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Time-delay concept-based approach to maintenance scheduling of HV cables

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Abstract: The associated daily maintenance effort and cost has been increasing with the growing use of high-voltage (HV) cable circuits. This study proposes a time-delay concept-based approach to maintenance scheduling of individual HV cable components, to allow periodicity of inspection to be optimised with consideration of time-delay interval between the instant of defect inception and final failure. Here, the progress from a defect to its resultant final failure can be represented as a two-stage process, one being a stochastic process of defect arrival and the other being a delay-time interval from defect to failure. Then an optimisation model is established to schedule maintenance activities based on the two statistical processes, where the objective function is set as the minimal maintenance cost. Cable circuits are divided into five components in accordance with the objects of inspection and testing. The components within different service ages are considered individually in the statistical models, and their accumulate failure numbers during each service year are used to automatically formulate and update periodicity of inspection. To illustrate the feasibility of the approach proposed, theoretical analysis on thousands of cable circuits are carried out. Results show that the economic expenditure could be reduced by 22.2% after optimisation.

1 Introduction

With the growing use of high-voltage (HV) cable circuits in urban power networks, potential cable failures are great threats to the operation of the power grid and may result in serious economic losses [1–3]. Preventive maintenance activities have been taken on a regular basis, such as inspection, online or offline testing, to ensure acceptable reliability of these essential assets [4–6]. By taking these pre-emptive actions, many defects and anomalies of cables can be located and eliminated prior to failure.

Maintenance management of HV cables around China is currently carried out at predetermined intervals, which is known as time-based maintenance [7, 8]. However, this maintenance scheduling without taking account of failure events in local networks through scientific analysis and reasoning may lead to a waste of large amounts of resources on unnecessary inspection and testing. The time-based maintenance fails to meet regulatory requirements that power utilities should make the best and most effective use of their expensive assets [9]. Recent research on the maintenance of electricity equipment included condition-based maintenance with expert knowledge or prescribed criteria [10–12]. Specifically, condition data of equipment monitored were assessed against subjective knowledge and criteria, before maintenance activities were scheduled. However for HV cables, condition monitoring and testing techniques have not been matured to allow reliable condition assessment criteria to be generated. As a result, further technological advancement will be required for condition-based maintenance to be effectively applied in practice, preferably with considerations of the following: (i) deviations between the results of assessment based on subjective expert knowledge and criteria and actual facts [13]; (ii) the causes contributed to cable failures vary due to manufacturing supplier, local climate conditions, installation methods etc., (iii) readily available failure and daily maintenance data have not been made use of to prevent similar future failures. According to the statistics of historical cable failure events, it takes time for a failure to develop from the instant when a defect exists, and the instant of the eventual failure, or when the cable asset becomes unable to provide normal service. This time interval gives an opportunity for the defect to be identified and eliminated prior to failure through daily inspection

and testing. In maintenance engineering, the interval between the instant of defect inception and the final failure is called time delay [14]. The concept of the time delay has successfully been applied to industrial maintenance problems. Scholars analysed the expected number of equipment failures under different maintenance intervals, and established multi-objective functions to determine the equipment maintenance periodicity in different situations [15–18]. However, the time-delay theory has only been used to optimise inspection schemes for a single device, and has not yet been applied to equipment which is composed of many components, such is the case for a cable system.

The present paper develops a time-delay concept-based approach to maintenance scheduling of individual HV cable components. In Section 2, the failure of a cable is represented as a random process that satisfies the statistical law based on the time-delay theory. In Section 3, a cable asset maintenance scheduling model is provided based on economic analysis. Periodicity of inspection of cable circuit components (cable conduit, cable terminations, joints, main bodies and the earthing systems) within different service ages are considered individually. Section 4 implements the proposed approach in a case study with data taken from a power network in southern China, to demonstrate the effectiveness of the proposed optimal maintenance scheduling model. Section 5 provides conclusions on the work and discusses future research opportunities.

