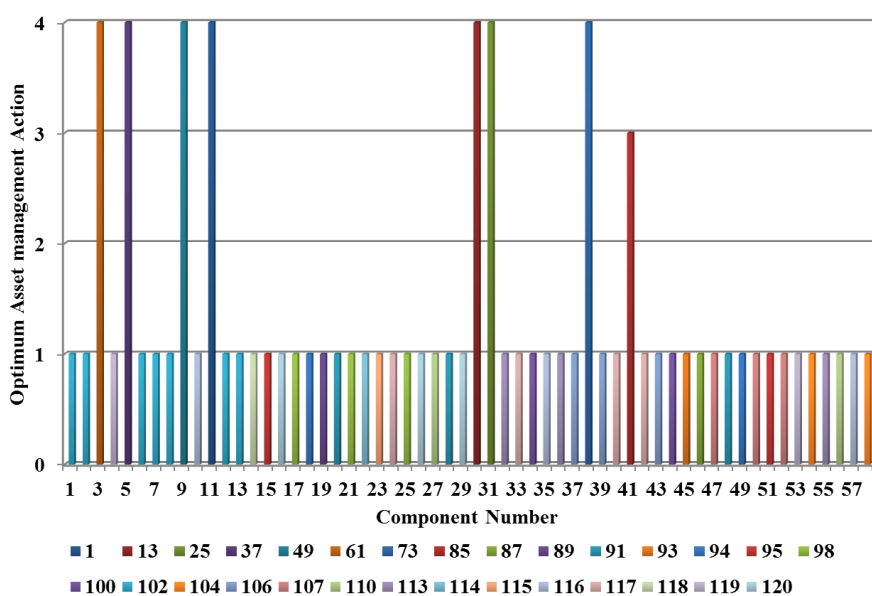


OPTIMAL IMPLEMENTATION OF RELIABILITY CENTERED ASSET MANAGEMENT FOR POWER SYSTEMS

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RISK- OCH
TILLFÖRLITLIGHETSANALYS



Optimal Implementation of Reliability Centered Asset Management for Power Systems

Using the Reliability Chain Concept

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Foreword

The Risk analysis program was in its second phase (2011-2015), when this project initiated. The aim of the project is to use the reliability chain to study how the component condition and power system reliability interact in order to find the optimum monitoring and maintenance schedule for a component to increase the whole system reliability i.e. the optimum monitoring and maintenance schedule for a component to increase the whole system reliability.

The project *Increased reliability in distribution networks in terms of maintenance and investment budget* (Ökad tillförlitlighet i distributionsnäten vid bibehållen underhålls- och investeringsbudget), is based on an algorithm where all the components of the system are be monitored and their initial states are transferred into the “health index” and the “component reliability”. A set of possible maintenance action for each component, together with the corresponding costs and impact on component reliability were provided. A cost-benefit optimization problem is proposed to select the optimum maintenance action for all components.

Finally, the status of each component is updated according to the assigned maintenance action.

The study has been accomplished by Ebrahim Shayesteh at the RCAM group, School of Electrical Engineering, KTH Royal Institute of Technology, Stockholm, Sweden. Ebrahim has worked together with Patrik Hilber who is Programme director of the Electric Power Engineering Master (TEPME) and head of the RCAM research group at Royal Institute of Technology.

A reference group consisting of Olle Hansson, Ellevio AB, Robert Saers, ABB AB, Nilanga Abeywickrama, ABB AB, Malin Ågren, Ellevio AB, Claes Ahlrot, E.ON Sverige AB, Tommie Lindquist, Svenska kraftnät, Lars Enarsson, Ellevio AB, Susann Persson, Jämtkraft AB, Ying He, Vattenfall AB, Johan Ockerman, Vattenfall AB, Fredrik Masman, Vattenfall Forskmark AB, Milan Radosavljevic, Svenska kraftnät, Matz Tapper, Energiföretagen Sverige, Erik Jenelius, KTH, och Thomas Welte, SINTEF have assisted in the project.

Many thanks to the program board for good initiative and support. The program Board consisted of the following persons:

- Jenny Paulinder, Göteborg Energi (chairman)
- Lars Enarsson, Ellevio
- Jonas Alterbäck, Svenska kraftnät
- Hans Andersson, Vattenfall Distribution
- Kenny Granath, Mälarenergi Elnät
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The following companies have been involved as stakeholders in the project. A big thanks to all the companies for their valuable contributions.

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Reported here are the results and conclusions from a project in a research program run by Energiforsk. The author / authors are responsible for the content and publication which does not mean that Energiforsk has taken a position.

Sammanfattning

Reliability Centered Asset Management (RCAM) ger ett effektivt sätt att ta hänsyn till både de ekonomiska och tekniska aspekterna av kraftsystemet vid asset management beslut. Även om denna teknik har studerats tidigare har det funnits förbättringspotential.

Denna studie föreslår metoder för optimal implementering av RCAM för kraftsystem. För att göra det presenteras tillförlitlighetskedjan som används för att utveckla ett optimeringsbaserat tillvägagångssätt för implementering av RCAM i kraftsystem. Denna metod startar med tillstånden för alla komponenter och som används för att utvärdera komponentens tillförlitlighet. I nästa steg listas alla potentiella åtgärder tillsammans med deras tillhörande kostnader och effekter på komponentens tillförlitlighet, detta görs för varje studerad komponent i systemet. Slutligen ställs ett "mixed-integer linear" optimeringsproblem upp för att bestämma den mest lämpliga åtgärden för varje komponent i systemet.

Det föreslagna programmet ger också den bästa tiden för att genomföra den optimala aktivitetshanteringsåtgärden som bestäms för varje komponent. Slutligen används det föreslagna optimeringsproblemet i en algoritm som tar hänsyn till komponentens driftsäkerhetsvariationer och tillförlitligheten i elsystemet. De simuleringsresultat som erhållits för ett svenskt elsystem används för att utvärdera effektiviteten hos den föreslagna metoden."

Summary

Reliability Centered Asset Management (RCAM) provides an effective means to take both the economic and technical aspects of power system into account when performing the asset management decisions. Although implementation of this technique for the power system has been studied earlier, the proficiency of the implementation has not been deliberated adequately. This study proposes methods for optimal implementation of RCAM for power systems. To do so, the subject of reliability chain is presented and utilized to develop an optimization-based approach for implementing the RCAM in power systems. According to this approach, first, the conditions of all system components are assessed and used to evaluate the component reliability. In the second step, all potential asset management actions together with their associated costs and impacts on component reliability are listed for each component of the system. Thirdly, a mixed-integer linear program is proposed 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 optimum asset management action determined for each component. Finally, the proposed optimization problem is used in an algorithm taking the component reliability variations and the power system reliability into account. The simulation results obtained for a Swedish power system are used to evaluate the effectiveness of the proposed method.

Introduction

This report is prepared based on the postdoctoral research performed by Ebrahim Shayesteh at Reliability Centred Asset Management (RCAM) research group, School of Electrical Engineering, KTH Royal Institute of Technology in Stockholm. The project duration was around two years (i.e., from February 2015 to May 2017) and was sponsored by the Swedish Energy Research Centre through Risk analysis program.

RCAM research group is leaded by Docent Patrik Hilber and involves some PhDs and several PhD students, all of them are working on power system risk and reliability issues. Apart from performing his postdoctoral research project, Ebrahim Shayesteh was also the co-supervisor of two PhD students and the main supervisor of 5 master thesis projects as follows:

A. PhD thesis projects

- Sajeesh Babu, "Reliability Evaluation of Distribution Structures Considering the Presence of False Trips".
- Sanja Duvnjak Zarkovic, "Security of Supply in Power Systems".

B. Master thesis projects

- Jia Yu, "Maintenance Optimization of Electric Power System Considering the Renewable Energy Resources".
- Yu Zhang, "Reliability centered asset management for power systems".
- Javier Romera, "Demand Response Application for Reliability Enhancement in Electricity Market".
- Jesus Paniagua, "Reliability-constrained Microgrid design".
- Berina Fazlagic, "Evaluation of the Swedish incentive scheme for the regulatory period 2016-2019".

In addition, two conference papers and two journal papers were developed based on the performed postdoctoral research project as follows:

- E. Shayesteh and P. Hilber, "Reliability-Centered Asset Management Using Component Reliability Importance", 2016 International Conference on Probabilistic Methods Applied to Power Systems (PMAPS 2016), Beijing, China, Oct. 2016.
- C. J. Arias, A. Rasouli, and E. Shayesteh, "An Assessment on the Impact of the Integration of Photovoltaic Power Generation on the Reliability of Distribution Networks", The 3rd Energy & Materials Research Conference (EMR 2017), Lisbon, Portugal, Apr. 2017.

- E. Shayesteh, J. Yu, and P. Hilber, "Maintenance Optimization of Power Systems with Renewable Energy Sources Integrated", Submitted to Journal of Energy (Elsevier).
- E. Shayesteh, P. Hilber, and Y. Zhang, "Optimal Implementation of Reliability Centered Asset Management for Power Systems Using the Reliability Chain Concept", Submitted to IEEE Transactions on Smart Grid.

