Optimal Asset Management of Distribution Transformers Considering Life Cycle Costs

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Abstract. *The optimal maintenance and replacement of distribution transformers can reduce the costs of maintenance and replacement and increase the transformer availability which can increase the system reliability as well. From the previous research works, they considered either maintenance or replacement of industrial equipment to determine the most appropriate scheme. Both maintenance and replacement of equipment have not been simultaneously considered before. Moreover, the asset value of the equipment has not been taken into account. Consequently, this paper presents the mathematical model of the optimal scheduling of transformer maintenance and replacement considering the asset value and the life cycle cost of the transformer. The purpose of the developed model is to minimize total cost while maintaining the defined level of transformer reliability. The considered costs compose of failure cost, maintenance and replacement costs. The Genetic Algorithm (GA) was applied to solve the optimization problem of the proposed model using MATLAB. The numeric results are presented as a graph for the system planner to decide for replacing and maintaining the transformer based on the life cycle cost of the transformer. The results from the proposed mathematical model can reduce the total cost by 36 % compared with the total cost before using the optimal schedule.*

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1. Introduction

Distribution transformers of the Provincial Electricity Authority (PEA) are the components for converting electricity voltage from 22 kV to 400 V or 230 V to suitably supply for customers. Because there are many distribution transformers installed in the system and the value of each transformer is typically high. Consequently, distribution transformers are very important in the distribution system. PEA is an organization that has to distribute electricity to customers who live in 74 provinces of Thailand except for Bangkok, Nonthaburi, and Samut Prakan. Distribution transformers are valuable assets in the distribution system and their quantity increases with higher energy consumption. The factors of transformers that may affect the efficiency of electrical power distribution are transformer aging and deterioration. Therefore, transformer management such as maintenance for the transformer that has a long service life is essential to maintain transformer availability at all times. The increase in transformer life through the method mentioned above is related to the value of the transformer.

Maintenance plays a vital role throughout a system's lifecycle. A survey of the operations and management of today's industries shows that maintenance activities contribute immensely to the success of PEA industrial concerns. Therefore, a good maintenance policy can increase the availability of equipment by managing between planned and unplanned downtime, which can cause major disruptions in manufacturing processes [1]. In addition, maintenance objectives were summarized under four headings which are: ensuring system function (availability, efficiency and product quality); ensuring system life (asset management); ensuring safety and ensuring human well-being [2]. When maintenance is carried out at predetermined intervals or according to prescribed criteria and intended to reduce the probability of failure or the degradation of the functioning of an item, it is known as Preventive maintenance [3]. Furthermore, when maintenance is carried out after fault recognition (equipment breakdown) and intended to put the unit back into a state in which it can perform a required function, this phenomenon is called Corrective maintenance. Reliability-Centered Maintenance programs are gaining in popularity and have been applied in some industries with good results. The goal of these programs is to provide the appropriate amount of maintenance at the right time to prevent forced outages while at the same time eliminating unnecessary maintenance. Condition-Based maintenance type relies on knowing the condition of individual pieces of equipment [4]. It deals with monitoring equipment parameters such as temperatures, pressures, vibrations, leakage, current, dissolved gas analysis, etc. The test is operated periodically and/or when equipment is suspected to have a problem. In this manner, maintenance schedule can be lengthened or perhaps shortened based on the experience of operator. Maintenance schedules can be completed at a shorter time horizon. The order of each activity is determined according to its priority and available manpower. It describes the timing of each activity. Scheduling maintenance is an important activity that can save time and money. it influences cost and time by reducing unnecessary preventative maintenance [5]. It also plays an important role to reduce costs and enhance product performance through maintenance response time that affects the life of the equipment.

