Cost Worth Evaluation of Reliability Centered Maintenance for Electrical Equipment in a Chemical Plant

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Abstract
This paper proposes a maintenance strategy for electrical equipment in a chemical plant from the reliability and cost worth perspective. Two types of the plant downtime cost are modeled. One is the planned downtime cost consisting of opportunity cost and scheduled maintenance cost. The other is the unplanned downtime cost consisting of opportunity cost, plant recovery operation cost, and damage of material loss. A risk of the condition without maintenance is assessed by using the downtime cost model and a modeled reliability curve of the electrical equipment and decision making for optimal frequency of maintenance is given through comparing the cost of scheduled maintenances and the evaluated risk of the unplanned plant shutdown. A demonstration using a simplified chemical plant model shows the effectiveness of the proposed approach.

Keywords: Reliability Centered Maintenance, Electrical Equipment, Chemical Plant

1. Introduction

Maintenance and its practice are necessary to keep the plant performance and the safety of workers. Maintenances have been planned and done with a certain interval according to the regulation or recommendation of the equipment vendors for the equipment performance and safety.

The maintenance interval can be appropriate if the condition of use follows the assumption of the equipment vendors. However, every customer has a different condition to use equipment and even for one customer, several conditions should be considered to use equipment efficiently.

Chemical plants are generally operated for two or three years without pausing because opportunity cost of plant pausing time is very large. Equipment in chemical plant is also required to work without any pausing as long as possible.

For long-run operation of chemical plant, maintenance with plant shutdown is very important and it has a large impact on asset management of a chemical plant.

Maintenance is done to ensure plant good performance and to avoid costly failure. However, if maintenance is done too often, maintenance cost will increase sharply, so maintenances with the optimal interval are necessary for asset management of the plant.

Recently, reliability centered management (RCM) [(1)-(4)] is applied to systems whose shutdown have a strong impact on company's profit or social life such as electric company and petrochemical plant and so on. RCM has an advantage that necessary maintenance can be done at necessary moment. However, it is difficult to know how many times maintenance will be done and how much it costs for a certain period.

Both of regular interval maintenance and condition-based maintenance such as RCM have advantages and disadvantages, and advantages and disadvantages are organized in reference (5). Whichever is chosen, maintenance cost and its efficiency should be balanced.

For asset management, maintenances with optimal frequency are necessary and the risk evaluation scheme is also necessary to decide the maintenance intervals.

This paper provides an evaluation method of plant downtime cost and a maintenance planning strategy for electrical equipment in a chemical plant. The proposed approach is applied to a simplified chemical plant model to verify its efficiency for maintenance planning. The results of numerical examples demonstrate the efficiency of the proposed approach.

2. Plant Downtime Cost Formulation

There are two types of plant downtime cost formulated in this paper. One is planned downtime cost (PDC) and the other is unplanned downtime cost (UDC).

2.1 Planned Downtime Cost

Planned downtime cost is modeled as a sum of opportunity cost during the downtime and planned maintenance cost of target electrical equipment and related mechanical equipment.

$$PDC(x,t) = \sum \{ OppCost(x,t) + MtnCost_{pl}(x,t) \} \quad (1)$$

where,
x: Vector of equipment in a plant
t: plant downtime
OppCost: Opportunity cost
MtnCostpl: Cost of planned maintenance

2.2 Unplanned Downtime Cost

Unplanned downtime cost is modeled as a damage of the plant process shutdown due to contingencies of electrical equipment.

When a contingency of electrical equipment occurs in a plant and plant process is stopped, repairing the failure equipment and recovery operations are necessary to clear the contingency and restart the plant process. Additionally, unplanned process shutdown will cause product errors, and some materials will be remained in plant facilities. The remained material and error products are disposed, and that is regarded as a loss. Therefore, the damage of the plant process shutdown, UDC, consists of opportunity cost during downtime, maintenance cost for repairing, recovery operation cost, and loss shown in equation (2).

$$UDC(x,t) = \sum \{ OppCost(x,t) + MtnCost_{upl}(x,t) + RcvOpr(x,t) \} + Loss \quad (2)$$

where,
MtnCostupl: Cost of unplanned maintenance
RcvOpr: Cost of recovery operation of the failure process
Loss: Material and/or product loss

3 Reliability Model of Plant

3.1 Equipment Reliability Curve

Generally, reliability of equipment is the highest at newly installation and will decrease with time. The risk of failure becomes higher with less reliable status of equipment.