2 Time-delay-based cable failure modelling

Due to factors such as the design, manufacturing, installation and environmental issues, a defect may occur any time, and it could eventually cause failure under various stresses while the cable is in operation [19]. Based on the time-delay concept, the progress of a cable failure can be regarded as a two-stage process, one being a stochastic process of defect arrival and the other being a time-delay interval from defect to failure, which can be expressed by a specific distribution statistically, hence a mathematical model for cable failure number prediction can be set up as follows. The estimation of cable failures under different inspection periods can be obtained.
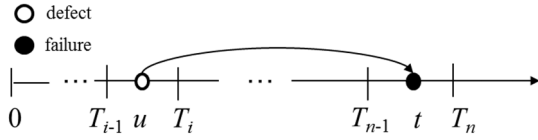
Fig. 1 *Development of a failure due to the defect occurring during (T_{i-1}, T_i)*

2.1 Process modelling and estimation of the number of cable failures

The occurrence of a defect and the process between the defect inception and the resultant failure can be considered as two independent random events. The probability of a cable failure caused by a defect is the product of the probabilities of the two incidents:

(i) The probability of defects occurring during a period of time is consistent with the nature of the Poisson distribution. The Poisson distribution is often adopted to describe a number of random events during a unit time (or space). Therefore, the probability of a number of cable defects arising within a certain period of time can be regarded as obeying the Poisson distribution $P(\alpha)$, given in (1):

$$P(X = k) = \frac{\alpha^k}{k!}e^{-\alpha}, \quad k = 0, 1, \dots \quad (1)$$

Here $P(X = k)$ represents the probability of cable defects occurring k times per unit time, where the parameter α is the rate of the occurrence of defects, which represents the average number of defects occurring per unit time.
(ii) Under the electrical, thermal and mechanical stresses, a defect eventually develops into a cable failure. Assume that the process takes a duration of h, which follows an exponential distribution [18, 20]. The exponential distribution is a probability distribution that describes the time between events in a Poisson process:

$$f(h) = \lambda e^{-\lambda h} \quad (2)$$

where λ is the time-delay parameter, and the inverse of λ represents the average time required for a defect to develop into a failure.

During the process of a cable failure, the original defect can be eliminated before it develops into a failure. However, the effectiveness of inspection and testing in practice is imperfect, or not all defects can be identified and eliminated, and part of them will eventually develop into failures consequently. The ratio or percentage of defects that can be detected through inspection is noted as β. Here, according to practical experiences, it is assumed that 65% of the defects can be eliminated during routine inspection and testing [21], or $\beta = 0.65$.

Take the time axis of the cable failure development process as an example, as shown in Fig. 1. The entire time axis can be divided into n periods according to the periodicity of inspection T. When a defect occurs in a certain time window u between the $(i-1)$th inspection and the ith inspection, or $T_{i-1} < u < T_i$. The defect has undergone $n-i$ times of inspections and none have been found and eliminated. However, the failure caused by the defect occurs at time instant t after the $(n-1)$th inspection, $T_{n-1} < t < T_n$. By using the time-delay model $f(h)$, when a defect occurs at time u, and the probability $p(t|u)$ of the defect that develops into failure at time t is given in (3):

$$p(t|u) =$$

$$\begin{cases} (1 - \beta)^{n-i} f(t-u), & T_{i-1} < u < T_i, \ i = 1, 2, \dots, n-1 \\ f(t-u), & T_{n-1} < u < t \\ 0, & u > t \end{cases} \quad (3)$$

Considering that the occurrence of a defect and the process between defect inception and the resultant failure are independent random events, based on the rate of the occurrence of defect α, the failure rate $v(t)$ is shown in (4). $v(t)$ represents the predicted number of failures occurring to all the five components of a local cable system per day:

$$v(t) = \alpha \int_0^t p(t|u)du$$
$$= \alpha \left\{ \sum_{i=1}^n (1-\beta)^{n-i} (F(t - T_{i-1}) - F(t - T_i)) + F(t - T_{n-1}) \right\} \quad (4)$$

We then need to study the asymptotic behaviour of the failure process, assuming that the number of inspections over a group of cable circuits is very large, let $n = \infty$, and for $F(h) = 1 - e^{-\lambda h}$, $T_i - T_{i-1} = T$, $v(t)$ is given by (5):

$$v(t) = \alpha \left[1 - \frac{\beta e^{-\lambda t} e^{\lambda T}}{e^{\lambda T} - (1 - \beta)} \right] \quad (5)$$

Given the failure rate $v(t)$, combined with the occurrence of cable defects that satisfy the Poisson distribution $P(\alpha)$, it can be known that the occurrence of a cable failure event satisfies the non-homogeneous Poisson process (NHPP). Therefore, the probability of m failures occurring during (t_{i-1}, t_i) is given in (6):

$$P(X_i = m) = \frac{\left(\int_{t_{i-1}}^{t_i} v(t)dt \right)^m}{m!} \exp\left(- \int_{t_{i-1}}^{t_i} v(t)dt \right) \quad (6)$$

