliability Equations

Likewise the load point data is the electric circuit diagram of the power grid available through the asset register and the SCADA system. There are two main challenges related during the data gathering. Firstly, the electrical circuit diagram must be extracted in an automated manner limit additional work. Secondly, the electrical circuit diagram must be converted to a reliability block diagram and further into reliability equations. For a particular system or substation is might be reasonable task to do it manually, however, for larger system this task becomes sophisticated and requires large resources.

3.1.2 Associated Costs

The current approach requires the optimization software GAMS which comes with considerable licence fee costs, see section 2.2.1. Particularly for smaller utilities this can be a significant cost factor because the cost benefit of running the optimization

algorithm still needs to be assessed. Therefore, the development of an open-source solution is suggested.

3.2 OPPORTUNITIES

3.2.1 Research

Dynamic reliability calculations for power systems (infrastructures)

The power system grid topology is translated from an electrical circuit diagram to a reliability block diagram to determine the system reliability equations and the load point reliability. Whereas formulating system reliability equations from reliability block diagrams is a straightforward approach with established theory and methods [8], the translation of an electrical circuit diagram of a substation, is due to Smart Grids and thus the ever more-complex control and protection architecture of power grids a very challenging task with no theory and methods established. Moreover, the load flow in the grid as well as the changing load centres and distributed generation affects the reliability topology of the grid. Considering all these factors, the translation from electric circuit diagrams to reliability block diagrams or rather reliability equations need to be dynamic to get a better input for the maintenance optimization. This would not solely benefit maintenance and replacement strategies but also control room operation, system planning, and switch placement.

Practical advancement of maintenance optimization

Currently, maintenance and replacement is formulated as the minimum of the total cost variations of interruption costs, and corrective and preventive maintenance costs based on the theory developed in [1]. From a utility perspective, the revenue cap based on the regulation and budget constraints are also important to consider. In fact, the asset value and depreciation, and thus the potential maximum revenue, are essential when considering system reliability and operational costs and profits. These factors should be considered as a possible advancement of the method in [1] to strengthen the practical implementation of the optimization approach.

Circuit Breaker reliability assessment and condition classification

During the implementation phase at GENAB, the condition assessment has been identified as essential to achieve better results for the maintenance optimization. Whereas power transformer condition monitoring data are available and rule based expert systems exist such as health index methods [6], for circuit breaker and disconnectors there are no rule based expert system widely available. Even though different condition monitoring methods are used and discussed in literature [9], thus far no rules have been established which classify a measured resistance, motor current, temperature, or vibration into a simplified health index scale. Future research should address actual condition classification based on the aforementioned condition monitoring methods.

3.2.2 Development

Using optimization software such as GAMS that requires an appropriate solver comes with considerable costs. This has been identified as a challenge for smaller utilities during the implementation phase at GENAB. As more detailed the power system is modelled with reliability equations, the more detailed and useful the optimization algorithm results become. However, to achieve this level of detail further research is required to dynamically model reliability calculations for power system, see section 3.2.1. A possible solution might be the development of the optimization algorithm with Python. This would also enable better documentation since Python has become a dominating programming language.

4 Conclusion

This project has been the continuation of the Energiforsk project “Optimal Implementation of Reliability Centered Asset Management for Power Systems”. Whereas the previous project focused on the theoretical and research perspective of developing the maintenance optimization algorithm, does this project focus on the practical implementation of the algorithm at the distribution system operator GENAB in Gothenburg, Sweden. To do so, the algorithm has been modified to use it for different power systems and user interface has been developed. The algorithm in GAMS with an EXCEL user interface has been identified as the best solution in this particular project due to the project resources and the software available at GENAB. During the implementation process, several practical implementation challenges as well as opportunities for research and development have been identified and are addressed in this report. Despite the good data availability and quality, the translation from condition monitoring to a failure rate had to be solved for power transformer but needs to be further developed for different components such as circuit breaker. Moreover, the development of the algorithm with open-source software solutions is recommended. This is particular of interest for smaller distribution system operator. However, this project successfully implemented the maintenance optimization algorithm for one substation and while doing further research possibilities have been identified.

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MAINTENANCE OPTIMIZATION OF RELIABILITY CENTERED ASSET MANAGEMENT FOR POWER SYSTEMS

This is the continuation of the Energiforsk project Optimal Implementation of Reliability Centered Asset Management for Power Systems.

The previous project focused on the theoretical and research perspective of developing the maintenance optimization algorithm. This study focus on the practical implementation of the algorithm at the distribution system operator GENAB in Gothenburg, Sweden. To do so, the algorithm has been modified to use it for different power systems and a user interface has been developed.

The algorithm in GAMS with an EXCEL user interface has been identified as the best solution in this particular project due to the project resources and the software available at GENAB.

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