Electrical equipment in a plant is one of the key elements of the plant operation. Especially for instrument and control devices, the interruption of electricity supply has a large impact. Therefore, it can be said that the plant performance depends on the reliability of electrical equipment. Additionally, the plant life cannot be independent of the reliability of protective devices such as over current relays, over/under voltage relays because the failure of them will make the life of equipment shortened.

As described above, unreliable status of electrical equipment will cause costly damage on a plant, so reliability evaluation scheme is necessary to reduce the risk of costly failure of a plant.

Although there are some variations of reliability decreasing speed among components, parts, or conditions of use, the reliability of equipment keeps its highest status for some period after its newly installation and start to decrease to unreliable status. Hence, the reliability of equipment can be approximated by sigmoid function curve. Fig. 1 shows a sample curve of electrical equipment reliability approximated by sigmoid function.

The proposed approach in this paper is based on this approximation.

3.2 Equipment Reliability with Maintenance

To improve the reliability of equipment, maintenance is done periodically or when regarded as necessary.

If maintenance is done before failure occurs, reliability of the target equipment will be improved as closely as its initial state. However, the reliability of it will decrease more quickly than that of new equipment. Therefore the reliability curve of equipment with maintenance can be expressed as a curve shown in Fig. 2.

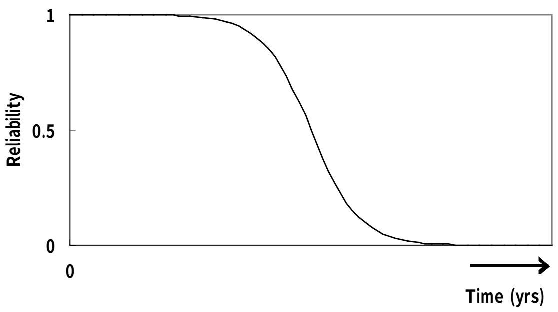

Fig. 1. Sample of the reliability curve of electrical equipment

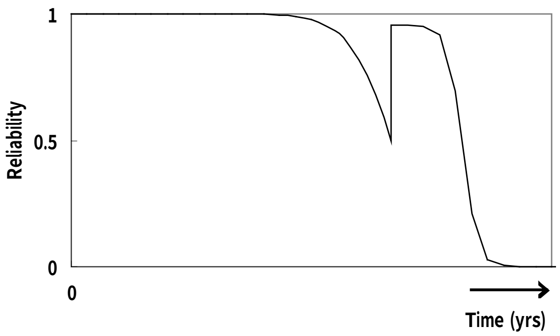

Fig. 2. Sample of the reliability curve of electrical equipment with maintenance

3.3 Plant Overall Reliability Curve

Integration of equipment reliability curves will become the reliability curve of the plant.

The integrated reliability of the equipment in a plant is determined from the multiplication of all the equipment reliabilities. Therefore, the plant reliability curve can be expressed as below.

$$RLBT_{Int} = RLBT_{E1} * RLBT_{E2} * \cdots * RLBT_{EN} \quad (3)$$

where,
$RRBT_{Eit}$: Reliability of the i th equipment
$RLBT_{Int}$: Integrated reliability of the plant

Failure rate is obtained from the curve and plant failure risk can be calculated as the expected value of the unplanned downtime cost.

$$FOR_{Plamt} = 1 - RLBT_{Intt} \quad (4)$$

$$ExUDC = UDC * FOR_{Plant} \quad (5)$$

where,
FOR_{Plant} : Forced outage rate of the plant
$ExUDC$: Expected value of unplanned downtime cost

When reliability curves are integrated, the risk of the plant shutdown depends on the reliability of the most unreliable equipment at the specific time. Therefore, integrated reliability of the plant is given as the minimum value of the plant equipment reliability at every time domain.

4. Chemical Plant Model

Chemical plant model introduced in this paper is a simplified monomer fluid plant. The model has three processes and one electrical system including two kinds of electrical equipment.

Fig. 3 shows the image of the introduced model.

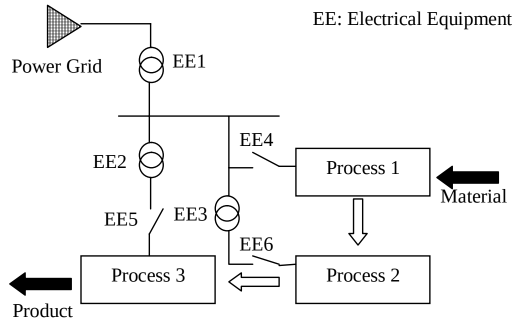

Fig. 3. Simplified chemical plant Model

Table 1 gives target electrical equipment description. The model plant has three transformers and three circuit breakers.