According to (5), it can be known that the probability of a failure occurrence is related to the periodicity of inspection T, and the expected number of failures per inspection period T is $E_N(T)$:

$$E_N(T) = \int_0^T v(t) \, dt = \alpha \int_0^T 1 - \frac{\beta e^{-\lambda t} e^{\lambda T}}{e^{\lambda T} - (1 - \beta)} dt = \alpha T$$
$$- \frac{\alpha \beta (e^{\lambda T} - 1)}{\lambda (e^{\lambda T} - (1 - \beta))} \quad (7)$$

The expected cumulative failures in 1 year can be obtained as $D_N(T)$:

$$D_N(T) = E_N(T) \frac{Y}{T} = \alpha Y - \frac{\alpha \beta (e^{\lambda T} - 1) Y}{\lambda (e^{\lambda T} - (1 - \beta)) T} \quad (8)$$

2.2 Estimation of the model parameters

The historical failure and time of inspections are required when the maximum likelihood estimation method is used to solve the parameter λ and the defect occurrence rate α in the time-delay distribution function. The likelihood function L is the product of the probability of a failure arising at time instants recorded in historical failure events and the probability of having no other failures between the recorded failures, shown as

$$L(\alpha, \lambda | \tau_k, T_l) = \prod_{k=1}^{FN} [p(A_k)] \prod_{l=1}^n p(B_l) \quad (9)$$

where $p(A_k)$ is the probability of failure at time τ_k, τ_k is the time of the kth failure recorded in chronological order, FN is the total number of historical failure records and T_l is the time instant of the lth inspection. $p(B_l)$ is the probability that no other failure will occur between failure events recorded within (T_{l-1}, T_l).

According to (6), the cable failure event is expressed by NHPP. So, for sufficiently small Δt, the probability of a failure arising in the time interval $(t, t + \Delta t)$ is shown in (10):

$$p(X = 1) = \int_{t}^{t+\Delta t} v(t)\mathrm{d}t = v(t)\Delta t \tag{10}$$

Then according to the failure data τ_k, the probability of failure at time τ_k, $p(A_k)$, can be obtained as

$$p(A_k) = \int_{\tau_k}^{\tau_k + \Delta t} v(t)\mathrm{d}t / \Delta t = v(\tau_k) \tag{11}$$

Also according to (6), the probability of no failure recurrence ($m = 0$) between each recorded failure τ_k is shown in (12):

$$p(X_k = 0) = \exp\left(-\int_{\tau_{k-1}}^{\tau_k} v(t)\mathrm{d}t\right) \tag{12}$$

Suppose that the number of failures recorded during (T_{l-1}, T_l) is k_l $_{-1}$, then the probability $p(B_l)$ of no other failure recurrence between each recorded fault event during (T_{l-1}, T_l) is shown in (13), where $\tau_{(l-1)q}$ represents the instant of occurrence of the qth failure recorded during (T_{l-1}, T_l):

$$\begin{aligned} p(B_l) &= \exp\left(-\sum_{q=1}^{k_{l-1}} \int_{\tau_{(l-1)(q-1)}}^{\tau_{(l-1)q}} v(t)\mathrm{d}t - \int_{\tau_{(l-1)k_{l-1}}}^{T_l} v(t)\mathrm{d}t\right) \\ &= \exp\left(-\int_{T_{l-1}}^{T_l} v(t)\mathrm{d}t\right) \end{aligned} \tag{13}$$

According to (9), (11) and (13), the likelihood function L can be obtained with the failure time τ_k and the historical time of T_l. Then take natural logarithms on both sides of the likelihood function as shown in (14). By setting the partial derivatives of $\ln L$ with respect to λ and α equal to 0, respectively, the estimated values of the parameters λ and α can be obtained as (see (14)) . Here, the chi-square goodness-of-fit test was used to test whether the theoretical calculation result of the statistical model is significantly different from the actual failure data. If not, the statistical model can be considered as having fit the data well and can be accepted.