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3 List of symbols

The indices, constants, and variables used in the formulation of this study are respectively defined in the following.

3.1 INDICES

i, j	Indices for system components running from 1 to N
L	Number of load points in the system
N	Number of components in the system
T	Duration of the studied time period

3.2 CONSTANTS

λ_i	Failure rate of component i (f/yr)
r_i	Repair time of component i (h/f)
U_i	Unavailability of component i (h/yr)
λ_s	Failure rate of the components serial connection (f/yr)
r_s	Repair time of the components serial connection (h/f)
U_i	Unavailability of the components serial connection (h/yr)
λ_p	Failure rate of the components parallel connection (f/yr)
r_p	Repair time of the components parallel connection (h/f)
U_p	Unavailability of the components parallel connection (h/yr)
P_l	Electric power consumption at load point l (kW)
k_l	Cost constant at load point l ($\text{€}^1/\text{f}, \text{kW}$)
c_l	Cost constant at load point l ($\text{€}/\text{kWh}$)
$\alpha_{i,a}^{AM}$	Cost of performing asset management action a for component i ($\text{€}/\text{action}$)
β_i^{CM}	Corrective maintenance cost of component i ($\text{€}/\text{f}$)
x_i^{max}	Total number of possible asset management actions for component i
n_a^{max}	The monitoring and maintenance capacity needed for performing the asset management action a

¹ € is the symbol for the “cost unit” used instead of any currency to make the formulations easier and more general.

n_{τ}^{max}	Total available monitoring and maintenance capacity for performing all types of asset management actions during τ time intervals
f_{inc}	Failure rate increment if no asset management action is done (%)
$\lambda_{i,t}^{var}$	Failure rate of component i at time interval t if no asset management action is done (f/yr)

3.3 VARIABLES

liH	Hazard rate index of component i ($\$/f$)
$\overline{I_i^H}$	Average hazard rate index of component i ($\$/f$)
Cs	Total interruption cost of the system ($\$/yr$)
$C_{i,t}^{AM}$	Cost of performing the asset management actions for component i at time interval t ($\$/yr$)
$C_{i,t}^{CM}$	Cost of corrective maintenance for component i at time interval t ($\$/yr$)
$C_{i,t}^{IC}$	Customer interruption costs due to failure in component i at time interval t ($\$/yr$)
TC	Total cost of the system ($\$/yr$)
λ_l	Failure rate at load point l (f/yr)
rl	Repair time at load point l (h/f)
$x_{i,a,t}$	Binary variable equal to 1 if asset management action a is performed on component i at time interval t and 0 otherwise
λ_i^{old}	Failure rate of component i at the beginning of the study period (f/yr)
$\lambda_{i,t}^{new}$	New failure rate of component i (after doing the asset management action) at time interval t (f/yr)
ω	Weighting factor used to set the desirable reliability level

4 Background

The concept of asset management plays an important role in power system operation and planning due to its specific features. Some of these features are high investment costs, very expensive components, and costly outages with high negative influences on the society. Therefore, performing an appropriate asset management is vital in nowadays power systems. However, the main challenge in performing a proper asset management in power systems is to address the technical concerns of the system (e.g., assuring an acceptable level of security in supplying electrical power) while considering economic issues. Reliability Centered Asset Management (RCAM) [1] is a promising technique which aims to make a correct balance between the technical and economic aspects.

RCAM is a generalization and further development of the well-known subject of Reliability Centered Maintenance (RCM) which was initially introduced in the aircraft industry in 1960s [2]. RCM was later applied in different industries including the electric power system [3]. The main goal of RCAM is to implement quantitative approaches to propose an optimum monitoring and maintenance plan for the power system considering both the technical (e.g., system reliability and performance) and economic (e.g., monitoring/maintenance and interruption costs) aspects.

Application of RCAM in power system context has previously been studied in the literature. For instance, a case study of RCAM has been done to the Mexican Sub-Transmission network in [4]. In [5], a RCAM model is proposed to improve the transmission reliability for the circuit breakers, transmission lines and the transformers in the Turkish transmission system. Reference [6] presents a research on the component reliability and life model for RCAM method and proposes a maintenance model for power distribution system. Besides the transmission and distribution system, the RCAM maintenance model is also studied for the wind power system in [7] and [8]. The RCAM method is also used to propose an improved maintenance plan for transformers in [9].

Even though some of the applications of RCAM in power system have earlier been studied (e.g., in [3]–[9]), there is still no well-defined implementation of this technique in power system. This is due to the fact that, in the previous studies, the RCAM has been more of a quantitative framework, building on concepts from RCM.

This study aims to fill the gap by proposing appropriate methods for optimal implementation of RCAM in power systems. To reach this goal, the subject of reliability chain [10] is introduced and employed to develop an optimization-based approach for implementation of RCAM in power systems. According to this approach, first, all components in the system are assessed and their conditions are investigated. Then, according to component conditions, the reliability of each component is defined in the form of a health index or failure rate. In the last preparatory step, all potential asset management actions together with their corresponding costs and impacts on component reliability are determined for each component in the system. In the next step, an optimization problem is developed

and used to decide the best asset management action for each component. The component conditions and reliabilities will then be updated according to the optimum asset management action. Finally, the reliability of the whole system, obtained based on the optimum asset management schedule for all components, will be compared to the desired level to make an appropriate balance between technical and economic requirements of the system.

The RCAM approach proposed in this paper has at least the following contributions and advantages. First, it is proposed based on a structured algorithm and could be simply applied to any power system. Second, it could be used with different information levels. That is, for successful application of the proposed approach, the current and future situations of the system (e.g., conditions of all system components, different asset management actions, and their impacts/costs) need to be known. This, however, does not limit the applications of the approach developed in this paper since the core structure of the proposed approach is general and could also be used for different situations. Thus, the proposed approach could be used with different information levels. It could even be used when detailed conditions of all system components are not known. In such cases, historical data and expert experiences should be used to provide condition estimation for each component.

Another important advantage of the proposed approach in this study is providing a structured and essential link between different power system perspectives including component monitoring, technical and economic system requirements, and general asset management decisions. In another word, the study proposes an approach to connect the individual component reliability via system aspects to total system reliability performance and provide a robust approach for reliable and efficient operation of modern power systems.

5 Method development and formulation

The concept of the reliability chain is used in this study in order to implement the RCAM for power system [10]. Fig. 1 shows a schematic of reliability chain (in solid blue color) as well as its relation to system operation (in dashed red color) and society observation (in dotted green color).

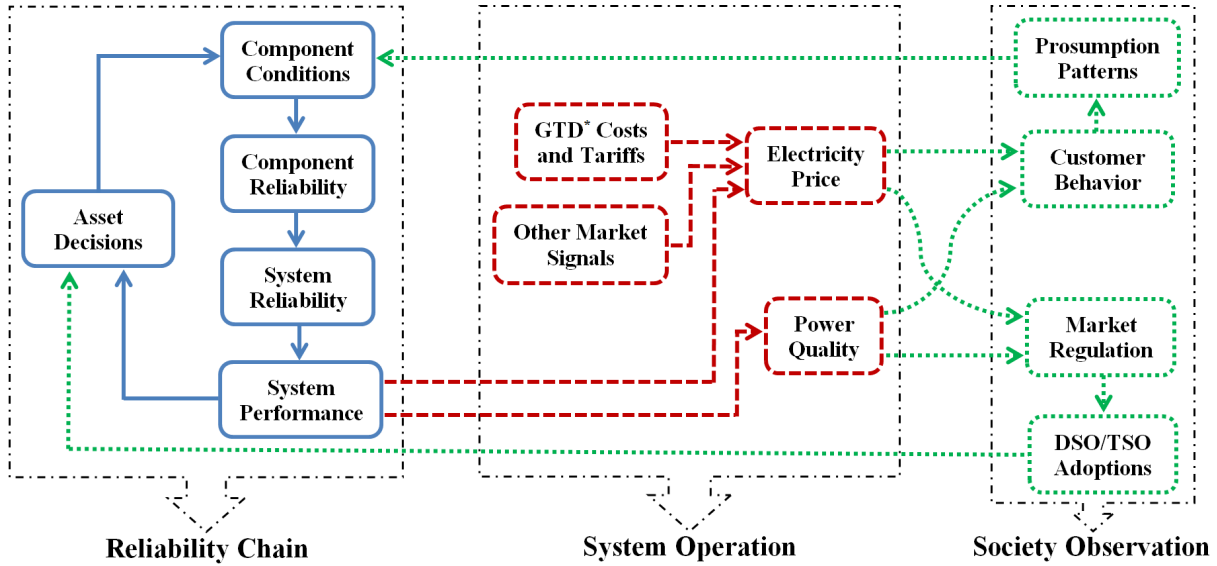


Fig. 1. The schematic of reliability chain and its relation to system operation and society (* GTD abbreviates Generation, Transmission, and Distribution)

Starting from the reliability chain part, one can see that it begins from evaluation of the component conditions. Then, the component conditions will be translated into a reliability measure for the component. After that, the system reliability is calculated based on reliability of different components and later used to evaluate the system performance. In the next step, the assessment process is performed and appropriate decisions are made according to the components conditions, overall system situation, and available actions.

