Imperfect Maintenance Scheduling for High Pressure Feedwater Heater System in Nuclear Power Plant

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***Abstract*—As a complex and safety-critical system, the reliability of a nuclear power plant (NPP) has significant importance and effective maintenance program is one of the key considerations for its safe operation. High Pressure Feedwater Heater (AHP) system as an important subsystem in NPP needs to be endowed with an effective maintenance strategy. In normal operation, the AHP system works on heating of feedwater flowing through two high pressure (HP) heater banks A and B. Typically, component inner degradation and sensor control malfunction would affect feedwater outlet flow and temperature. This would further cause power coastdown and increase the operation and maintenance cost. This paper focuses on the optimization of the imperfect maintenance scheduling for an AHP system served in an NPP based on the Markov process and fault tree analysis. In particular, the component condition is modeled as a multi-state Markov process so to determine the component's reliability curve under maintenance intervention. The system reliability function is then obtained by fault tree analysis that characterizes all the undesired outcomes with respect to feedwater outlet flow and temperature. To achieve a cost-effective maintenance satisfying system reliability requirement, a problem-specific genetic algorithm is developed and ultimately determines optimal periodic maintenance intervals for critical components in the AHP system. This study provides an understanding of the maintenance effects on the system reliability, and can also work as the basis to improve the nuclear maintenance management plan.**

***Index Terms*—imperfect maintenance scheduling, Markov process, reliability, fault tree analysis**

I. Introduction

Nuclear energy is one of the primary sources of power energy. Nowadays, NPP is playing a more and more important role in the power generation area. Besides, the failure of NPP can have severe consequences for society. Therefore, the reliability of NPP is crucial for power supply and social security. As a critical thermal subsystem in NPP, AHP utilizes the exhaust of the high-pressure cylinder of the steam turbine to heat the feedwater and receives the water vapor from the steam-water separation reheater to improve the efficiency of the thermodynamic cycle. To meet the required thermal performance during all operating conditions, an effective maintenance strategy needs to be scheduled for all the components in AHP. An adequate maintenance strategy helps AHP meet the required thermal performance, protect the turbine against the reverse flow of steam or feedwater, ensure forward flow to the steam generator, minimize the risks of erosion and corrosion and minimize the number of components subject to replacement.

Most of the researches related to the feedwater heater focus on the diagnostics and simulation. Kang, Kim, Heo and Song [1] implement a fuzzy inference system to diagnose performance degradation in feedwater heaters among generation facilities. Barszcz and Czop [2] focus on the tuning and validation process of the feedwater heater model intended for a model-based diagnostics approach as part of a power unit model. Little former work can be found associated with the maintenance of the feedwater heater system. Krishnasamy, Khan and Haddara [3] propose a risk-based maintenance strategy to minimize the risk resulting from breakdowns and failures for the thermal power generation plant. However, the maintenance objective is the entire oil-fired electrical power plant system rather than the feedwater heater.

Maintenance scheduling optimization of single component and single failure mode are widely studied by utilizing different maintenance actions [9] [10]. For multi-component system, Martinod, Bistorin, Castañeda, and Rezg [7] develop a maintenance schedule consisting of both preventive maintenance and corrective maintenance. The optimal policy is obtained by clustering the maintenance actions. Moreover, for multi-state systems, the optimal replacement policy, which is a perfect maintenance policy, is determined by a non-homogeneous

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continuous time Markov model [8].