For the optimization methods to solve the scheduling problem, deterministic optimization algorithms and dynamic programming have been proposed by various authors. Reference [6] presented a two-tier hierarchical model that optimizes preventive maintenance scheduling in the semiconductor manufacturing process. They developed Markov's decision-making process using compound integer linear programming models. Reference [7] developed a non-linear optimization model to reduce the total cost of maintenance and replacement operations under the constraint of reliability for production machines. Their model considers a machine failure function as the Weibull distribution function which can be used as a decision support system for scheduling. Reference [8] presented an optimization method for scheduling preventive maintenance of a gas turbine power plant. They developed the model for maximizing profit with the consideration of power plant performance and reliability in the dynamic market. Reference [9] proposed an optimization model to schedule preventive maintenance of power plants during the planned time. They considered the total cost of operations as an objective function and used Bender's decomposition to solve the problem of mixed-integer linear programming models. Reference [10] proposed the linear model for scheduling preventive railway maintenance. The objective of this work is to minimize overall costs including occupancy costs, maintenance costs, and fines for pre-determined maintenance activities. Reference [11] presented the optimization model for maintenance scheduling and production planning of a single machine based on cumulative damage processes. Reference [12] presented an optimization model to schedule the best preventive maintenance job of all machines in a single product line. Reference [13] presented the optimal maintenance scheduling of the system considering maintenance cost and system constraint by using genetic algorithms to find the best preventive maintenance schedule. Reference [14] proposed decision variables in a preventive maintenance scheduling model for the production process that uses heuristics algorithms to solve this problem. Reference [15] presented a general framework for optimizing preventive maintenance in chemical processes. They devised the Weibull model for calculating failure rates and considered the various maintenance activities. They developed a method that combines Monte Carlo simulation with genetic algorithms to solve prospective maintenance problems. Reference [16] developed an optimization model for scheduling preventive maintenance in the production process considering multi-state systems. A combination of genetic algorithms and simulation models of preventive maintenance and replacement schedules were used to solve the model. Reference [17] presented a combination of an ant colony and genetic algorithms to solve the large-scale preventive maintenance scheduling in the production system. In the year 2010, Le Li and Wei Huang [18] presented the method for making the decision of transformer replacement considering the life cycle cost of transformers. The objective was to minimize the life cycle cost of transformers which consists of construction cost, procurement cost, installation cost, operating cost, maintenance cost, outage cost, and a salvage value of transformer. This work compared the two transformers which have the same capacity but different manufacturer. The results indicated that the transformer which has lower core loss provided lower life cycle cost than the high core loss transformer. In this work, the reliability of transformers was not considered. In the year 2012, Sung Hun Lee [19] presented the new determination of economic life cycle for power transformer based on life cycle cost analysis. The objective was to minimize the life cycle cost of transformers and power loss. The determination of transformer life cycle cost followed the IEC 60300-3-3 standard with the least square regression. In this work, the reliability of transformers was not considered. In the year 2014, Kamran S. Moghaddam [20] presented the preventive maintenance and replacement optimization on CNC machine using multi-objective evolutionary algorithm. The objective was to minimize the total cost of CNC machine and the increase of CNC machine failure rate while the reliability was considered as a constraint. The considered operations consisted of maintenance, replacement, and do nothing. In this work, the life cycle cost of CNC machine was not taken into account. In the year 2017, Jianpeng Bian and Su Yang [21] presented the determination method of biasing variables for transformer maintenance and replacement costs which affect the lifetime of transformers by considering the failure rate of transformers. The tool for solving optimization problems was the graphical optimization method. The objective of this work was to minimize the transformer life cycle cost while the transformer reliability was considered as a constraint. The testing cases were separated into three cases consisting of absent maintaining transformers, maintaining transformers and replacing transformers. The results showed that the replacing transformers provided minimize the transformer life cycle cost. However, this work did not consider the maintenance and replacement of transformers in the plan simultaneously.

From the previous research works, the optimization models dealing with optimal maintenance and replacement schedules are mostly considered in the manufacturing process of the industry. Presently, the asset management of the equipment is not interested and its maintenance pattern is still not clear. For example, the industry with a manufacturing process will mainly focus the profit and reduce the manufacturing cost. When the failed component was found, the failed component will be replaced immediately. For PEA, the optimal scheduling of transformer maintenance and replacement have not been considered before. In addition, the previous research works considered either maintenance or replacement of industrial equipment to determine the most appropriate scheme. Both maintenance and replacement of equipment have not been simultaneously considered before. Moreover, the asset value of the equipment has not been taken into account before. Consequently, this paper proposes the optimal scheduling of distribution transformers maintenance and replacement considering the life cycle cost of the transformer. The objective is to minimize the transformer fixed cost, maintenance cost, replacement cost, and outage cost due to transformer failure while the considered constraint is transformer reliability. The Genetic Algorithm (GA) was applied to solve the optimization problem. In addition, the asset value of each transformer which has a useful life of 20 years is considered.

The remainder of this paper is organized as follows. In Section 1, a transformer failure model and genetic algorithm (GA) are presented. In Section 2, the proposed problem formulation and optimization process are presented. The experimental result is explained in Section 4. Finally, the conclusion, discussion, and the suggested future work are presented in Section 5.

2. Methodology

We handle a modeling approach to find optimal preventive maintenance and replacement schedules for distribution transformers. A new closed-form optimization model is constructed based on the cost and reliability characteristics of the transformers. The model is solved using a standard optimization procedure. The first stage is the transformer failure model which the Weibull distribution function was considered to evaluate a function of a probability density function for explaining the equipment failure function that relates to the using time of the transformer. The second stage is the transformer reliability model that the maintenance and replacement of the distribution transformer can improve reliability. Finally, the process of genetic algorithm (GA) which is used for solving the optimization problem is presented.