Apart from its role in the reliability chain, the system performance could also affect the quality and price of the electric power and, therefore, influence the electricity market and end-use customers. The electric power production and consumption (presumption) patterns of the end-use customers will on the contrary change the component conditions since they can change the components loading and operation patterns and hence directly affects the aging process. Additionally, market regulations for DSO/TSO adoptions might change the decisions in the asset management process since these regulations can change the performance requirements and economic ramifications such as assigned budget for performing the maintenance actions.

The existing sequence among different blocks of the aforementioned reliability chain is used in the following sub-sections to propose a structured algorithm for implementation of RCAM into power system.

5.1 COMPONENT-LEVEL ACTIONS

The first step in implementing the RCAM approach based on reliability chain is to monitor and evaluate the conditions of all system components and present their conditions in the form of quantitative indices. The condition monitoring could be done in different degrees starting from knowing only the component manufacture/model and its location in the system structure. In a more detailed monitoring however, more properties of the component such as age, loading history, and isolation status of the component should be known. Thus, to apply the proposed RCAM approach, detailed information of all system components are not necessarily required but more accurate evaluations will be performed if the component conditions are modelled more accurately.

To indicate the component conditions in a quantifying way, different indices (e.g., different health indices) could be used [11]. The failure rate, repair time, and unavailability of the component as the most common indices for representing the component reliability are used for this purpose in this study. Equation (1) clarifies the relation among these three indices for each component:

$$U_i = \lambda_i \cdot r_i, i \in \{1, 2, \dots, N\} \quad (1)$$

In conclusion, the component-level activities of the proposed algorithm could be summarized as follows. The component conditions of each component in the system will be monitored and evaluated to estimate the failure rate, the repair time, and the unavailability of the component. As mentioned above, the accuracy of this estimation, however, depends on the comprehensiveness of the collected information for the component. At the end of this step, failure rates, repair times, and unavailabilities of all components are known.

5.2 SYSTEM-LEVEL ACTIONS

In the second step, named system-level actions, the reliability indices of all components, calculated in the first step, are used to evaluate the reliability of the whole system. That is, depending on the parallel or serial connections of each pair of the system components, equations (2) or (3) are used to calculate the reliability indices for the connection of two corresponding components [12], [13]. It is assumed here that there are only serial and parallel connections among the components and, in case of having other connections (e.g., k out of n connection [12]), these connections could be replaced by serial and parallel connections.

Application of equations (2) or (3) is continued until the aforementioned reliability indices (i.e., the failure rate, repair time, and unavailability) are calculated for all load points in the system.

$$\lambda_s = \lambda_i + \lambda_j, i, j \in \{1, 2, \dots, N\} \quad (2a)$$

$$U_s = (\lambda_i \cdot r_i) + (\lambda_j \cdot r_j), i, j \in \{1, 2, \dots, N\} \quad (2b)$$

$$r_s = \frac{U_s}{\lambda_s} = \frac{(\lambda_i \cdot r_i) + (\lambda_j \cdot r_j)}{\lambda_i + \lambda_j} \quad (2c)$$

$$\lambda_p = \lambda_i \cdot \lambda_j \cdot (r_i + r_j), i, j \in \{1, 2, \dots, N\} \quad (3a)$$

$$U_p = \lambda_i \cdot \lambda_j \cdot r_i \cdot r_j, i, j \in \{1, 2, \dots, N\} \quad (3b)$$

$$r_p = \frac{U_p}{\lambda_p} = \frac{r_i \cdot r_j}{r_i + r_j}, i, j \in \{1, 2, \dots, N\} \quad (3c)$$

Once the reliability indices at all load points of the system are known, these indices could be used to calculate appropriate indices for evaluating the reliability of the whole system. Total interruption cost of the system is used in this study for reliability evaluation of the whole system. The failure rate and repair time at all load points of the system are taken into account when calculating this index as follows [14]:

$$C_s = \sum_{l=1}^L \lambda_l \cdot (k_l \cdot P_l + c_l \cdot P_l \cdot r_l) \quad (4)$$

The total interruption cost of the system, presented in (4), is then used to calculate an index called component reliability importance (CRI) index for all components in the system. This index will be used in the next block of the proposed reliability chain (i.e., asset management decision-level actions) to prioritize the asset management actions. Indeed, there are different CRI indices in the literature [14], [15]. However, since the basic principles of these indices are similar, many of them could be calculated based on other indices [14]. Thus, in this study, one of these CRI indices named hazard rate index (I^H), is introduced and applied for the sake of RCAM implementation. The main idea in calculation of hazard rate index for each component of the system is to determine how the total interruption cost of the system is affected by variation in the reliability of each component. In other word, the CRI index I^H , calculated by (5), shows how important is the component reliability when calculating the total interruption cost of the system.

$$I_i^H = \frac{\partial C_s}{\partial \lambda_i}, i \in \{1, 2, \dots, N\} \quad (5)$$

According to (4) and (5), both the total interruption cost and the hazard rate index are linearly related to power consumption at different load points and, therefore, are time dependent. To consider the variations of the I^H index in the optimization problem proposed in the next sub-section, an average hazard rate index over the studied time period is defined and calculated through (6).

$$\overline{I_i^H} = \frac{1}{T} \cdot \left[\int_{t=0}^T (I_i^H(t) \cdot dt) \right], i \in \{1, 2, \dots, N\} \quad (6)$$

At the end of this step, i.e., system-level actions, an average hazard rate index is calculated for each component of the system.

5.3 DECISION-LEVEL ACTIONS

The decision-level step is the main step in implementing the proposed reliability chain-based RCAM into power system. To do so, an optimization problem is proposed to decide the optimum asset management action for each component of

the system according to the conditions and CRI index of the component as well as the cost and effectiveness of available asset management actions. Consequently, before presenting the objective function and constraints of the optimization problem, possible asset management actions and their corresponding impacts on the component reliability need to be defined.

Several types of asset management actions could be defined and performed for each component in the system, any of which has a different cost and different impact on the component failure rate. In a general definition, four types of actions could be performed for each component.

Starting from the one with the highest impact on the component failure rate, one can completely replace the old component with a new one to have the best component reliability improvement. It is however obvious that this option is the most expensive asset management action. The second and third actions are to perform a major and a minor preventive maintenance action, respectively. An asset management action which suggests performing a major preventive maintenance leads to a higher improvement in component failure rate than the one suggesting a minor preventive maintenance but it obviously costs more as well. The last action, which is also the cheapest one, is to neither replace nor performing any preventive maintenance. Instead, it suggests to only perform required tests and measurements for a condition monitoring. The condition monitoring could be done through remote sensors or through online/offline tests. In any case, this asset management action does not improve the component failure rate but it costs to be done, even if the cost is much lower than the cost of the three previous actions. The important gain of performing the last asset management action is that it provides a better and more accurate estimation of component conditions and its failure rate. In other words, if it is not efficient to perform any of the three previous actions for a special component in the current study period, this condition monitoring with a low budget is done to provide an estimation of component failure rate for the next study period.

It should be noted that any of four asset management actions presented in this study represents a bigger classification and might include different actions. For instance, the last asset management action, i.e., the condition monitoring action, could be further divided into: 1) remote monitoring through sensors: when the component is connected to the grid and used during condition evaluations, 2) online monitoring: when the component is connected to the grid but not used during condition evaluations, 3) offline monitoring: when the component is disconnected from the grid during condition evaluations. The cost of performing condition monitoring is different for any of these divisions while for this special asset management action, all divisions have the same impact on component failure rate (i.e., no impact). Nevertheless, other asset management actions could be divided into different divisions with different costs and different impacts on component failure rate.

The asset management actions defined for each component together with their corresponding impacts on component failure rate as well as the CRI indices of all components, calculated in the previous sub-section, are used as inputs in an

optimization problem to determine the optimum asset management action and, therefore, appropriate failure rate for each component.

The main goal of the proposed optimization problem is to provide an appropriate balance between costs spent on performing asset management actions and costs spent on compensating the lack of reliability. Thus, the objective function of the optimization problem includes two terms: 1) cost of performing the asset management actions, 2) outage cost (including the cost of corrective maintenance and customer interruption costs). In a smaller scale, the goal is to make a balance between the costs of preventive and corrective maintenances. However, the proposed optimization problem includes more general aims since the asset management actions are not limited only to preventive maintenances and customer compensations are also taken into account.