To the best of the authors' knowledge, this paper is the first work considering the maintenance scheduling of the feedwater heater system. Since the high pressure feedwater heater system in the nuclear power plant is a complex system comprising a large number of different components with a staggered connection structure, the complexity of the maintenance scheduling is high. Each component in AHP faces one or more failure modes. Each failure mode corresponds to several maintenance options. An effective maintenance scheduling can save the maintenance cost and guarantee the system works safely and reliably. The main contributions of our study can be summarized as follows:

- The maintenance scheduling for a multi-component system is more complex than that for the single component system, especially when considering multiple failure modes. From the system characteristic's view, the connectivity relationship among the components in the AHP system are complicated and special. The components are connected by the pipes transporting steam or water. The performance of the system is highly influenced by the pressure, flow, and temperature. A variety of components and failure modes are considered in this model.
- From the application view, the optimization framework can largely decrease the maintenance cost of the NPP after applying the maintenance scheduling framework, which has been proved by the numerical example. Moreover, the AHP system has been widely used in various power plants, e.g. thermal power plant, and the AHP system in different power plants have similar components and structures [4]. The maintenance scheduling approach has the potential to decrease the maintenance cost in various power plants.

In this paper, both imperfect maintenance scheduling and inspection is considered in our model. The Markov chain is implemented to formulate the deterioration process of each component. The maintenance cycle and strategy of imperfect maintenance, the inspection cycle and whether to take the replacement action are determined in the decision process. The reliability curve of each component is obtained by fault tree analysis. Finally, the genetic algorithm (GA) is proposed to determine the optimal periodic maintenance intervals by minimizing the total maintenance cost of AHP.

The remainder of the paper is organized as follows. Section II presents the component deterioration process formulated by Markov process. The reliability curve of each component under maintenance intervention is determined with the combination of fault tree analysis. Section III introduces a genetic algorithm framework to determine the optimal periodic maintenance intervals for the critical components of AHP. The numerical results and discussion are provided in Section IV. Section V concludes the major contribution and suggests possible future work.

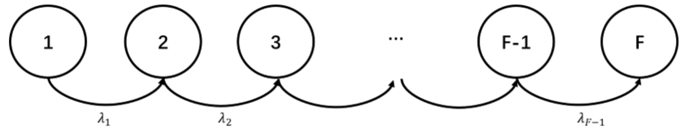

Fig. 1. Transition diagram of Markov process.

II. Markov Process of Component Deterioration

A. Deterioration Process Without Maintenance

The deterioration process of each component in AHP is modeled as a Markov decision process. In the Markov decision process model, the deterioration process is defined by several discrete states. Let $S = \{1, 2, \ldots, j-1, j, j+1, \ldots, F\}$ denote the component states set. State 1 indicates that the component is as good as new and state F indicates that the component totally fails. The deterioration degree increases from 1 to F. The component continuously ages until the failure occurs. When a failure occurs, the component cannot be operated normally.

Since the system is built in a continuous state, the component in AHP cannot deteriorate more than one state at a time. The transition diagram is shown in Fig. 1. The state can only jump from state j to state $j+1$, $j = 1, \ldots, F-1$. The component is continuously deteriorating over time without the intervention of the maintenance activities. The rate of deterioration from state j to state $j+1$ is λ_j. The corresponding generator matrix $\mathbf{Q}$ of the continuous Markov chain is given by

$$\mathbf{Q} = [q_{ij}] = \begin{bmatrix} -\lambda_1 & \lambda_1 & 0 & \cdots \\ 0 & -\lambda_2 & \lambda_2 & \cdots \\ 0 & 0 & -\lambda_3 & \cdots \\ \vdots & \vdots & \vdots & \ddots \end{bmatrix} \tag{1}$$

where $q_{ii} = -\lambda_i, q_{i(i+1)} = \lambda_i$ for $i = 1, ..., F-1$ and $q_{FF} = 0$. The transition probability matrix at time t, $\mathbf{P}(t)$, is derived by the forward Kolmogorov equations

$$\mathbf{P}'(t) = \mathbf{P}(t)\mathbf{Q}, \tag{2}$$
$$\mathbf{P}(0) = \mathbf{I}. \tag{3}$$

For a new component in AHP system, it has not suffered any damage. The state probability distribution $\mathbf{S}(0) = [1, 0, 0, \ldots, 0]^T$. The state probability distribution at time t, $\mathbf{S}(t) = \{s_j(t)\}$, can be derived from that at time 0,

$$\mathbf{S}(t) = \mathbf{S}(0)\mathbf{P}(t). \tag{4}$$

The reliability degree is a function of time t starting from value 1, which is calculated by Monte Carlo simulation. If no maintenance task is executed, the reliability degree continuously decreases due to the deterioration process, which is shown in the top left corner of Fig. 2.