2.1 Transformer Failure Model

The problem to be considered is the maintenance scheduling issue for the transformer. Any maintenance or replacement activities of the transformer result in an interruption of the entire process. The service life of most transformers in the PEA's distribution system is higher than 20 years which results in a higher failure rate. To explain the failure rate of the transformers, the failure rate function assessed by a using distribution function model is generally applied. In this issue, the Weibull distribution function is a continuous distribution that was publicized by Waloddi Weibull in 1951. It is widely used, especially in the reliability field. The Weibull distribution's popularity has resulted from its ability to be used with small sample sizes and its flexibility. The Weibull distribution model is an uncertain distribution function depending on the parameters indicating the size and shape. The using time of the equipment inversely affects its reliability and when the equipment fails, its reliability will reduce. This paper uses the Weibull distribution model to describe the reliability function of the equipment by using the equipment failure rate. Analysis of the Weibull distribution provides the information needed for troubleshooting, classifying failure types, scheduling preventive maintenance and scheduling inspections. In order to determine the appropriate maintenance or replacement plan for the transformer considering the life cycle, the Weibull distribution function was considered to evaluate a function of a probability density function for explaining the equipment failure function that relates to the using time of the transformer. The Weibull probability density function can be modeled by using the least-squares method as shown below.

1.1.1) The failure data of all transformers are collected after that the median of each transformer failure data is evaluated by equation (1).

$$S_p = \frac{p-0.3}{L+0.4} \tag{1}$$

S_p is the median of transformer failure data p, p is the order of failure data, L is the number of total failures.

1.1.2) Find the shape and scale parameters by equations (2)-(7).

$$y_p = mx_p + c \tag{2}$$

$$y_p = \ln\left(\ln\left(\frac{1}{1-S_p}\right)\right) \tag{3}$$

$$x_p = \ln\left(t_p\right) \tag{4}$$

$$m = \beta = \frac{\sum_{p=1}^{L} X_p Y_p - \frac{\sum_{p=1}^{L} X_p \sum_{p=1}^{L} Y_p}{L}}{\sum_{p=1}^{L} X^2 - \frac{\left[\sum_{p=1}^{L} X_p\right]^2}{L}} \tag{5}$$

$$c = \frac{\sum_{p=1}^{L} y_p}{L} - m\frac{\sum_{p=1}^{L} X_p}{L} \tag{6}$$

$$\alpha = e^{-[\frac{c}{m}]} \tag{7}$$

where, t_p is the time of failure order p, β is a shape parameter of the transformer, α is a scale parameter of the transformer, X_p and Y_p are the parameters in the Weibull distribution function, c is a constant and m is the slope of the linear equation.

2.2 Transformer Reliability Model

Nowadays, reliability is very important for distribution systems. The maintenance and replacement of the distribution transformer can improve reliability. Therefore, reliability has to be taken into account in the maintenance and replacement plan. The reliability function is a measure of the reliability of the transformer resulted from the failure rate function because when the transformer fails, the reliability will be reduced. The individual transformer reliability and total reliability can be written as shown in equations (8) and (9), respectively.

$$R_{i,j} = e^{\left[\int_{x_{i,j}}^{x'_{i,j}} v_i(t)dt\right]} = e^{-\left[\alpha_i\left(X'_{i,j}\right)^{\beta_i} - \left(X_{i,j}\right)^{\beta_i}\right]} \quad (8)$$

$$reliability = \prod_{i=1}^{N}\prod_{j=1}^{T} e^{-\left[\alpha_i\left(X'_{i,j}\right)^{\beta_i} - \left(X_{i,j}\right)^{\beta_i}\right]} \quad (9)$$

$$X_{i,j} = 0, i = 1, ..., N \quad (10)$$

$$X_{i,j} = (1 - m_{i,j-1})(1 - r_{i,j-1})X_{i,j-1} + m_{i,j-1}(\zeta_i . X'_{i,j-1}),$$
$$i = 1, ..., N, \; j = 2, ..., T \quad (11)$$

$$X'_{i,j} = X_{i,j} + \frac{T}{J} \quad (12)$$

$$m_{i,j} + r_{i,j} \le 1 \quad (13)$$

$$m_{i,j}, r_{i,j} = 0 \quad (14)$$

$$X_{i,j}, X'_{i,j} \quad (15)$$

where, $m_{i,j}$ and $r_{i,j}$ are binary variables of maintenance and replacement actions for a component i in the period j, respectively and they cannot be equal to one simultaneously. $X_{i,j}$ denotes the effective age of transformer i at the start of period j (year). $X'_{i,j}$ denotes the age of transformer i at the end of period j (year). (If transformer i is replaced in period j, we assume that the replacement cost is the initial purchase price of transformer i). $R_{i,j}$ is the reliability of transformer i at the end of period j. $V_i(t)$ is the probability density function of the failure event of transformer i. ζ is an improvement factor N is the number of transformers. T is the number of periods. β_i is a shape parameter of transformer i. α_i is a scale parameter of transformer i. $m_{i,j-1}$ and $r_{i,j-1}$ are binary variables of maintenance and replacement actions for a transformer i at the period j-1, respectively. $X_{i,j-1}$ is the effective age of transformer i at the period j-1 (year) however $i = 1, ...N$ and $j = 1, ..., T$.