The optimization problem proposed in this study for implementing the RCAM into power systems is formulated as follows.

$$\min_{\{x_{i,a,t}\}} \sum_{i=1}^I \sum_{t=1}^T TC_{i,t} \quad (7a)$$

s.t.

$$TC_{i,t} = (1-\omega) \cdot [C_{i,t}^{CM} + C_{i,t}^{IC}] + \omega \cdot [C_{i,t}^{AM}] \quad (7b)$$

$$C_{i,t}^{CM} = \lambda_{i,t} \cdot \beta_i^{CM} \quad (7c)$$

$$C_{i,t}^{AM} = \sum_{a=1}^A (x_{i,a,t} \cdot \alpha_{i,a}^{AM}) \quad (7d)$$

$$C_{i,t}^{IC} = \Delta \lambda_{i,t} \cdot \overline{I_{i,t}^H} + C_{i,t}^{IC0} \quad (7e)$$

$$\lambda_{i,t}^{new} = \lambda_{i,t-1}^{new} \cdot f_{inc} + \sum_{a=1}^A [x_{i,a,t} \cdot (\lambda_{i,t}^{fix} - \lambda_{i,t}^{var})], t \geq 2 \quad (7f)$$

$$\lambda_{i,t}^{new} = \lambda_i^{old} + \sum_{a=1}^A [x_{i,a,t} \cdot (\lambda_{i,t}^{fix} - \lambda_{i,t}^{var})], t = 1 \quad (7g)$$

$$\Delta \lambda_i = \lambda_{i,t}^{new} - (\lambda_{i,t-1}^{new} \cdot f_{inc}), t \geq 2 \quad (7h)$$

$$\Delta \lambda_i = \lambda_{i,t}^{new} - \lambda_i^{old}, t \geq 1 \quad (7i)$$

$$\sum_{a=1}^A \sum_{t=1}^T x_{i,a,t} = x_i^{max} \quad (7j)$$

$$\sum_{a=1}^A \left(n_a^{max} \cdot \sum_{t=\theta}^{\theta+\tau} \sum_{i=1}^I x_{i,a,t} \right) \leq n_\tau^{max}, 0 \leq \theta \leq T - \tau \quad (7k)$$

$$\lambda_{i,t}^{var} = \lambda_i^{old} \cdot (f_{inc})^{t-1} \quad (7l)$$

$x_{i,a,t}$ is a binary variable. (7m)

Equations (7a) and (7b) define the objective functions of the optimization problem. As mentioned before, the objective function includes two terms including asset management cost and the outage cost. Equation (7b) distinguishes these two terms and assigns weighting factor ω to the asset management cost and weighting factor $(1 - \omega)$ to the outage cost. As indicated in (7b), it should be noted that the outage cost is divided into the cost of corrective maintenance and customer interruption costs.

The main reason for defining ω -based weighting factors for these two terms is to make it possible to determine the desirable reliability level in the RCAM implementation. That is, the higher the weighting factor ω is, the lower reliability is achieved. The reason is that having a low weighting factor results in a lower outage cost in the system and, therefore, the optimization problem minimizes the cost of asset management. Consequently, less asset management actions are performed and the system reliability is decreased.

Constraints (7c)–(7e) define the corrective maintenance cost, asset management cost, and customer interruption cost. Constraints (7f) and (7g) describe the component failure rate at different time intervals while (7h) and (7i) calculate the variations in the component failure rate during the studied time period. Constraint (7j) limits the number of asset management actions for each component during the studied period while (7k) determines the capacity for performing each asset management action at each time intervals. Finally, (7l) makes the proposed algorithm congruous with the reality by guaranteeing an increasing failure rate in case no asset management action (or only a condition monitoring action) is done. As specified by (7m), the variables of the proposed optimization problem are binary variables indicating when and which asset management actions should be performed for each component in the system.

It is also possible to reformulate the optimization problem (7a)–(7m) such that variations of total cost (instead of total cost itself) are considered. That is, the objective function (7a) is the total cost of performing a reliability centered asset management, which should be minimized. This objective function is based on the assumption that no asset management action is beforehand assigned to each component. Therefore, all possible asset management actions are separately studied and their costs are considered in total cost calculation. Then, optimum asset management action for each component is determined such that the total cost is minimized.

There is, however, another model which could be taken into account when defining the objective function of the optimization. The model is based on the assumption that there is already an asset management action assigned to each component. This assigned asset management action could be to do no preventive maintenance or condition monitoring, meaning to run the system until it fails. Thus, the optimization problem should decide whether the current asset management action (assigned to each component) is optimum or not. Accordingly, the objective function is defined based on this fact that the asset management action should change for each component if it is not the optimal one. In this regard,

it is possible that the asset management action of a component changes and reduces the total cost.

According to this new model, the new objective function of the optimization could be either positive or negative (depending on the changes in the asset management actions of different components). Contradictory, the old objective function, i.e., objective function (7a), is always positive since it is the summation of original costs (not the cost variations) for asset management actions of all components.

Based on the explanations provided above, the formulation proposed for implementing the RCAM into power systems is reformulated as follows.

$$\min_{\{x_{i,a,t}\}} \sum_{i=1}^I \sum_{t=1}^T \Delta TC_{i,t} \quad (8a)$$

s.t.

$$\Delta TC_{i,t} = (1 - \omega) \cdot [\Delta C_{i,t}^{CM} + \Delta C_{i,t}^{IC}] + \omega \cdot [\Delta C_{i,t}^{AM}] \quad (8b)$$

$$\Delta C_{i,t}^{CM} = \Delta \lambda_{i,t} \cdot \beta_i^{CM} \quad (8c)$$

$$\Delta C_{i,t}^{AM} = \sum_{a=1}^A (\Delta x_{i,a,t} \cdot \alpha_{i,a}^{AM}) \quad (8d)$$

$$\Delta C_{i,t}^{IC} = \Delta \lambda_{i,t} \cdot \overline{I_{i,t}^H} \quad (8e)$$

$$\lambda_{i,t}^{new} = \lambda_{i,t-1}^{new} \cdot f_{inc} + \sum_{a=1}^A [x_{i,a,t} \cdot (\lambda_{i,t}^{fix} - \lambda_{i,t}^{var})], t \geq 2 \quad (8f)$$

$$\lambda_{i,t}^{new} = \lambda_i^{old} + \sum_{a=1}^A [x_{i,a,t} \cdot (\lambda_{i,t}^{fix} - \lambda_{i,t}^{var})], t = 1 \quad (8g)$$

$$\Delta \lambda_i = \lambda_{i,t}^{new} - (\lambda_{i,t-1}^{new} \cdot f_{inc}), t \geq 2 \quad (8h)$$

$$\Delta \lambda_i = \lambda_{i,t}^{new} - \lambda_i^{old}, t \geq 1 \quad (8i)$$

$$\sum_{a=1}^A \sum_{t=1}^T x_{i,a,t} = x_i^{max} \quad (8j)$$

$$\sum_{a=1}^A \left(n_a^{max} \cdot \sum_{t=\theta}^{\theta+\tau} \sum_{i=1}^I x_{i,a,t} \right) \leq n_\tau^{max}, 0 \leq \theta \leq T - \tau \quad (8k)$$

$$\lambda_{i,t}^{var} = \lambda_i^{old} \cdot (f_{inc})^{t-1} \quad (8l)$$

$$x_{i,a,t} \text{ is a binary variable.} \quad (8m)$$

5.4 THE FLOWCHART OF THE PROPOSED RCAM METHOD

This sub-section summarizes all the previous sub-sections and explains how the proposed optimization problem (7a)–(7m) is used to implement the reliability chain-based RCAM into a power system context. To achieve this goal, a flowchart for the whole method is presented and explained. However, there is an important issue which should be first indicated. According to the proposed optimization problem (7a)–(7m), performing different asset management actions changes the failure rates of different components and, consequently, changes the failure rate at load points and CRI index I^H for different components. One way to take these CRI index variations into account is to assume the CRI indices fixed in the optimization problem and calculate the optimum asset management plan and new failure rate for all components. Then, one can update the CRI indices based on the new component failure rates and rerun the optimization problem. This process is done until negligible variations in the component failure rates are observed. The aforementioned process is an internal loop in the flowchart of the whole method. Thus, the understanding of the whole flowchart will be easier if the schematic of the mentioned process is presented separately first. Accordingly, Fig. 2 illustrates a schematic for the aforementioned process.

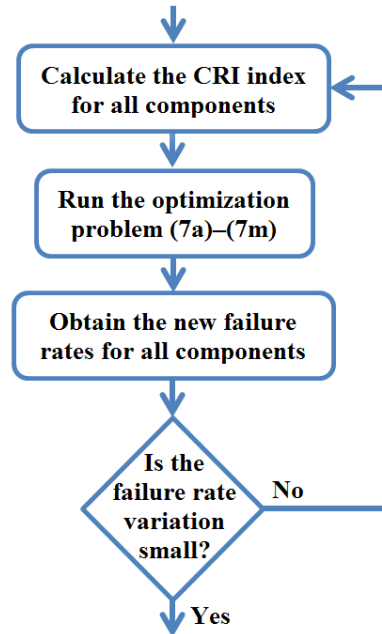


Fig. 2. The schematic used to consider the CRI index variations

Moreover, Fig. 3 presents the flowchart of the whole method proposed in this study for optimal implementation of RCAM in power systems.