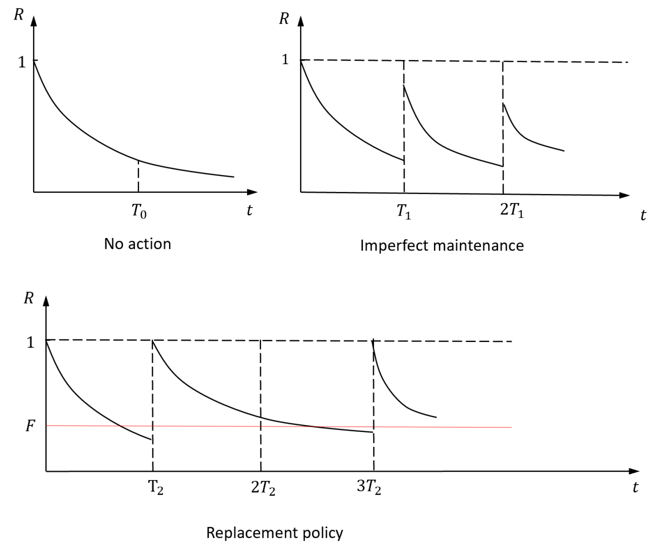

Fig. 2. Reliability degree curve under different policies.

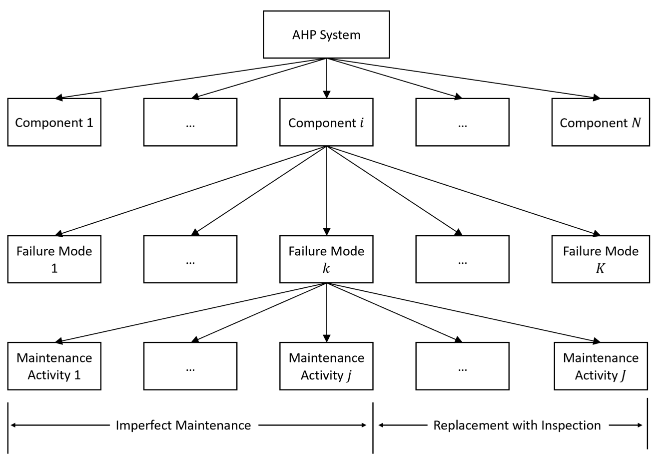

Fig. 3. Structure of maintenance policies.

B. Maintenance Policy

Each component faces multiple failure modes. Different maintenance policies are adapted to deal with the corresponding failure modes. One failure mode can adopt one or multiple maintenance policies to fix the problem. The maintenance policies can be divided into two groups, the imperfect maintenance policy and the inspection. The maintenance policies of all components with multiple failure modes in the system is shown in Fig. 3.

1) Imperfect Maintenance Intervention: In this paper, we consider that the imperfect maintenance strategy is adopted when some failure modes happen on the components. The imperfect maintenance action is executed periodically. The maintenance interval is T_1. After the imperfect maintenance, the reliability degree is greatly improved, but is lower than the reliability value at time 0, which is equal to 1. The reliability degree curve is shown in the top right corner of Fig. 2. With the intervention of the imperfect maintenance, two aspects of decisions are considered in the maintenance scheduling.

- The maintenance level of the imperfect maintenance activities.
- The maintenance cycle of the imperfect maintenance activities.

The maintenance level is corresponding to the next state after the maintenance. Since the component performs better after the maintenance, the optional next states after the maintenance at state j are between state 1 and state $j-1$. If the maintenance is very efficacious, the system can be as good as new and returns to state 1. If only a small part of the faults are repaired, the next state can be very close to the original state. The assumption is that every repair state of the component always has two optional maintenance levels, i_1 and i_2, which follows the relationship that $1 < i_1 < i_2 < j$.