2.3 Genetic Algorithm (GA)

Genetic algorithm (GA) [22] is the optimization method based on the natural selection principle shown in figure 1. For the first time, it has been introduced since 1975 [23, 24]. GA has been proven to be the most powerful optimization technique in various fields [25]. For example, GA is applied in image processing [22] and other fields [26, 27]. GA can be used to find an exhaustive solution which generally consumes high computation time.

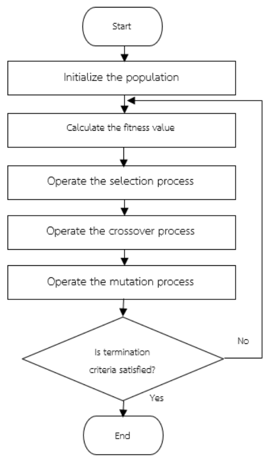

Fig. 1 Framework of GA algorithm

3. The Proposed Problem Formulation and Optimization Process

In this section, the problem formulation and optimization process are proposed. Firstly, the problem formulation consisting of the objective function and the constraints are presented. After that, the optimization process using the genetic algorithm (GA) for solving the optimal transformer maintenance and replacement schedule is presented.

3.1 The Proposed Problem Formulation

The objective of the scheduling of transformer maintenance and replacement is to minimize the transformer fixed cost, maintenance cost, outage cost due to transformer failure and replacement cost as presented in equation (16). To maintain the transformer reliability, the reliability constraint is written as shown in equation (17).

$$Total\_cost = \sum_{i=1}^{N}\sum_{j=1}^{T}\left[F_i.\lambda_i((X_{i,j}{}^{'})^{\beta_i} - (X_{i,j}{}^{i})^{\beta_i} M_i.m_{i,j} + R_i.r_{i,j}\right] + \sum_{j=1}^{T}\left[Z_i(1 - \prod_{i=1}^{N}(1-(m_{i,j}+r_{i,j}))))\right] \quad (16)$$

$$R(i) \ge R_{required} \quad (17)$$

$$\lambda_i = \frac{1}{\alpha_i^{\beta_i}} \quad (18)$$

where, $R(i)$ is the reliability of the transformer i, $R_{required}$ is required reliability of the transformer. $m_{i,j}$ and $r_{i,j}$ are binary variables of maintenance and replacement actions for transformer i at the period j, respectively and they cannot be equal to one simultaneously. $X_{i,j}$ is the effective age of transformer i at the start of period j (year). $X'_{i,j}$ is the age of transformer i at the end of period j (year). (If transformer i is replaced in period j, we assume that the replacement cost is the initial purchase price of the transformer i). R_i is the replacement cost of the initial purchase price of the transformer i (USD). N is the number of transformers. T is the number of periods. β_i is a shape parameter of transformer i. α_i is a scale parameter of transformer i. λ_i is a failure rate of transformer i (failures/year). F_i is the outage cost due to failure of transformer i (USD/failure event). M_i is a maintenance cost of transformer i (USD). Z_i is the investment cost of transformer i (USD).

3.2 Optimization Process

The first step in the proposed GA is the generation of the initial population. The cutting conditions are generated by random sampling inside the specific limits. The other values are calculated with selected cutting conditions. The initial population is produced either by making random changes to a single parent using the mutation operation or by combining the vector entries of a pair of parents using the crossover operation. The number of transformer breakdown times was used to calculate the reliability of the transformer. The process of the proposed method to solving the optimal scheduling of the distribution transformer is presented in Figure 2.

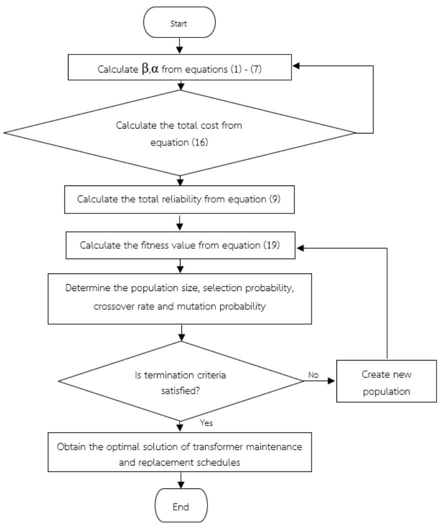

Fig. 2 Process of the proposed method to solving the optimal scheduling of the distribution transformer

A fitness function is a specific type of objective function that can define chromosome quality. The ideal fitness function is closely related to the goal of the algorithm as shown in Figure 2. The fitness function can be calculated as shown below.

$$Fitness = w_1\left(\frac{TotalCost}{Cost_{\max}}\right) + w_2(-reliability) \tag{19}$$

The fitness function reduces the total cost and increases the reliability of the system. The $\left(\frac{1}{Cost_{\max}}\right)$ is considered as the standardization coefficient to normalize the total cost. The weighting factors w_1 and w_2 are defined for the total cost and total reliability, respectively.