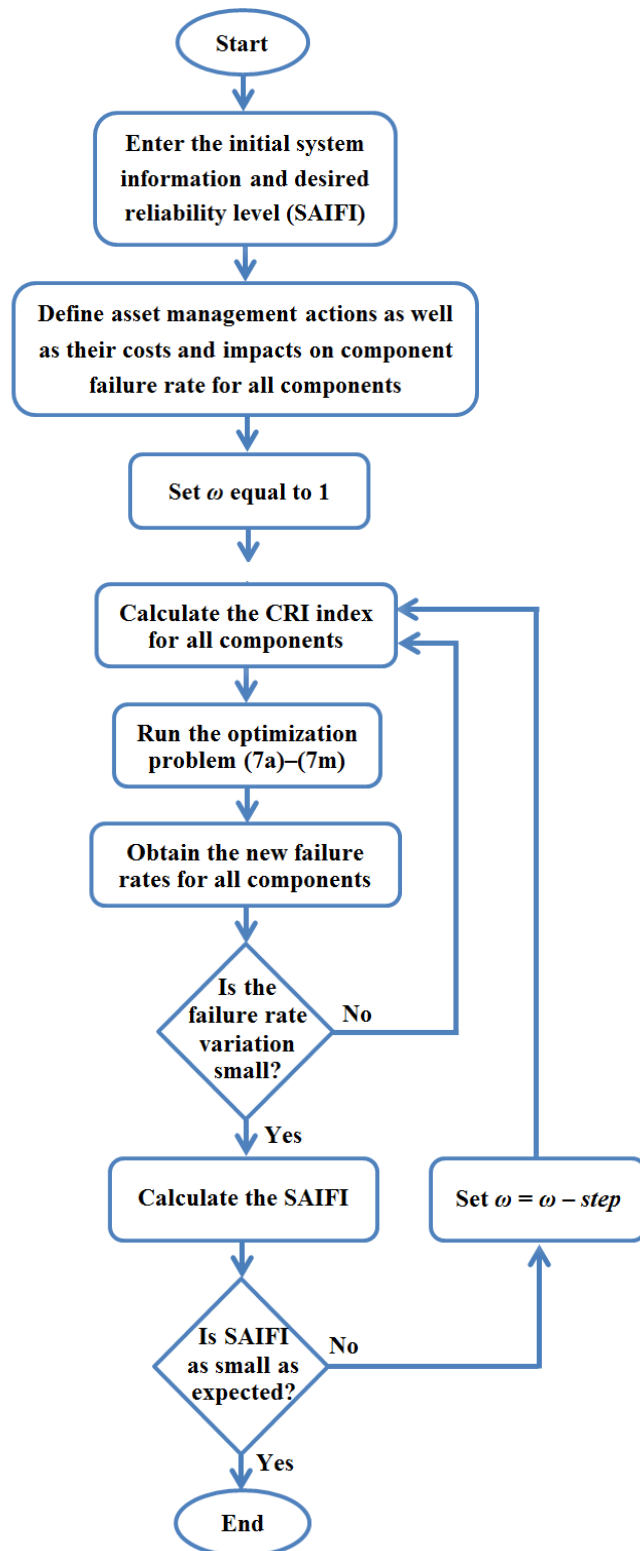


Fig. 3. The algorithm of the whole method proposed in this study

According to the flowchart, the method starts by receiving the initial system information (e.g., system structure and component initial conditions) and desired reliability level in the form of a reliability index (e.g., system average interruption frequency index abbreviated as SAIFI). The amount of weighting factor ω is then set to 1 to consider the minimum possible cost for performing the asset management actions, resulting in the minimum reliability level for the system.

It can be seen that the whole schematic mentioned in Fig. 2 is the next blocks in the flowchart which is executed to obtain the optimum asset management plan and new failure rate for all components based on the considered assumption (i.e., $\omega=1$). The SAIFI index for the system is then calculated and compared to the desirable one. In case the SAIFI index is higher than expectations, the weighting factor is reduced to force the optimization problem to consider more effective asset management actions. This process is continued until the desirable SAIFI index is achieved.

It should be noted that in both Figs. 2 and 3, only optimization problem (7a)–(7m) was included. Both of these figures are, however, also applicable for optimization problem (8a)–(8m). This means that in both Figs. 2 and 3, optimization problem (7a)–(7m) could be replaced by optimization problem (8a)–(8m) and total cost variation be studied instead of total cost in the asset management implementation.

Table 1. Different asset management actions together with their costs and impacts on component failure rate

Number	Description	Cost (\$)	Impact on Failure Rate
1	Condition monitoring	100	Remain the same
2	Minor preventive maintenance	700	10% reduction
3	Major preventive maintenance	6000	40% reduction
4	Component replacement	75000	80% reduction

The cost of corrective maintenance is also assumed to be \$20450, i.e., around ten times larger than the average cost for performing asset management actions [14].

6.2 METHOD IMPLEMENTATION WITH OPTIMIZATION PROBLEM (7A)–(7M)

The results of implementing the proposed RCAM method to the considered test system are presented in this sub-section. Fig. 5, in this regard, depicts the total cost of the system for different values of weighting factor ω . Please note that the *step* considered for reducing the weighting factor ω is 0.02. Thus, there are 50 iterations in the proposed algorithm in which weighting factor ω starts from one and goes continuously down to zero by fixed steps equal to 0.02. Moreover, all different parts of the total cost including the cost of performing the asset management actions, the cost of corrective maintenance, and customer interruption costs are presented in Fig. 5.

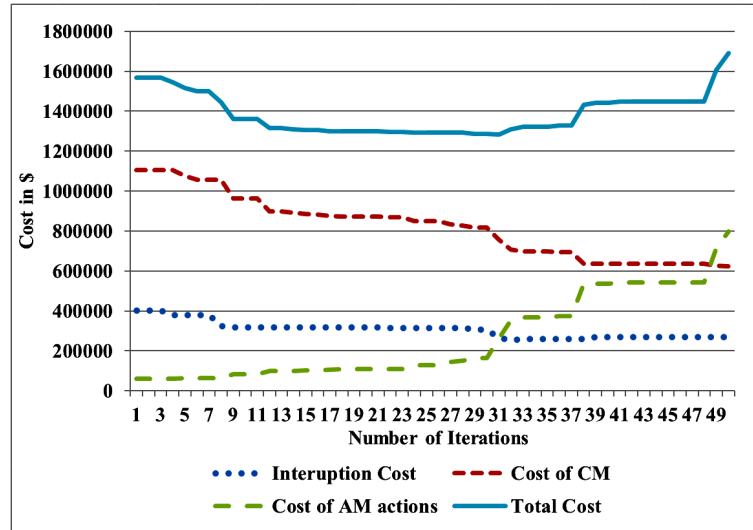


Fig. 5. The total cost of the system for different values of weighting factor (CM and AM abbreviate Corrective Maintenance and Asset Management respectively)

It can be seen in this figure that the cost of corrective maintenance and interruption cost of the system increase when weighting factor ω reduces while the cost needed for performing the asset management actions has an opposite behavior. The reason for these variations is that in the first iterations (when the weighting factor ω is

close to one), the cost of performing asset management actions is more emphasized in the objective function and, therefore, the optimization problem propose to perform the minimum and cheap asset management actions. Consequently, the reliability of the system reduces and results in high outage costs (i.e., high interruption cost and corrective maintenance cost). In the last iterations, in contrast, an opposite behavior is observed.

On the other hand, the total cost of the system, which the summation of all mentioned costs, shows a bathtub curve which has its minimum value when weighting factor ω is equal to 0.4.

Fig. 6 presents the amount of SAIFI index in different iterations, i.e., for different values of weighting factor ω . As expected, the higher the weighting factor ω , the higher value of SAIFI index is obtained.

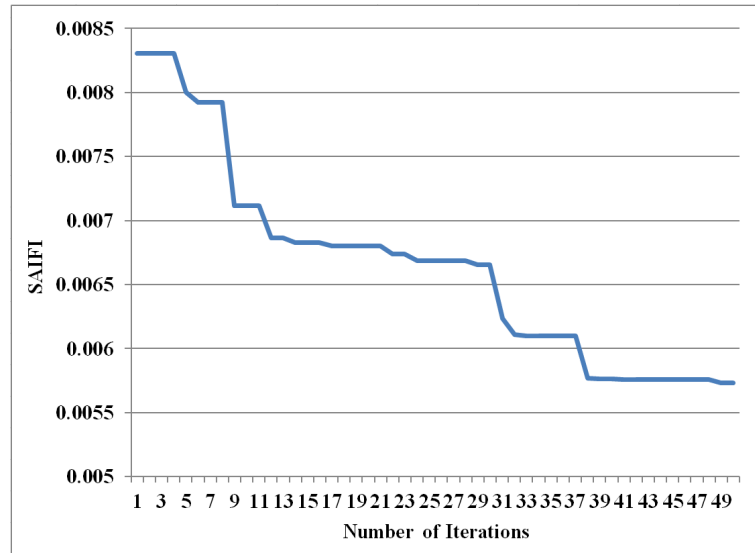


Fig. 6. The amount of SAIFI for different values of weighting factor (f/yr)

Four types of asset management actions were defined for each component in this study. In this regard, for each value of weighting factor ω , an optimum asset management schedule is suggested by the proposed algorithm for each component. Fig. 7 shows the optimum asset management schedule for all components when the weighting factor ω is equal to 0.4, corresponding to the minimum total cost of the system.