The maintenance cycle is the interval between two adjacent maintenance events. Since the maintenance time is far less than the length of the maintenance cycle, the maintenance time is ignored in our model. The assumption is that the maintenance is finished instantaneously. Hence, the maintenance cycle is approximately the deterioration time of the component. Once the maintenance level is determined, the next maintenance cycle begins. The next state of the component is the initial state of the next cycle.

2) Inspection: Besides the imperfect maintenance strategy, some components are inspected to determine whether they should be replaced. The states of the components can not be observed in real time. Sensors detect the states regularly at some time intervals. The inspection interval T_2 are fixed. The reliability degree curve of inspection is shown in the bottom of Fig. 2.

If the system is inspected at time T_2 and the reliability degree is higher than the threshold value of replacement F, no action is taken, which means that $\mathbf{S}(t)$ will not change. Otherwise, if the degree value is lower than the threshold, the component is replaced directly. The state of the system returns to $\mathbf{S}(0)$. Since the replacement time is far less than the inspection interval, the replacement time is ignored in our model. The decision corresponding to the inspection is the inspection cycle of the sensors T_2 and whether to replace the component.

III. Fault Tree Analysis

After the Markov process obtains the reliability degree of each component, fault tree analysis is implemented to pool the reliability of all components together to obtain the system reliability constraint of the entire AHP. The relationship is shown in Fig. 4 Fault tree analysis translates a physical system into a structured logic diagram, in which certain specified causes lead to one specified top event of interest. [5]

The top event of the fault tree is that the water temperature is lower than the requirement. It is caused by three second-level events, "Heating line fault", "Faulty heating line cannot be isolated", and "Loss of thermal efficiency". All the failure modes of the critical components are analyzed in the fault tree.

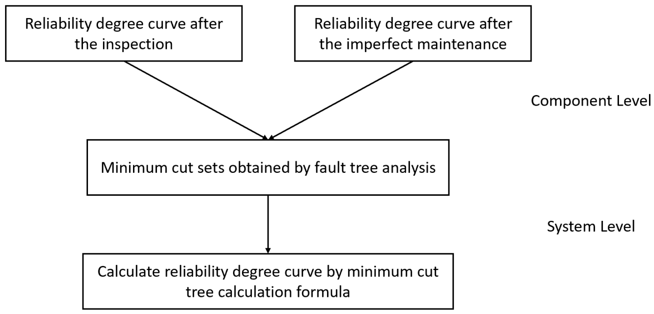

Fig. 4. Fault tree analysis with reliability degree curve.

TABLE I
BASIC EVENTS OF THE FAULT TREE

Basic event	Definition	Basic event	Definition
X_1	Component 117VL adjust malfunction	X_{10}	Component 103VV inleakage
X_2	Component 119VL adjust malfunction	X_{11}	Component 101VL inleakage
X_3	Component 118VL adjust malfunction	X_{12}	Component 102VL inleakage
X_4	Component 120VL adjust malfunction	X_{13}	Component 601RE scaling
X_5	Component 601RE pipe leakage	X_{14}	Component 701RE scaling
X_6	Component 701RE pipe leakage	X_{15}	Component 009VL incorrect opening
X_7	Component 001VV inleakage	X_{16}	Component 008VL inleakage
X_8	Component 002VV inleakage	X_{17}	Component 006VV incorrect opening
X_9	Component 101VV inleakage	X_{18}	Component 108VV incorrect opening

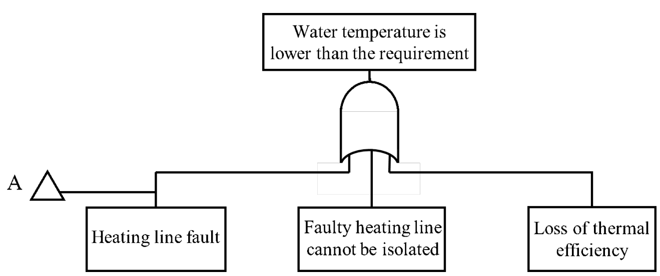

Fig. 5. Top event of fault tree.