4. Experimental Result and Discussion

In this paper, MATLAB R2020a is utilized to develop the genetic algorithm as well as to calculate the fitness functions. We investigated the computational efficiency of the algorithms in terms of CPU time. The simulation is run on a laptop computer (Intel Core i5, 2.50 GHz and 16 GB of RAM).

We run the genetic algorithms with the fitness function in equation 19 with the set of weighting factors for the objective functions that are equal to 0.8 and 0.2 for the total cost (w_1) and the total reliability (w_2). The maintenance cost of each transformer is defined as 36 USD. The required reliability of each transformer is defined as 0.9. The planning horizon is defined as 36 months. In addition, The parameters of genetic algorithms are defined as presented in Table 1. The failure data of the PEA distribution transformer is presented in Table 2 and the transformer operation costs are defined as presented in Table 3. For the PEA method, transformers are defined to be maintained in the fifth year after installation. The maintenance costs will gradually increase for a series of years. The transformer will be replaced when it cannot operate. Transformers are maintained every year until they fail to operate, therefore, the number of replacements and the replacement cost equal to zero. The results when using the PEA method are given in Table 4.

For the results of the proposed optimal scheduling method, the effective age of transformer No. 1 as shown in Figure 3 is used to explain. It can be seen that the effective ages at months 13, 20 and 29 are zero which means that the transformer has to be replaced by a new transformer. Moreover, the effective ages at months 4, 7, 10, 16, 24, 26 and 31 are decreased which means that the transformer has to be maintained to increase its effective age. The maintenance and replacement of each transformer can be scheduled by using the data from Figure 3. The optimal scheduling of each distribution transformer is presented in Table 5.1-5.3. Finally, the costs and reliability from optimal scheduling of each distribution transformer are calculated as shown in Table 6.

From Tables 4 and 6, the results from the PEA method and the proposed optimal scheduling methods are compared. The number of maintenances of the proposed optimal scheduling decreases from 127 times to 48 times which leads to the reduction of maintenance cost. However, the numbers of replacement of the proposed optimal scheduling increase from 0 times to 17 times which leads to the increase in replacement cost. For the outage cost, the outage cost obtained from the proposed optimal scheduling decreased from 108,800 USD to 48,280 USD due to the increase of transformer reliability which is defined as a constraint in the proposed method.

Consequently, the total cost of the proposed optimal scheduling can reduce by 36% compared with the total cost of the PEA method and the average transformer reliability can be increased by 39.86% compared with the result from the PEA method.

In order to study the relationship between the transformer life cycle cost and transformer reliability, sensitivity analysis of these two values can be plotted as shown in Figure 4.

From Figure 4, when the required transformer reliability increases, the total cost of transformers will increase because they need more maintenance and replacement operations. This analysis study is useful for the system operator to approximate the total cost of designed transformer reliability.

Parameters	Value
Generation number	500
Population size	2000
Selection probability	0.2
Crossover rate	0.40
Mutation probability	0.40

Table 1 Parameter of GA

Transformers No.	Transformers capacities (kVA)	Location	Number of failures of each year									
			2009	2010	2011	2012	2013	2014	2015	2016	2017	2018
1	250	Udonthani road	1	3	1	2	4	5	7	8	9	11
2	160	Government pharmaceutical organization Udonthani	3	2	6	7	7	5	8	5	11	13
3	160	Srichomchuen road	1	1	3	4	4	6	7	7	9	14
4	250	Royal forest department Udonthani	1	2	2	4	5	7	7	8	10	10
5	315	Charoen Cha	2	3	2	4	5	2	5	5	4	7
6	250	Soi Yothawitthaya	3	4	6	7	9	11	10	11	12	15

Table 2 Failure data of the PEA distribution transformers

Transformers No.	Failure cost (USD/failure event)	Replacement cost (USD)	Maintenance cost (USD)
1	2,840	5,159	36
2	2,840	4,217	36
3	2,840	4,217	36
4	2,840	6,320	36
5	2,840	5,159	36
6	2,840	5,159	36

Table 3 Operation costs of the PEA distribution transformers

Transformer No.	**Number of maintenance**	**Number of replacement**	**Fixed cost (USD)**	**Replacement cost (USD)**	**Maintenance cost (USD)**	**Outage cost (USD)**	**Total cost (USD)**	**Reliability**
1	22	0	1,945	0	792	17,000	19,737	0.7289
2	25	0	1,841	0	900	20,400	23,141	0.5852
3	22	0	1,945	0	792	18,700	21,437	0.6133
4	21	0	1,841	0	756	18,700	21,297	0.6988
5	19	0	1,945	0	684	18,700	21,329	0.7264
6	18	0	1,841	0	648	15,300	17,789	0.8016
Total	127	0	11,359	0	4,572	108,800	124,731	0.6924