2.3 Modelling of cable failures without the concept of time delay

When the time-delay model is adopted, both the frequency of failures and the time delay when the defect develops into a failure are considered. Here the model of estimated failure number with consideration of time delay is compared with the model without. According to the previous work of the present authors [22], the model ignoring the time delay is shown in (15):

$$m_{hT} = \frac{(1-\beta)\left[1 - (1-\beta)^{Y/T}\right]kT}{\beta} \tag{15}$$

m_{hT} is the expected cumulative number of failures in 1 year according to the model without considering time delay. β is also noted as the rate of defects that can be detected through inspection. k is the rate of failure, T is the periodicity of inspection and Y represents 1 year.

To compare the two models numerically, a set of practical failure data collected from a metropolitan city in southern China was used as an example: 400 cable circuits and the inspection period T is 100 days. It is assumed that 25 failures occurred within 1 year.
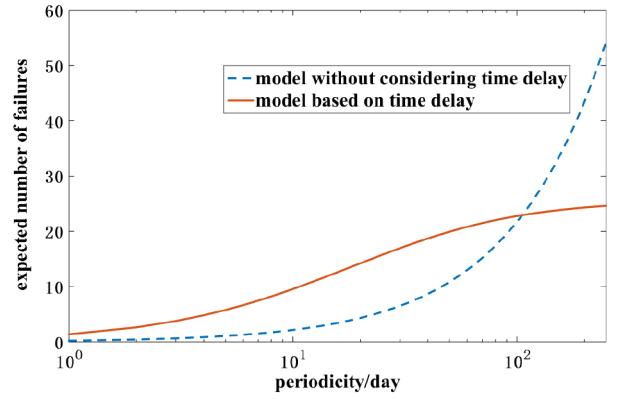

Fig. 2 *Expected number of failures with and without considering the time delay*

The expected number of failures under different periodicity of inspection is calculated using the two models separately. The result is shown in Fig. 2. It can be seen that when the time delay was not considered, the role of the inspection was exaggerated. The number of cable failures increased sharply as the number of inspections decreased, which obviously does not agree with the actual situation. In fact, it takes a certain period of time for the defect to develop into a failure. When the periodicity of inspection is shorter than the interval, the effect of inspection and maintenance becomes obvious (the number of failures is significantly reduced). Specifically, when applying the model based on the time-delay concept, the time-delay parameter λ was set to 0.0543, meaning that the average time required for a defect to develop into a failure is 18 days (1/0.0543), the defect occurrence rate was 0.0718 in this case. Therefore, when the periodicity of the inspection was <18 days, the number of failures would change significantly. Conversely, when the periodicity of the inspection was longer than the time delay, the defect could not be eliminated in time and it would develop into a failure consequently. So as the periodicity increased from 18 days, the number of predicted failures gradually stabilised (it is because that most defects have developed into failures).

Therefore, with the time-delay model, the periodicity of inspection can be scheduled optimally, so as to avoid unnecessary inspection and manpower to be wasted on maintenance.

3 Maintenance scheduling based on time-delay failure model

An approach to maintenance scheduling of HV cable system needs to consider the following two factors:

(i) A cable system failure event may be caused (triggered) by the failure of an individual component. From a practitioner's perspective, cable circuits can be divided into cable conduit, cable terminations, joints, main bodies and earthing systems, for this facilitates inspections and testing.
(ii) On the other hand, a failure may occur at any time instant of its life cycle, depending on its causes and operational stresses [22]. It is known that failure rate curves over the life cycle of most equipment are bathtub shaped. Similarly, cable failure behaviour follows the shape and varies with service age. So the development of failures in different service age is considered individually.

Therefore, in daily inspection management, it is necessary to develop differentiated maintenance activities for different components with different service age.

$$\begin{aligned} \ln L(\alpha, \lambda \,|\, \tau_k, T_l) &= \ln\left[\prod_{k=1}^{FN} v(\tau_k)\exp\left(-\int_0^{T_n} v(t)\mathrm{d}t\right)\right] \\ &= \sum_{k=1}^{FN} \ln\left[\alpha - \frac{\alpha\beta e^{\lambda\tau_k}e^{-\lambda T_0}}{1 - (1-\beta)e^{-\lambda T_0}}\right] - \alpha T_n + \frac{\alpha\beta\left(e^{\lambda T_0} - e^{-\lambda(T_n - T_0)}\right)}{e^{\lambda T_0} - (1-\beta)} \end{aligned} \tag{14}$$

3.1 Expected number of component failures with different service age

Firstly, cable circuits are grouped separately according to the service age. The parameter λ_i of time delay and the occurrence rate of defects α_i for different service age i are estimated separately by (14). Then failure criticality index based on certain system characteristics of interest (failure) is adopted, which is the contribution of individual components to a system failure occurrence [23]. Failure criticality index of each cable component is shown in (16):

$$\gamma_{ij} = \frac{n_j(i)}{\text{FN}(i)}, \quad j = 1, 2, 3, 4, 5 \tag{16}$$

Among them, j denotes 1–5, respectively, cable main bodies, joints, terminations, earthing systems and conduit; γ_{ij} represents the failure index of the cable components of type j that have been on service for i years, and $n_j(i)$ is the number of cable failures caused by components of type j that have been in service for i years; $\text{FN}(i)$ represents the total number of cable failures with i years of service.