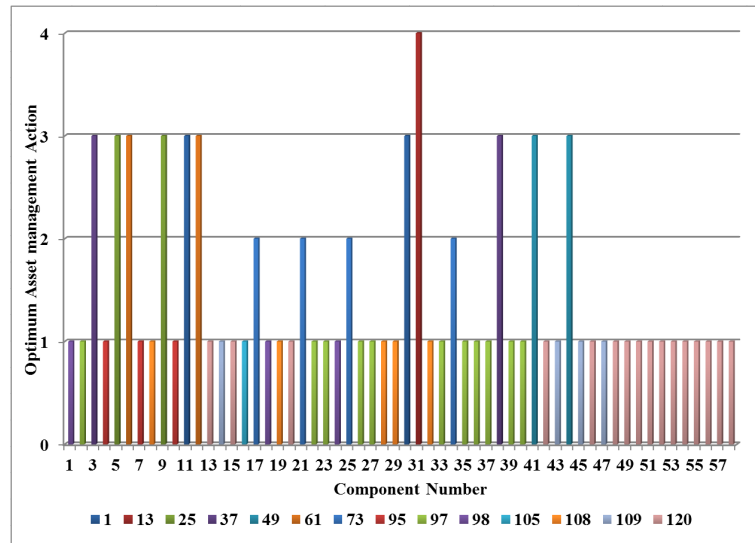


Fig. 7. The optimum asset management schedule for all components for weighting factor ω equal to 0.4

It can be seen that due to the capacity definition for performing asset management actions, the optimum asset management actions for all component cannot be done simultaneously and the proposed algorithm has also determined the optimum months (in different colors) for performing optimum asset management actions of all components. The correct month corresponding to each color is clarified below the optimum asset management actions in Fig. 7.

According to this figure, asset management action 4 (i.e., component replacement) should be done for component 31 during month 13. Moreover, the optimum asset management action for some of the components like component 3 and 5 is to perform the major corrective maintenance, while the proposed algorithm suggests performing the condition monitoring action for most of the components.

Finally, Fig. 8 depicts the variations of failure rates of all 58 components of the test system during the studied time period. These variations are obtained based on the optimum time and optimum type of asset management action, both suggested by the proposed algorithm for each component.

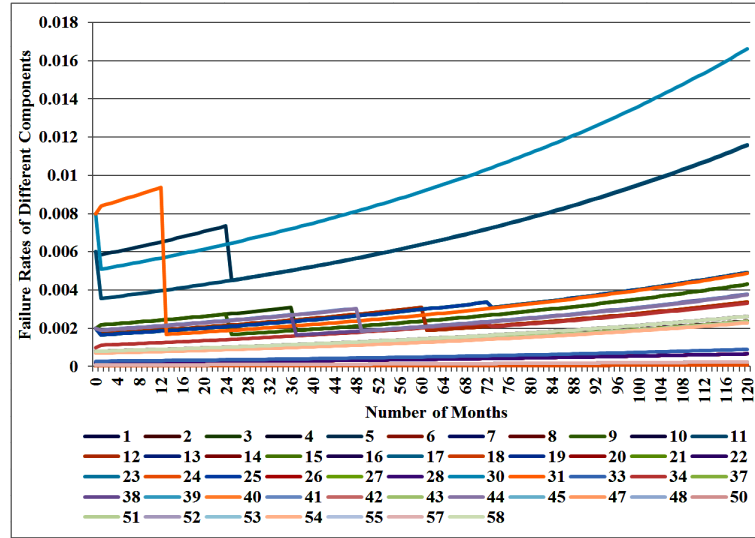


Fig. 8. Failure rates of all 58 components during the studied time period for weighting factor ω equal to 0.4

It can be seen that the algorithm suggests performing the asset management actions first for the components with high failure rates. Moreover, asset management action 1 (i.e., condition monitoring) is proposed to be done for components with relatively low failure rates.

Figs. 7 and 8 respectively show the optimum asset management schedule and variations in the failure rates of all components when the weighting factor ω is equal to 0.4 (i.e., the best weighting factor for total cost minimization). It is, however, interesting to see how the optimum asset management schedule and failure rate variations of each component will change when the weighting factor ω changes. Figs. 9 and 10 show the optimum asset management schedule and variations in the failure rates of all components when the weighting factor ω is equal to 1, corresponding to the minimum cost for performing asset management actions and therefore the minimum reliability. Moreover, Figs. 11 and 12 display the same features when the weighting factor ω is equal to 0, corresponding to the best power system reliability. It should be noted that these two weighting factors (i.e., weighting factor ω is equal to 1 and 0) corresponds to two completely different optimization problems since the first one minimizes the cost of asset management while the second one maximizes the system reliability. Moreover, all other weighting factors (i.e., when weighting factor ω is between 0 and 1) is a mixed of these two different optimization problems.

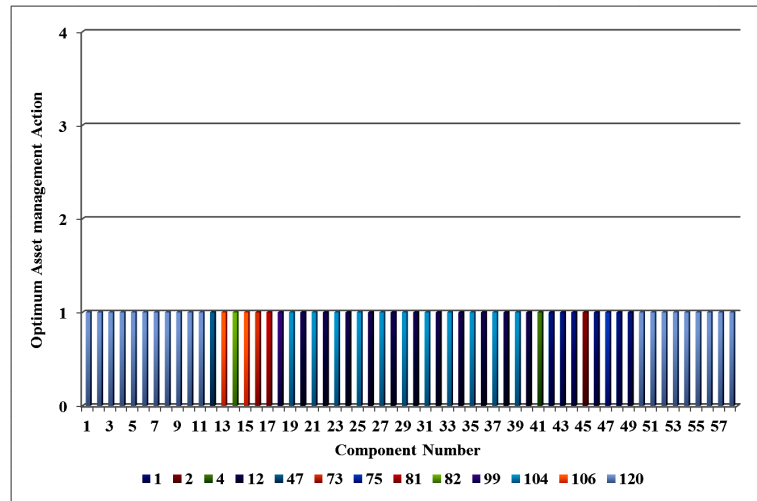


Fig. 9. The optimum asset management schedule for all components for weighting factor ω equal to 1

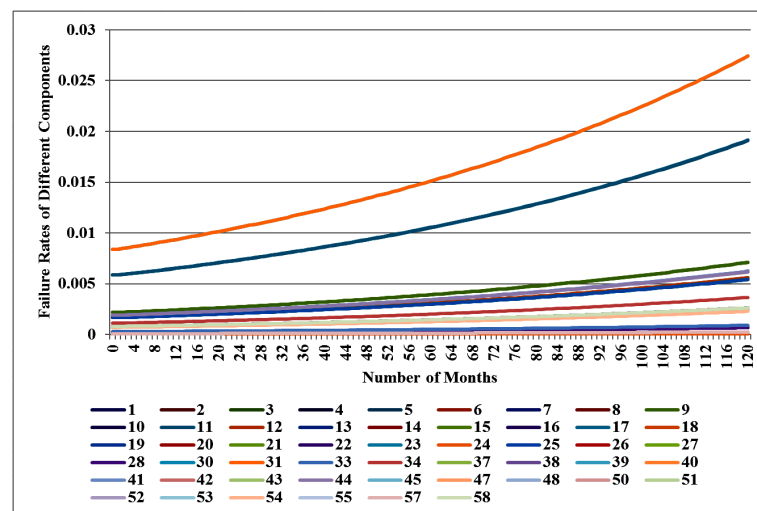


Fig. 10. Failure rates of all 58 components during the studied time period for weighting factor ω equal to 1

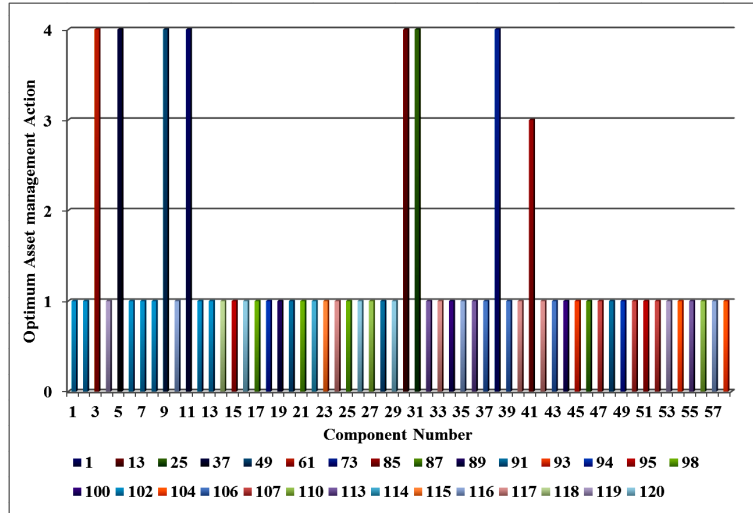


Fig. 11. The optimum asset management schedule for all components for weighting factor ω equal to 0