Table 4 The results of the PEA method

Transformers No.	Month											
	1	2	3	4	5	6	7	8	9	10	11	12
1				M			M			M		
2	R		M		M		M		M			
3				M		M			M			
4		R		R		M		M				
5				M		R					M	
6				M			M				M	R

Table 5.1 Optimal scheduling of each distribution transformer (1st-12th months)

Transformers No.	Month											
	13	14	15	16	17	18	19	20	21	22	23	24
1	R			M				R				M
2	M						M		M			M
3	M			M		R		M				M
4		R		M					M			M
5	M		R			R					R	
6			M		M					R		

Table 5.2 Optimal scheduling of each distribution transformer (13st-24th months)

Transformers No.	Month											
	25	26	27	28	29	30	31	32	33	34	35	36
1		M			R		M					
2		M			M					M		
3			M		M			M				R
4	M		R				R					
5	M	M				M					M	
6			M		M							

Table 5.3 Optimal scheduling of each distribution transformer (25th-36th months)

Note: M = maintenance operation and R= replacement operation

Transformer No.	Number of maintenance	Number of replacement	Fixed cost (USD)	Replacement cost (USD)	Maintenance cost (USD)	Outage cost (USD)	Total cost (USD)	Reliability
1	7	3	1,945	5,159	252	8,520	7,356	0.9681
2	11	1	1,841	4,217	396	2,840	6,454	0.9796
3	10	2	1,945	5,160	360	5,680	7,465	0.9787
4	6	5	1,841	4,217	216	14,200	6,274	0.9601
5	7	4	1,945	5,160	252	11,360	7,357	0.9556
6	7	2	1,841	4,217	252	5,680	6,310	0.9683
Total	48	17	11,359	28,131	1,728	48,280	89,498	0.9684

Table 6 The costs and reliability from optimal scheduling of each distribution transformer