According to (7) and (8) in Section 2, a cumulative number of failures of each cable component with different service years is expected to be as shown in (17) combined with γ_{ij}:

$$D_{N_i}(T_{ij}) = \gamma_{ij} E(T_{ij}) \frac{Y}{T_{ij}} = \gamma_{ij} \alpha_i Y - \frac{\gamma_{ij} \alpha_i \beta_i \left(e^{\lambda_i T_{ij}} - 1\right) Y}{\lambda_i \left(e^{\lambda T_{ij}} - (1 - \beta_i)\right) T_{ij}} \tag{17}$$

i denotes the service age of a cable circuit, and $D_{Ni}(T_{ij})$ is the expected number of accumulated failures of a component of type j with a service age of i years, under the periodicity of inspection T_{ij}. It can be known that the cumulative number of failures expected in 1 year of cable components is related to the periodicity of inspection T_{ij}, then optimised inspection and maintenance schedule can effectively reduce cable failure events.

3.2 Analysis of maintenance cost

The overall cost of the HV cable maintenance includes failure loss, daily inspection and test cost. Had the periodicity of maintenance increased, the daily inspection and test cost would be reduced, but the failure loss would increase with the increasing number of failures. With the aim of improving the economic benefits, it is necessary to optimise the periodicity T to balance the failure loss and daily inspection costs, as shown in Fig. 3.

Specifically, the failure loss covers the power outage loss C_f, equipment replacement cost C_c, and expenditure C_r for outsourced personnel and construction work during the installation.

Power outage loss C_f is evaluated from (18). Relevant data parameters are obtained by survey methods [24, 25], including repairing time t, amount of power supply p and unit power price n:

Fig. 3 *Analysis of relationship between cable outage and maintenance cost and inspection cycle*

$$C_f = p \cdot t \cdot n \tag{18}$$

Equipment replacement cost C_c, which is the purchase cost of different cable components, is based on quotes from cable manufacturers. Expenditure C_r is evaluated based on the experience of maintenance engineers.

The daily cable inspection and test cost are mainly labour cost C_m, evaluated by wages of workers shown in (19):

$$C_m = q \cdot x_m \cdot L_T \tag{19}$$

Here, q represents the salary payment to workers, yuan/(per hour, per person); x_m represents the number of workers required for each circuit each time; L_T is the average time required for inspection of each circuit, the unit is an hour.

With the total cost of outage and maintenance as the objective function, the optimisation of the inspection period for each component of the cable circuit is established as shown in (20). When the total cost of outage and maintenance management is the lowest per inspection period in 1 year, the corresponding inspection period then represents the optimal result:

$$\min \sum_i \sum_{j=1}^5 D_{N_i}(T_{ij})(C_f + C_r + C_c) + N_i \frac{Y}{T_{ij}} C_m \tag{20}$$

The number of accumulated cable failures in 1 year is $D_N(T)$; N represents the total number of circuits and Y represents a period of 1 year.

4 Case study

China Southern Power Grid Corporation has commissioned a large number of HV cables in recent years [26]. The cable circuits at the 110 kV level and above commissioned over the last 5 years reached a total of 2578 km, and the number of circuits stood at more than one thousand. As the cable population is still relatively young, there has, as yet, been no sign of age-related failures. Seventy-eight failure cases with different service ages of 0–5 years have been collected. In order to demonstrate the proposed optimal maintenance scheduling model in practical situations, a group of 1065 HV circuits (service age within 5 years) from China Southern Power Grid Corporation have been selected in the case study.

4.1 Application of the maintenance scheduling model based on time-delay concept

The number of failures of cable components classified by service age within 5 years is shown in Table 1. According to 'Detailed Implementation Rules for Transmission Line Operation and Maintenance Strategy' [10] and daily inspection records, the average daily inspection periodicity for HV cables is 4 months.