The basic event corresponds to one of the failure modes of a component. Table I lists all the definitions of the basic events.

Fault tree analysis and Markov process link the component fault model to the system maintenance scheduling. Minimum cut sets is an important fault tree quantitative analysis technique. It represents the possible combination of component failures which leads to the failure of the whole system. Define M_i the ith minimum cut set and mcs the number of the minimum cut sets. The upper bound of the system reliability degree at time t, $R_s(t)$, is derived by the inequality (5). The upper bound is used to estimate the system reliability degree.

$$R_s(t) \leq 1 - \sum_{j=1}^{mcs} P[M_j] + \sum_{i=1}^{mcs-1} \sum_{j=i+1}^{mcs} P[M_i M_j]. \quad (5)$$

Denote R_k the reliability degree of component k. The occurrence probability of minimum cut set M_j is derived from the value of the reliability degree of all the components in the set, which is calculated by Equation (6). The occurrence probability of the union of minimum cut set $M_i M_j$ is derived from the value of the reliability degree of all the components in the union set of M_i and M_j, which is calculated by Equation (7).

$$P[M_j] = P[\prod_{X_k \in M_j} X_k] = \prod_{X_k \in M_j} (1 - R_k),\ j = 1, ..., mcs. \quad (6)$$

$$\begin{aligned} P[M_i \cap M_j] &= P[\prod_{X_k \in M_i \cap M_j} X_k] \\ &= \prod_{X_k \in M_i \cap M_j} (1 - R_k), i, j = 1, ..., mcs, i \neq j. \end{aligned} \quad (7)$$

IV. Cost-based Maintenance by Genetic Algorithm

GA has been widely used to search for the optimal solution by simulating the natural evolution process. The performance of GA on global optimization has been verified [6]. The final maintenance strategy is decided by applying GA to minimize the total cost of maintenance activities.

A. Cost-based Maintenance Scheduling Model

The maintenance cost of the AHP system contains two parts, the cost of the maintenance activity and the resource consume cost during the maintenance process. To minimize the maintenance cost of an overall AHP system under reliability constraint, the problem is first formulated as a mixed integer programming problem with linear and nonlinear constraints, which is represented as follows:

$$\text{Minimize} \quad C_{AHP} \quad (8)$$

$$\text{Subject to} \quad C_{AHP} = C_T + C_M + C_D \quad (9)$$

$$x_{i_1} + x_{i_2} = 1, i \in M \quad (10)$$

$$C_T = \sum_{i \in M} \lfloor \frac{L}{T_{1i}} \rfloor C_{ai} \quad (11)$$

$$C_M = \sum_{i \in M} \lfloor \frac{L}{T_{1i}} \rfloor (x_{i_1} \sum_{j=1}^{i_1} c_{i_1 j} P_j + x_{i_2} \sum_{j=1}^{i_2} c_{i_2 j} P_j) \quad (12)$$

$$C_D = \sum_{j \in D} \lfloor \frac{L}{T_{2j}} \rfloor C_{ej} + \sum_{j \in D} \sum_{k=1}^{\lfloor \frac{L}{T_{2j}} \rfloor} c_{wj} y_{jk} \quad (13)$$

$$R_s(t) = 1 - \sum_{j=1}^{mcs} P_j + \sum_{i=1}^{mcs-1} \sum_{j=i+1}^{mcs} P_{ij} \quad (14)$$

$$R_s(t) \geq R_0, t \in [0, L]. \quad (15)$$

The decision variables are T_{1i}, T_{2i}, x_{i_1}, x_{i_2} and y_{jt}. T_{1i} is the cycle length of the imperfect maintenance activity i and T_{2j} is the cycle length of the inspection. x_{i_1} and x_{i_2} are binary variables, which indicate the maintenance level of imperfect maintenance activity i. For one maintenance activity, x_{i_1} and x_{i_2} can not be equal to 1 at the same time. If i_1 is determined as the maintenance level, we have $x_{i1} = 1$ and $x_{i2} = 0$. y_{jk} is also a binary variable, which indicates whether the component is replaced at the kth inspection of inspection activity j.