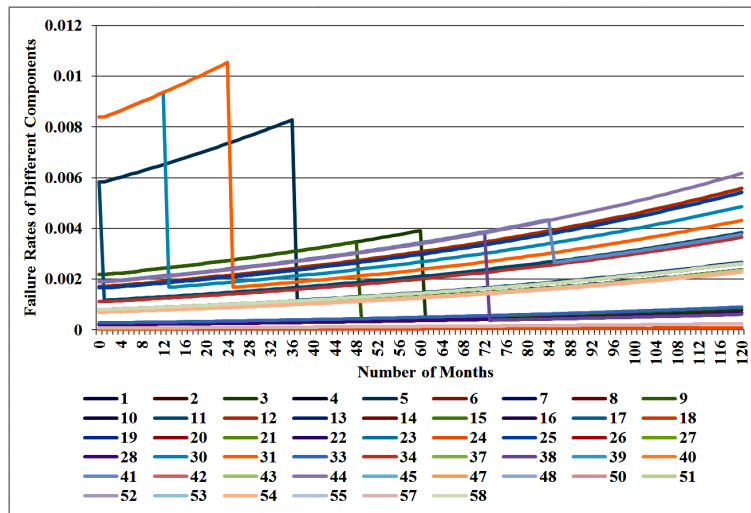


Fig. 12. Failure rates of all 58 components during the studied time period for weighting factor ω equal to 0

Starting from the results presented in Figs. 9 and 10, one can see that the optimization problem suggests not doing any asset management action which affects the component failure rates when the weighting factor ω is equal to 1. According to Figs. 11 and 12, however, it is optimum to perform the most effective asset management action (i.e., the component replacement) for the components which have highest failure rates and performing the first asset management action for other components. The selection of the first asset management action for most of the components is due to the capacity limitation of performing asset management actions. Nevertheless, the optimum asset management action schedule will considerably change if the capacity of performing asset management actions increases. In this regard, Figs. 13 and 14 depict the optimum asset management schedule and variations in the failure rates of all components when

the weighting factor ω is equal to 0 and capacity of performing asset management actions is 4 times increased.

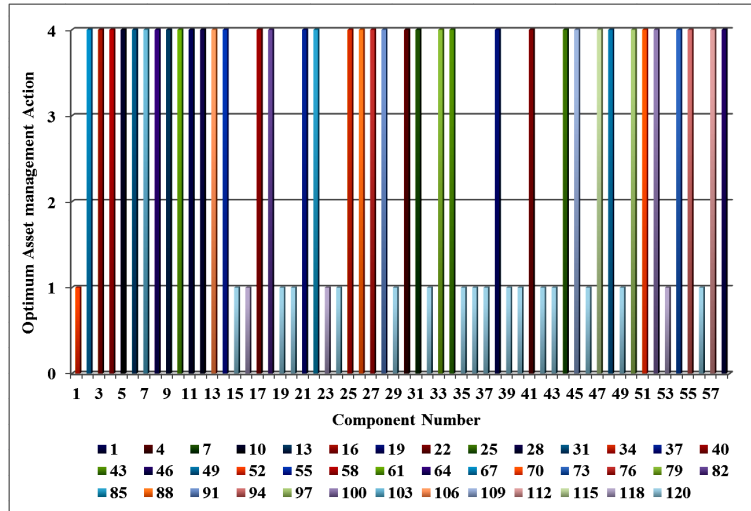


Fig. 13. The optimum asset management schedule for all components for weighting factor ω equal to 0 (with extra capacity of asset management actions)

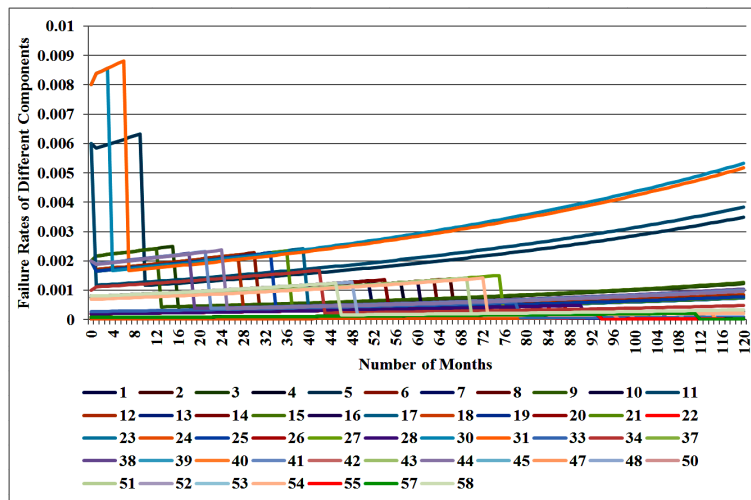


Fig. 14. Failure rates of all 58 components during the studied time period for weighting factor ω equal to 0 (with extra capacity of asset management actions)

Comparing Figs. 11 and 13, it can clearly be seen how the capacity of performing asset management actions has changed the optimum asset management action for each component.

6.3 METHOD IMPLEMENTATION WITH OPTIMIZATION PROBLEM (8A)–(8M)

It was mention in the previous section (i.e., Method development and formulation) that optimization problem (7a)–(7m) in the algorithm proposed in this study could be replaced by optimization problem (8a)–(8m) to achieve the optimum asset management action for each component. The results presented in Figs. 5–14 are based on using optimization problem (7a)–(7m) in the proposed algorithm. In this subsection, some of the results obtained by applying optimization problem (8a)–(8m) to the developed algorithm are presented.

Figs. 15 and 16 respectively present the total cost of the system and SAIFI index for different values of weighting factor ω when optimization problem (8a)–(8m) is used in the proposed algorithm. Please note that, apart from the total cost of the system, all different parts of the total cost including the cost of performing the asset management actions, the cost of corrective maintenance, and customer interruption costs are also presented in Fig. 15.

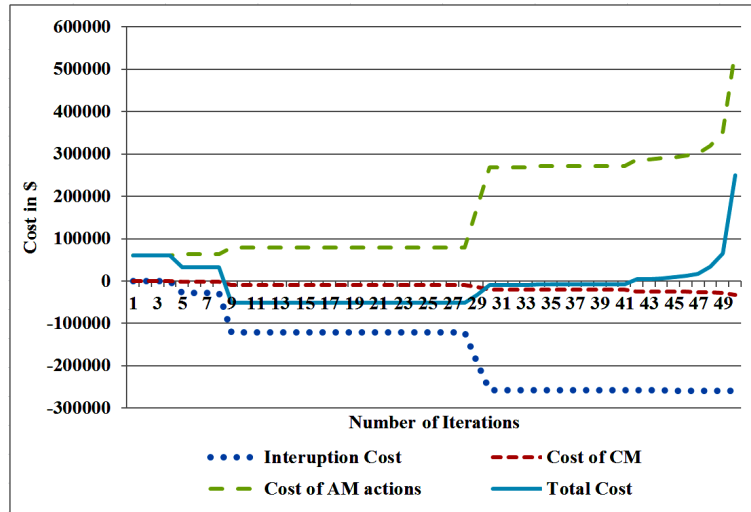


Fig. 15. The total cost of the system for different values of weighting factor using optimization problem (8a)–(8m) (CM and AM abbreviate Corrective Maintenance and Asset Management respectively)

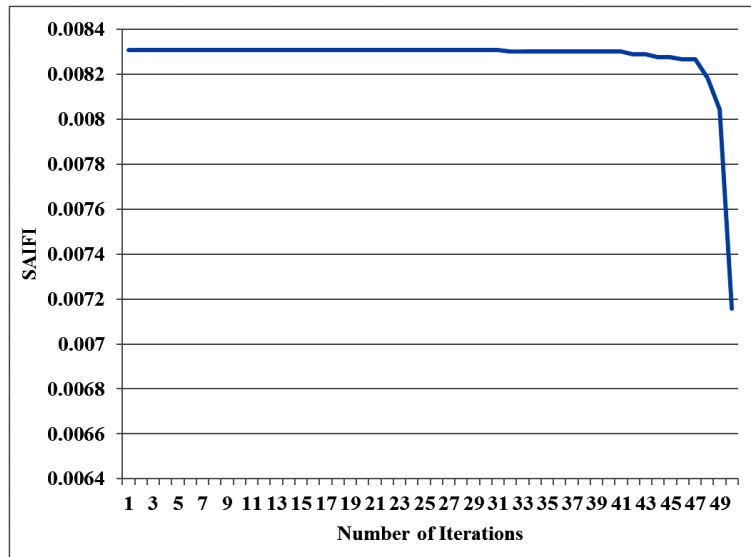


Fig. 16. The amount of SAIFI for different values of weighting factor using optimization problem (8a)–(8m) (f/yr)

It can be seen in these figures that both the total cost of the system and SAIFI index show small variations for different values of weighting factor ω (except the last iterations, in which the weighting factor ω is close to 0). The reason is that when cost variations (instead of original costs) are used in the problem formulation, it is mathematically optimum to perform no asset management action for components until the last months of the study period since the higher the component failure rate is, the higher failure rate reduction is obtained by performing an asset management action. Thus, to maximize the reduction in the cost of corrective maintenance and interruption cost of the system, the optimization problem suggest letting the failure rates increase during the first months and perform the major corrective maintenance for some of them during the last months of simulation period. It basically performs the major corrective maintenance for components which will have higher failure rate reductions. This issue is shown more clearly in Figs. 17 and 18.