According to (16) and historical failure data of each component in Table 1, the failure criticality index γ_{ij} of each component with different service years is shown in Table 2. Clearly, the failure index of the cable joints and terminations and conduits are significantly higher than other components.

The first step was to substitute the historical failure time τ_k of the cable in each of the service years and the historical inspection period T_0 into (14). Matlab programming was used to estimate the parameters required. The estimated results that include defect occurrence rate α_i and time-delay parameter λ_i are shown in Table 3. It can be known that as the cable service age increases, the time-delay parameter λ of the failure gradually decreases. In other words, the corresponding average time for defect developing into failure gradually increases. The occurrence rate of defects α is related to the number of failures in each of the service years. The greater the number of cable failures, the higher the occurrence rate of defects. Then using (17) with parameters related to cable circuits, the cumulative expected number of failures of cable components in every year of service age with a different periodicity of inspection was obtained.
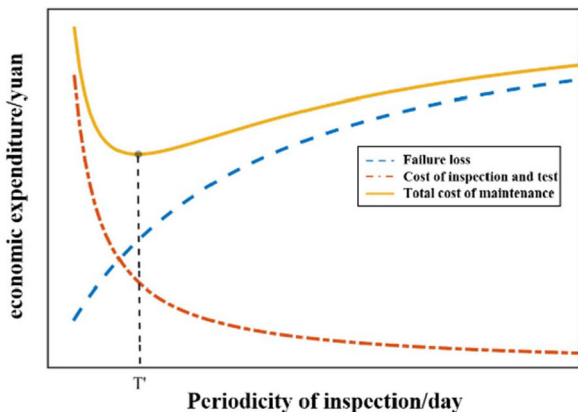
Table 1 Cable circuits data and failure sample data

| Service time/year | Number of failures of cable components | | | | | total |
	Body	Joint	Termination	Earthing	Conduit	
0–1	2	10	7	2	5	26
1–2	0	9	3	0	4	17
2–3	0	7	0	1	9	17
3–4	2	0	1	0	3	6
4–5	1	3	3	1	4	12

Table 2 Failure criticality index of different components of cable circuits

Service time/year	Body	Joint	Termination	Earthing	Conduit
0–1	0.077	0.385	0.269	0.077	0.192
1–2	0.000	0.529	0.176	0.000	0.235
2–3	0.000	0.412	0.000	0.059	0.529
3–4	0.333	0.000	0.167	0.000	0.500
4–5	0.083	0.250	0.250	0.083	0.333

Table 3 Estimation of parameters

Service time/year	Number of past failure events	Parameter of delay-time of defect, λ	The rate of occurrence of defects, α
0–1	26	0.1438	0.0691
1–2	17	0.0553	0.0467
2–3	17	0.0291	0.0466
3–4	6	0.0195	0.0164
4–5	12	0.0140	0.0329

Table 4 Details of the total maintenance cost

Category	Detail of cost	Value
loss of electricity C_f	average unplanned interruption time (t): 48 h, power outage cost (n): 0.565 ¥/kWh; average hourly power consumption: 49,500 kWh	about ¥1.34 million（= 48 × 0.565 × 49,500）
cost of repair and installation C_r	cost of external staff and mechanical equipment	about ¥50,000
cost of replacement C_c	average length of cable needed to be replaced is about 50 m for a single failure, cost of cable and conduit construction is 1000 and ¥4000 /m, respectively; ¥75,000 per joint; ¥65,000 per termination	main body: about ¥250,000 joint: about ¥275,000 termination: about ¥275,000 earthing system: about ¥30,000 conduit: ¥200,000
cost inspection and test C_m	inspection for one circuit requires two workers, and the average working time is 3 h. The pay is about ¥50 /(person·hour)	about ¥300/ time

Table 5 Comparison between periodicity of maintenance before and after optimisation for components of circuits with different age

| Service time/year | Body | | Joint | | Termination | | Earthing | | Conduit | |
	Before	After	Before	After	Before	After	Before	After	Before	After
0–1	120	180	120	12	120	180	120	120	14	30
1–2	120	180	120	9	120	28	120	120	14	21
2–3	120	180	120	12	120	180	120	120	14	12
3–4	120	18	120	180	120	32	120	120	14	16
4–5	120	48	120	22	120	24	120	58	14	21