Table 1. Target electrical equipment

No	Name	Connecting Equipment 1 (Upstream)	Connecting Equipment 2 (Downstream)
EE1	Transformer 1	Power Grid	EE2, EE3, EE4
EE2	Transformer 2	EE1	EE5
EE3	Transformer 3	EE1	EE6
EE4	Circuit Breaker 1	EE1	Process 1
EE5	Circuit Breaker 2	EE2	Process 3
EE6	Circuit Breaker 3	EE3	Process 2

5. Application of Proposed Method

With the assumption of the product price, material cost, plant downtime length, and parts and labor cost for planned/unplanned maintenance, PDC will be obtained from (1) and UDC will be obtained from (2). Expected value of UDC, ExUDC in equation (5), gives the risk of costly failure damage.

Maintenance should be done to have some cost efficiency. When an extra maintenance is planned, its cost efficiency is depended on the total cost of the maintenances that have been already done.

Comparison of expected value of UDC at maintenance at time tm and sum of PDC at time tm can give a judgment for the cost efficiency of the maintenance as shown below.

$ExUDC > PDCsum$: Maintenance is done too little
$ExUDC < PDCsum$: Maintenance is done too often
$ExUDC = PDCsum$: Appropriate interval

where,
PDCsum: Sum of the maintenance cost already done

6. Assumptions of Simulation

6.1 Electrical Equipment Reliability

Shown in fig. 3 and table 1, the model plant has three transformers and three circuit breakers.

In this simulation, the reliability curve of each transformer is assumed to be the same curve and that of circuit breakers is also assumed to be the same.

All the target equipment in the plant is newly installed at time 0 of the simulation. Reliability of the j-th equipment is given by the sigmoid function expressed in the equation below and coefficients for the function are shown in Table 2.

$$RLBT_j(t) = \frac{1}{1+\exp(A(t-T_L))} \quad (6)$$

where
$RLBTj\ (t)$: Reliability of j-th equipment
A : Multiplier for reliability decreasing speed
T_L: Curve shaping coefficient

Table 2. Coefficients for sigmoid function

Equipment No.	Equipment Name	A	T_L
1	Transformer 1 (EE1)	1.25	15
2	Transformer 2 (EE2)	1.25	15
3	Transformer 3 (EE3)	1.25	15
4	Circuit Breaker 1 (EE4)	2.5	15
5	Circuit Breaker 2 (EE5)	2.5	15
6	Circuit Breaker 3 (EE6)	2.5	15

Target operation period is assumed to be 4 years. The reliability curve of transformers and circuit breakers is described in fig. 4 and 5 respectively. Picking up the lower value of reliability of equipment forms the plant reliability curve. The reliability curve of the plant is shown in fig. 6.

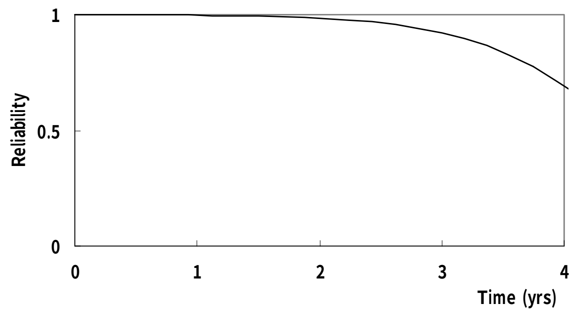

Fig. 4. Reliability curve of transformer

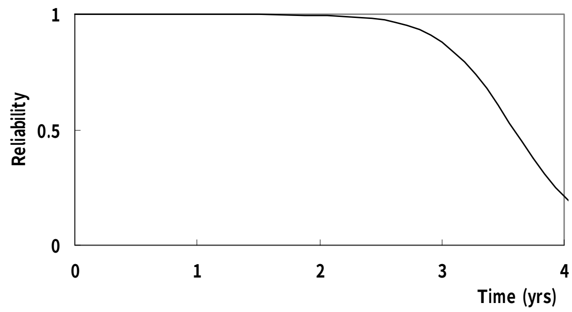

Fig. 5. Reliability curve of circuit breaker

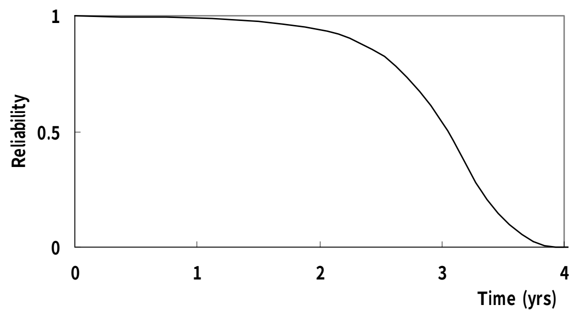

Fig. 6. Reliability curve of the plant

6.2 Plant Operation Cost and Product Price

Plant operation cost at normal state consists of the material cost, electrical cost, and operators' labor cost. Table 3 gives the assumptions of plant operation cost and the product price.