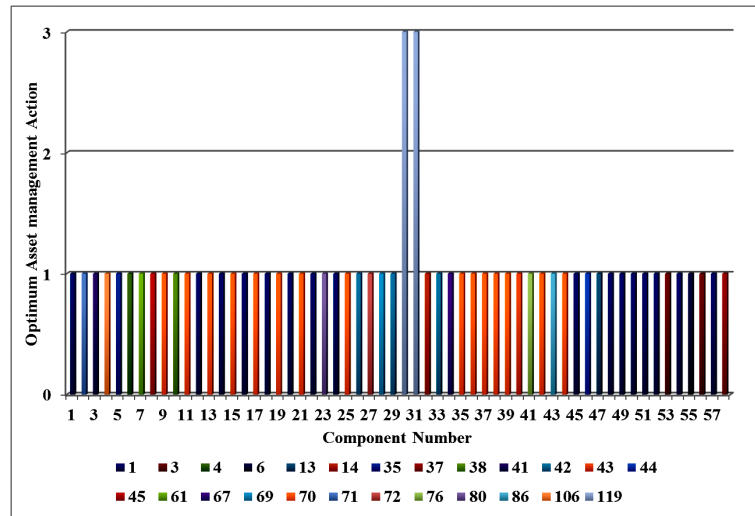


Fig. 17. The optimum asset management schedule for all components for weighting factor ω equal to 0.66 using optimization problem (8a)–(8m)

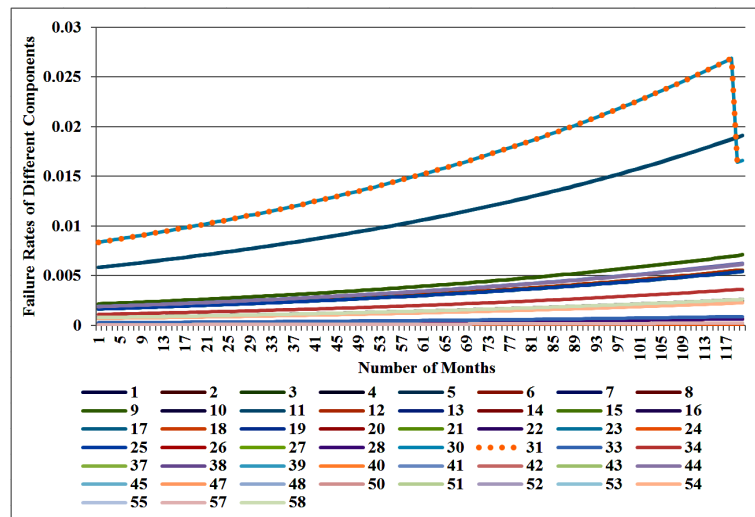


Fig. 18. Failure rates of all 58 components during the studied time period for weighting factor ω equal to 0.66 using optimization problem (8a)–(8m)

Please note that the weighting factor ω is fixed to 0.66 in Figs. 17 and 18 since this weighting factor corresponds to the minimum total cost of the system.

To investigate the results of applying optimization problem (8a)–(8m) to the proposed RCAM method more clearly, the capacity of performing asset management actions is increased and its impacts on the simulation results are studied here. Moreover, in order to achieve the maximum reliability for the studied power system, the weighting factor ω is set equal to 0 in the next simulation results.

Figs. 19 and 20 present the optimum asset management schedule and variations in the failure rates of all components when the weighting factor ω is equal to 0 and capacity of performing asset management actions is 4 times increased.

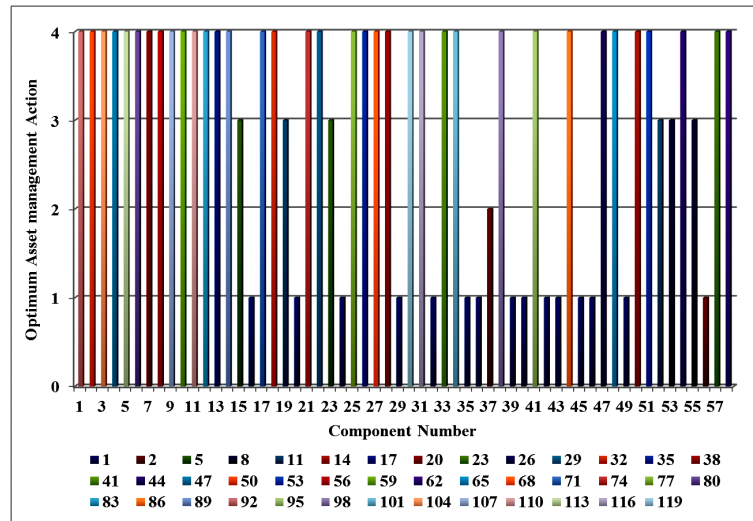


Fig. 19. The optimum asset management schedule for all components for weighting factor ω equal to 0 using optimization problem (8a)–(8m) (with extra capacity of asset management actions)

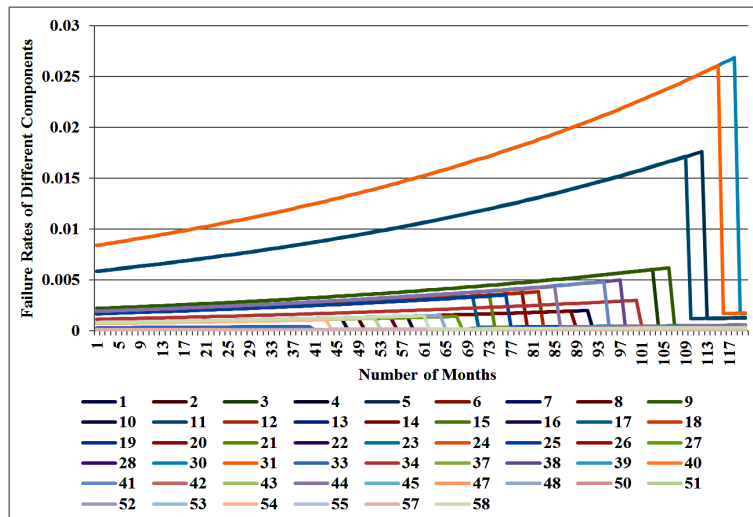


Fig. 20. Failure rates of all 58 components during the studied time period for weighting factor ω equal to 0 using optimization problem (8a)–(8m) (with extra capacity of asset management actions)

It can be seen in these figures that the optimum solution, when there is a higher capacity of performing asset management actions, is to do the asset management action with the highest possible impact on component failure rate as late as possible to have the highest variations in component failure rates. Hence, it seems that implementing optimization problem (8a)–(8m) into the proposed RCAM method is more applicable when the best system reliability at the end of study period is desired. Nevertheless, when the optimum reliability during the study period is required, optimization problem (7a)–(7m) should be used in the proposed RCAM method.

7 Conclusion

This study proposes a rigorous methodology for implementing the reliability centered asset management into power systems through introducing the concept of reliability chain. The proposed algorithm is based on an optimization problem which suggests the optimum asset management action for each component in the system by making a balance between the cost of asset management actions and outage cost of the system. However, a weighting factor is assigned to any of these two costs to provide the advantage of achieving the desirable power system reliability. Two different formulations are developed for the optimization problem. The first optimization problem minimizes the original asset management and outage costs, while the variations in these costs are considered in the second one.

The results of applying the proposed algorithm to a Swedish distribution system reveal the effectiveness of the algorithm in developing appropriate tools for applying the RCAM into power systems. It is also observed that linear variations in the considered weighting factor do not necessarily result in linear variations in power system reliability and total cost of the system. Thus, it has a great importance to choose appropriate reliability level when performing RCAM in power systems.

For the studied distribution system, the weighting factor ω equal to 0.4 is selected as an appropriate weighting factor when original asset management and outage costs are considered since this weighting factor results in the minimum total cost of the system and provides the best balance among the cost of performing asset management actions and outage cost. Similarly, for the optimization problem considering the cost variations, the weighting factor ω equal to 0.66 is selected as an appropriate value for the studied system.

The comparison of results obtained by two different formulations reveals that considering the original asset management and outage costs in the optimization problem results in obtaining the optimum reliability during the study period, while taking the cost variations into account is more appropriate when the optimum system reliability at the end of study period is desired.

The model could be improved and evaluated more in future works by applying to other real case systems with different failure rates and costs.

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OPTIMAL IMPLEMENTATION OF RELIABILITY CENTERED ASSET MANAGEMENT FOR POWER SYSTEMS

This study proposes a methodology for implementing the reliability centered asset management into power systems through introducing the concept of reliability chain. The proposed algorithm is based on an optimization problem which suggests the optimum asset management action for each component in the system by making a balance between the cost of asset management actions and outage cost of the system.

The results of applying the proposed algorithm to a Swedish distribution system reveal the effectiveness of the algorithm in developing appropriate tools for applying the RCAM into power systems. It is also observed that linear variations in the considered weighting factor do not necessarily result in linear variations in power system reliability and total cost of the system. Thus, it has a great importance to choose appropriate reliability level when performing RCAM in power systems.

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