Based on the maintenance scheduling model proposed in Section 3, the aim of the optimal maintenance was to minimise the total maintenance cost in 1 year, or the year under consideration. The breakdown of total maintenance cost is given in Table 4. In order to ensure the reliable operation of the cable, the cable main body and accessories should be inspected at least once every 6 months, and the conduit is inspected at least once a month, which are used as constraints in (21). Applying (21) to cable circuits and components selected, the rescheduled periodicity of maintenance can be obtained. This is given in Table 5:

$$\min \sum_i \sum_{j=1}^{5} \gamma_{ij} D_{N_i}(T_{ij})(C_f + C_r + C_c) + N_i \frac{Y}{T_{ij}} C_m \tag{21}$$

$$\text{s.t. } T_{i1} \leq 180;\ T_{i2} \leq 180;\ T_{i3} \leq 180;\ T_{i4} \leq 120;\ T_{i5} \leq 30$$

where T_{i1} to T_{i5} are periodicities of inspection of main bodies, joints, terminations, earthing systems and conduits, respectively.

Table 6 Number of cable failures estimated after optimisation

Service time/year	Body	Joint	Termination	Earthing	Conduit	Total
0–1	1.9	6.6	6.7	1.9	4.2	21.4
1–2	0.0	3.1	1.9	0.0	2.3	7.3
2–3	0.0	1.9	0.0	0.8	2.4	5.1
3–4	0.5	0.0	0.4	0.0	0.7	1.6
4–5	0.4	0.7	0.8	0.5	0.9	3.3
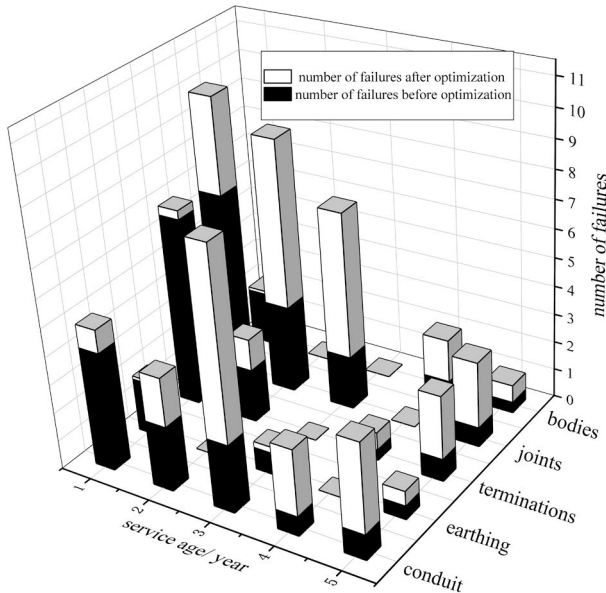
Fig. 4 *Number of failures before and after optimisation*

4.2 Observations and discussions

Table 5 gives a comparison of the periodicity of maintenance for different cable components before and after optimisation. The present schedule of maintenance performs an average inspection of the cable conduit once every 2 weeks (14 days), and an average inspection and test of the remaining cable components every 4 months (120 days). By the optimal approach proposed, the periodicity of maintenance for cable components of different service years can be scheduled individually. In this way, the cumulative expected number of cable failures with different service age is shown in Table 6, as well as illustrated in Fig. 4 with the contrast of results before rescheduling. The total estimated number of failures for cable circuits collected can be reduced to 39 theoretically, as the optimised approach effectively eliminates some cable defects prior to failure. It can also be seen that the effect of inspection of cable components in 0–1 year was not as obvious as that of 1–5 years, the total number of failures in 0–1 year was just reduced from 26 to 22. The parameter of delay time of defect λ in 0–1 year was obviously higher than all others, and the corresponding average time for a defect developing into the failure was too short to eliminate it.

By applying the time-delay concept, manpower and resources wasted on unnecessary maintenance activities can be avoided. The saving stands at 81.934 million yuan, representing a reduction of 22.22% on previous operation and maintenance cost of ¥10,534,500, which greatly improves the economic efficiency of the maintenance management for HV cable.

5 Conclusion

An optimal maintenance scheduling model based on the time-delay concept is proposed in this paper. The progress of cable failure is regarded as a random event that satisfies the statistical law, based on which the process representing cable failures is established. Then, based on the time delay and the estimated number of future failure events, the periodicity of inspection for different cable components can be optimised with the aim of minimal outage maintenance costs.