L is the time length of the scheduling horizon. M is the set of imperfect maintenance activities and D is the set of inspection activities. P_j and P_{ij} are the abbreviation of $P[M_j]$ and $P[M_iM_j]$, respectively. The system should satisfy the reliability constraints. The system reliability at any time $R_s(t)$ is higher than the minimum reliability value R_0 and is calculated by Equation (14), which is obtained from the fault tree analysis.

C_{AHP} indicates the total cost of all maintenance activities of the AHP system, which is the optimization objective in the model. The total cost consists of three parts. C_T is the total imperfect maintenance cost, where the parameters C_{ai} is the imperfect maintenance cost each time. C_M is the total resource waste cost of imperfect maintenance, where c_{i_kj} is the unit resource waste cost when the maintenance level is i_k. C_D is the total inspection cost, where C_{ej} is the cost of detection each time and c_{wj} is the cost of each replacement.

B. Population representation and initialization

Individual chromosomes consist of the information about the length of the maintenance and inspection cycles, the maintenance level of each activity and the replacement decision. They are represented in integer format. The initial population of GA is randomly generated between the lower and upper bounds of the decision variables.

C. Fitness Function

The fitness function evaluates the quality of each chromosome in the population. It is composed of the objective function (8) and the penalty function of violating the reliability constraint, which is shown in Equation (16). Let P denote the degree of constraint violation. Big M is implemented in the fitness function to guarantee that the constraints are satisfied.

$$Fitness = \frac{1}{C_{AHP} + M \times P}. \tag{16}$$

D. Selection, Crossover and Mutation

In the selection stage of GA, the individual with a higher fitness function has a higher probability to be selected to the next generation, which corresponds to a lower objective value and fewer constraints violation. In the crossover stage, a two-point crossover technique is implemented. The chromosomes of the two elite individuals from the last generations are exchanged at some points. In the mutation stage, a single point method is applied to change some points of a part of chromosomes randomly to avoid premature convergence. Solution repair operator is designed to repair the infeasible solution into a feasible one.

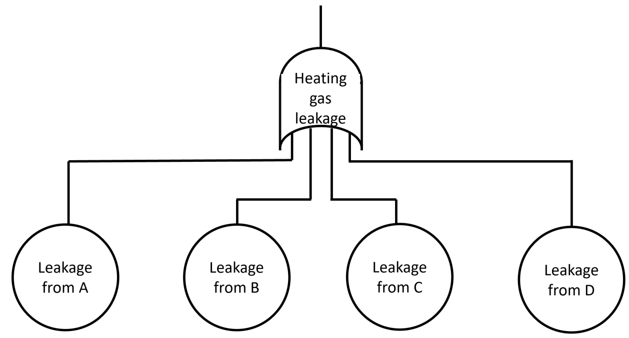

Fig. 6. Fault tree of gas leakage part.

V. Numerical Examples

In this section, we investigate a case study on the maintenance plans of a real-world AHP system in NPP within 40 years. The multi-component system contains 50 components. The minimum cut sets obtained by the fault tree analysis are summarized in Table II. Take basic event $M_1 = X_5$ as example. The basic event X_5 corresponds to the failure mode "Pipeline Leakage" of component 601RE.

Since the number of maintenance activities is huge, we choose one of the critical components, 6A, to show the effectiveness of the model. The input parameters of 6A is listed below in Table III. The input parameters of other components are organized in the same way with different failure modes, maintenance activities and cost values. Due to the commercial reasons, the failure modes and maintenance activities in the table is represented by some codes. Most cost parameters are modified from the data in the operational manual. The rest parameters are approximately estimated by the trial-and-error approach. The problem is modeled in Python 3.6 and solved on a PC with Intel(R) Core(TM) i7-8550U CPU @ 1.80GHz 1.99GHz, 8.00GB RAM. The fault tree analysis is executed on the Isograph reliability workbench. The branch of the fault tree related to the leakage of 6A is shown in Fig. 6. The 57 minimum cut sets of the AHP system are obtained by fault tree analysis in Isograph.