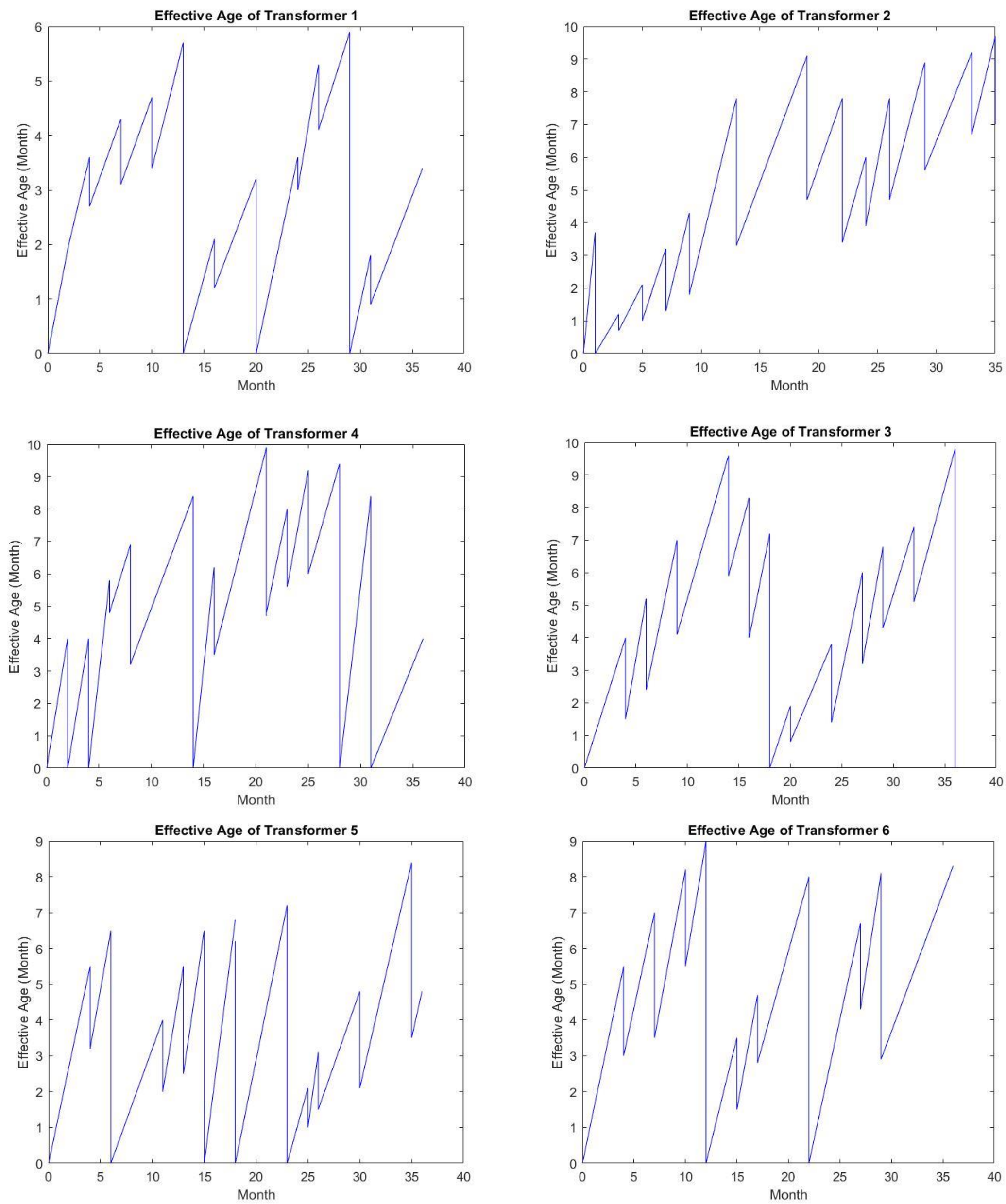

Fig. 3 Effective age of each distribution transformer

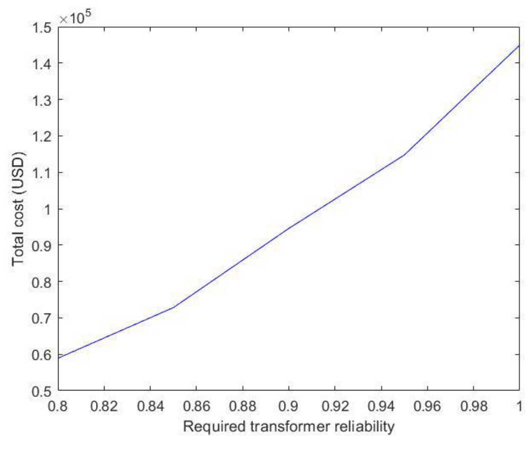

Fig. 4 sensitivity analysis of the transformer life cycle cost and transformer reliability

5. Conclusions

From the previous research works, they considered either maintenance or replacement of industrial equipment to determine the most appropriate scheme. Both maintenance and replacement of equipment have not been simultaneously considered before. Moreover, the asset value of the equipment has not been taken into account before. Consequently, this paper presents the mathematical model of the optimal scheduling of transformer maintenance and replacement considering the asset value and life cycle cost of the transformer. The purpose of the developed model is to minimize total cost while maintaining the defined level of transformer reliability. The considered costs compose of failure cost, maintenance and replacement costs. The Genetic Algorithm (GA) was applied to solve the optimization problem of the proposed model using MATLAB. From the comparison results of the PEA method and the proposed optimal scheduling methods. The number of maintenances of the proposed optimal scheduling decreases from 127 times to 48 times which leads to the reduction of maintenance cost. However, the numbers of replacement of the proposed optimal scheduling increase from 0 times to 17 times which leads to the increase in replacement cost. For the outage cost, the outage cost obtained from the proposed optimal scheduling decreased from 108,800 USD to 48,280 USD due to the increase of transformer reliability which is defined as a constraint in the proposed method. Consequently, the total cost of the proposed optimal scheduling can reduce by 36% compared with the total cost of the PEA method and the average transformer reliability can be increased by 39.86% compared with the result from the PEA method.

For future works, to manage maintenance and replacement schedules of transformers to be more effective and accurate, additional factors that increase failure rates should be taken into accounts such as the use of transformers during the peak load time, the unbalanced current that will result in the transformer malfunction, the effectiveness of the transformers, and the probability to be failed due to natural disaster. Moreover, the future work may consider the distribution system reliability indices such as System Average Interruption Frequency Index (SAIFI), System Average Interruption Duration Index (SAIDI), and Expected Energy Not Supplied (EENS) before and after the scheduling transformers in order to evaluate the increase of system reliability.

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References

[1] O. Ladi, A. A. Sosimi, K. O. Shittu, E. O. Oyetunji and S. A. Oke, "Maintenance job scheduling: a multi-criteria Approach under stochastic-fuzzy uncertainty", *Kmitl sci. Tech. J.*, Vol. 7, no. 2 jul -dec. 2007.

[2] D. Rommert, "Applications of maintenance optimization models: a review and analysis", *Reliability Engineering and System Safety, Elsevier Science Limited Printed in Northern Ireland*, pp. 229-240.

[3] H. Z. Wang, and H. Pham, "Reliability and Optimal Maintenance", *Springer*, 2006.

[4] S. Ho-Joon, "Optimal Maintenance of a Multi-Unit System Under Dependencies", *School of Aerospace Engineering, Georgia Institute of Technology*, December 2008, pp. 7-29, 2008.

[5] A. A. Abdullah, D. B. Peter, and T. Ashutosh, "Applications of simulation in maintenance research", *World Journal of Modelling and Simulation*, Vol. 9, No. 1, pp. 14-37, 2013.

[6] X. Yao, E. Fernandez-Gaucherand, M. C. Fu, and S. L. Marcus, "Optimal preventive maintenance scheduling in semiconductor manufacturing", *IEEE Transactions on Semiconductor Manufacturing*, v 17, n 3, August 2004, pp. 345-356, 2004.