Table 3. Plant operation cost and product price

Item	Cost / Price ($/hour)
Material Cost	2400
Electrical Cost	100
Operators' Labor Cost	500
Product Price	6000

The opportunity cost of the plant downtime can be expressed the difference between the product price and operation cost. Recovery operation cost is set twice times as expensive as operators' labor cost of normal state.

6.3 Maintenance Cost

The maintenance cost consists of the maintenance staffs labor cost and the cost of spare parts for target equipment.

The maintenance staffs labor cost for planned maintenance is set $1000 per hour and the cost of spare parts for a transformer is set $3000, and that of a circuit breaker is set $1500. It is assumed that maintenance staffs stay and work at the plant during the downtime. The maintenance staffs labor cost of unplanned maintenance is set twice times as expensive as that of planned maintenance. The cost of spare parts is not changed regardless of planned or unplanned maintenance.

6.4 Plant Shutdown Condition

Each process will be stopped when any of electrical equipment is in failure. The remained material in case of plant shutdown is equal to the amount processed for one hour per process.

7. Numerical Examples

In planned maintenance, all the transformers and circuit breakers are maintained. Time for maintenance is set to eight hours. That means plant downtime for planned maintenance is twelve hours. Under this setting, PDC is $61500.

Table 4 shows the plant downtime and UDC. In this paper, four kinds of plant downtime for a failure are assumed.

Table 4. Plant Downtime and UDC

Plant Downtime (hrs)	UDC ($)
24	151200
36	223200
48	295200
72	439200

The first maintenance interval can be obtained from table 4 and fig. 6. The first interval is given as the point at which ExUDC becomes equal to PDC. Fig. 7 shows the ExUDC of the plant downtime domain. Fig. 7 also shows the PDC of the plant, and the first maintenance intervals of each plant downtime are shown as the cross point of PDC line and respective ExUDC curves.

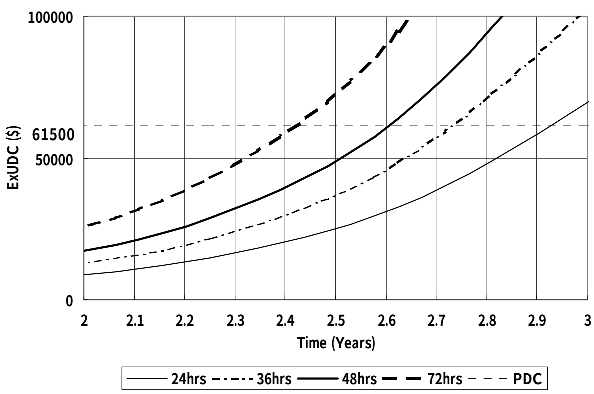

Fig. 7. Expected UDC of No-maintenance Case

Table 5 shows the first maintenance interval for assumed plant downtime. From table 5, it can be said that the plant having longer plant downtime needs earlier maintenance because the damage of plant shutdown is larger than the plant having shorter downtime.

Table 5. First maintenance interval

Plant Downtime (hrs)	Interval (years)
24	2.93
36	2.73
48	2.61
72	2.42

The second maintenance timing can be obtained as the point at which ExUDC becomes equal to PDC twice. Assumed that reliability decreasing speed of the plant becomes twice times as quick as newly install plant, the second maintenance timing in line with the reliability curve of the plant with maintenance can be obtained. The second maintenance timing and the interval between the first and second maintenance are shown in table 6.

Table 6. Second maintenance timing

Plant Downtime (hrs)	Timing (years)	Interval (years)
24	4.08	1.15
36	3.73	1.00
48	3.50	0.89
72	3.17	0.75

The third maintenance timing can be obtained as the point at the third time equality of ExUDC to PDC. The reliability curve of the plant should be with two maintenance executions.

Repeating this procedure can give the optimal maintenance interval in the target period.

8. Conclusion

A strategic maintenance interval decision scheme has been proposed and verified its efficiency by application to simple chemical plant model. Through the numerical examples, the relationship between optimal maintenance interval and plant downtime cost has been clarified.

Future studies include combination analysis of electrical equipment failure and plant operation status.

Further researches for lifetime of electrical equipment and equipment reliability are expected to improve the accuracy of the proposed approach.

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