We conduct the maintenance scheduling method with cost minimization and reliability constraints on GA. In order to obtain a better solution with fast convergence, the parameters of GA are set as the following in Table V.

The optimal inspection strategy related to component 6A is listed in Table IV. For each maintenance activity, the inspection cycle is obtained and the replacement threshold is also shown in the table. The optimal imperfect maintenance cycle for maintenance activity A3 is $T_1 = 10261$ hours. During 40 years, there are 34 rounds of maintenance activities. The maintenance level is chosen from 0.4 and 0.6. The optimal solution shows that maintenance level 0.4 is preferred in all 34 rounds.

Fig. 7 depicts the convergence process of GA. The convergence rate is fast. The value of total system maintenance cost C_{AHP} decreases from more than $\$4.8 \times 10^7$ to around

TABLE II
MINIMUM CUT SETS OF THE AHP FAULT TREE

Minimium Cut Set Index u	1	2	3	4	5	6	7	8	9	10	11	12
Minimum Cut Set M_u	X_5	X_6	X_{13}	X_{14}	X_{15}	X_{16}	X_{17}	X_{18}	X_1X_3	X_1X_4	X_2X_4	X_2X_3

TABLE III
PARAMETERS RELATED TO ONE CRITICAL COMPONENT IN AHP

Component	Maintenance type	Maintenance activity	Failure mode	Maintenance Level %	Labor cost	Spare parts cost	Total cost
6A	Inspection	A1	M1	60	\$3712	0	\$3712
	Inspection	A2	M2	60, 40, 20	\$25312	\$5245	\$30558
	Imperfect Maintenance	A3	M3	40	\$3456	0	\$3456

TABLE IV
INSPECTION STRATEGY FOR COMPONENT 6A

Maintenance activity	Failure mode	Inspection cycle T_2 (h)	Replacement threshold F
A1	M1	133839	0.4
A2	M2	547	0.2

TABLE V
THE PARAMETER VALUE OF GA

Population size P	40
Iteration number N_{max}	200
Crossover rate μ	0.6
Mutation rate λ	0.05

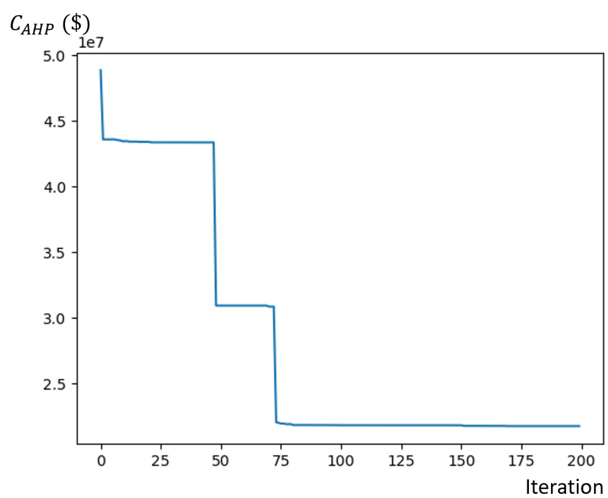

Fig. 7. Convergence curve of GA.

$\$2.1 \times 10^7$, which hugely reduces the maintenance cost of the NPP.

VI. CONCLUSION

In this paper, an imperfect maintenance scheduling strategy with the combination of inspection policy is proposed for the AHP system in NPP, which is a multi-component system. Each component suffers from several failure modes. Each failure modes have multiple maintenance strategies. The maintenance scheduling significantly decreases the maintenance cost of NPP. Since the AHP system is widely used in power plant, the research result can also benefit the maintenance scheduling of AHP system in other types of power plants. In the future, in order to enhance the relationship between the different components in the system, the stochastic dependency can be considered in the AHP model.

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