[7] B. J. Han, X. M. Fan, and D. Z. Ma, "Optimization of preventive maintenance policy of manufacturing equipment based on simulation", *Computer Integrated Manufacturing Systems*, v 10, n 7, July 2004, pp. 853-857, 2004.

[8] Y. Zhao, V. Volovoi, M. Waters, and D. Mavris, "A sequential approach for gas turbine power plant preventive maintenance scheduling", *2005 ASME Power Conference*, 5-7 April 2005, Chicago, IL, USA, pp. 353-362, 2005.

[9] S. V. Canto, "Application of Benders' decomposition to power plant preventive maintenance scheduling", *European Journal of Operational Research*, v 184, Issue 2, January 2006, pp. 759-777. 2006.

[10] G. Budai, D. Huisman, and R. Dekker, " Scheduling preventive railway maintenance activities", *Journal of the Operational Research Society*, v 57, n 9, September 2006, pp. 1035-1044, 2006.

[11] Y. Kuo, and Z. A. Chang, "Integrated production scheduling and preventive maintenance planning for a single machine under a cumulative damage failure process", *Naval Research Logistics*, v 54, n 6, September 2007, pp. 602-614, 2007.

[12] G. Cavory, R. Dupas, and G. Goncalves, " A genetic approach to the scheduling of preventive maintenance tasks on a single product manufacturing production line", *International Journal of Production Economics*, v 74, n 1-3, December 2001, pp.135-146, 2001.

[13] R. Bris, E. Chatelet, and F. Yalaoui, " New method to minimize the preventive maintenance cost of series-parallel systems", *Reliability Engineering and System Safety*, v 82, n 3, December 2003, pp. 247-255, 2003.

[14] P. Limbourg, and H. D. Kochs, "Preventive maintenance scheduling by variable dimension evolutionary algorithms", *International Journal of Pressure Vessels and Piping*, v 83, n 4, April 2006, pp. 262-269, 2006.

[15] J. S. Tan, and M. A. Kramer, "A general framework for preventive maintenance optimization in chemical process operations", *Computers and Chemical Engineering*, v 21, n 12, 1997, pp. 1451 1469, 1997.

[16] M. A. Shalaby, A. H. Gomaa, and A. M. Mohib, "A genetic algorithm for preventive maintenance scheduling in a multiunit multistate system", *Journal of Engineering and Applied Science*, v 51, n 4, August 2004, pp. 795- 811, 2004.

[17] M. Samrout, F. Yalaoui, E. Chatelet, N. Chebbo, "New methods to minimize the preventive maintenance cost of series-parallel

systems using ant colony optimization", *Reliability Engineering and System Safety*, v 89, n 3, September 2005, pp. 346-354, 2005.

[18] L. Li, W. Huang, X. Ma, J. Ge, and L. Yang, "Investment Decision-making of Power Distribution *Transformers Transformation Based on Life Cycle Cost Theory*", pp. 1–6, 2010.

[19] S. H. Lee, A. K. Lee, and J. O. Kim, "Determining Economic Life Cycle for Power Transformer Based on Life Cycle Cost Analysis," 2012 *IEEE Int. Power Modul. High Volt. Conf.*, pp. 604–607, 2012.

[20] K. S. Moghaddam, "Preventive maintenance and replacement optimization on CNC machine using multiobjective evolutionary algorithms," pp. 2131–2146, 2015.

[21] Z.-N. Ma, L.-H. Zhong, K. Lu, and C.-J. Xia, "Study on the maintenance strategy of power equipment based on the optimal life cycle cost," *Dianli Xitong Baohu yu Kongzhi/Power Syst*.

[22] N.R. Harvey, S. Marshall. The design of different classes of morphological filter using genetic algorithms. *IEE fifth international conference on image processing and its applications*, pp. 227 – 231, 1995.

[23] P. W. M. Tsang, A.T.S. Au. A genetic algorithm for projective invariant object recognition. *Conference proceedings*, 1996 *IEEE TENCON: Digital Signal Processing Applications*, pp.58 – 63, 1996.

[24] S.E. Papadakis, P. Tzionas, V.G. Kaburlasos, J.B. Theocharis. A genetic based approach to the type I structure identification. *Informatica*, Vol.16, No. 3, pp. 365 – 382, 2005.

[25] A. Misevicius. Experiments with hybrid genetic algorithm for the grey pattern problem. *Informatica*, Vol.17, No.2, pp. 237 – 258, 2005.

[26] H.P Schwefel, G. Rudolph. Contemporary evolution strategies. *Advances in artificial life*, pp. 893 – 907, 1995.

[27] F. W. Gembicki, *Vector Optimization for Control with Performance and Parameter Sensitivity Indices,* Ph.D. Thesis, Case Western Reserve University., Cleveland, Ohio, USA., 1974.

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