The result of the theoretical analysis showed that the economic efficiency of maintenance management can be greatly improved. The periodicity of inspection based on the delay time interval can help avoid unnecessary inspection and manpower to be wasted on maintenance, compared with the model ignoring the time delay.

When contrasted with the existing practice of maintenance strategy, the proposed approach does not rely on human expertise to assess the condition data. Instead, the proposed method takes historical failure events data as input, and the maintenance activities can be scheduled automatically when the failure data becomes available. It can also be updated on a regular basis as failure data changes.

Limited by the number of samples, no analysis calculations were performed for HV cables with a long running time. The life cycle and replacement for elder cables need to be considered in subsequent studies.

6 References

[1] Zhou, Y., Zhao, J., Liu, R., *et al.*: 'Key technical analysis and prospect of high voltage and extra-high voltage power cable', *High Volt. Eng.*, 2014, **40**, (9), pp. 2593–2612 (in Chinese)

[2] Zhang, Z., Zhao, J., Zhao, W., *et al.*: 'Influence of morphological variations on the AC breakdown of XLPE insulation in submarine cable factory joints', *High Volt.*, 2020, **5**, (1), pp. 69–75

[3] Li, M., Zhou, C., Zhou, W., *et al.*: 'Feasibility study on lengthening the high-voltage cable section and reducing the number of cable joints via alternative bonding methods', *High Volt.*, 2019, **4**, (4), pp. 292–299

[4] Zhou, C., Yi, H., Dong, X.: 'Review of recent research towards power cable life cycle management', *High Volt.*, 2018, **2**, (3), pp. 179–187

[5] Sheng, B., Zhou, W., Yu, J., *et al.*: 'On-line PD detection and localization in cross-bonded HV cable systems', *IEEE Trans. Dielectr. Electr. Insul.*, 2014, **21**, (5), pp. 2217–2224

[6] Gulski, E., Smit, J.J., Seitz, P.N., *et al.*: 'On-site PD diagnosis of power cables using oscillatory wave test'. IET Int. Symp. on High Voltage Engineering, London, UK, August 1999, pp. 5112–5115

[7] Q/GDW 171−2008: 'Guide for condition evaluation of power equipment', 2008 (in Chinese)

[8] Guangdong Power Grid Corporation: 'Implementation rules of operation and maintenance strategy and control mechanism of transmission lines', 2018 (in Chinese)

[9] ISO 55000: 'Asset management – overview, principles and terminology', 2014

[10] Liang, M., Li, X.: 'Cable risk prediction model based on fuzzy theory', *Sichuan Electr. Power Technol.*, 2015, **38**, (6), pp. 5–8 (in Chinese)

[11] Xia, X., Zhang, Q, Li, M., *et al.*: 'Research on insulation assessment of XLPE cables based on evidence and fuzzy theory integrated method', *Power Syst. Protection Control*, 2014, **42**, (20), pp. 13–18 (in Chinese)

[12] Zhang, P., Qi, P., Li, W., *et al.*: 'Differentiated evaluation method of transformer considering the part and its performance', *Proc. CSEE*, 2019, **39**, (20), pp. 6138–6147

[13] Zhou, C., Li, M., Wang, H., *et al.*: 'Review of condition assessment and maintenance strategy of power cable assets', *High Volt. Eng.*, 2016, **42**, (8), pp. 2521–2530 (in Chinese)

[14] Christer, A.H.: 'Yield management ‖ developments in delay time analysis for modelling plant maintenance', *J. Oper. Res. Soc.*, 1999, **50**, (11), pp. 1120–1137

[15] Christer, A.H.: '*A review of delay time analysis for modelling plant maintenance//stochastic models in reliability and maintenance*' (Springer, Berlin, Heidelberg, 2002)

[16] Christer, A.H.: 'The robustness of the semi-Markov and delay time single-component inspection models to the Markov assumption'. *IMA J. Manag. Math.*, 2001, **12**, (1), pp. 75–88

[17] Zhao, J., Chan, A.H.C., Roberts, C., *et al.*: 'Reliability evaluation and optimization of imperfect inspections for a component with muti-defects', *Reliab. Eng. Syst. Safe.*, 2007, **92**, pp. 65–73

[18] Lv, W., Zheng, R.: 'The delay-time-based inspection models and their comparison', *J. Manage. Sci.*, 2007, **20**, (1), pp. 18–21

[19] Tang, Z., Zhou, C., Jiang, W., *et al.*: 'Analysis of significant factors on cable failure using the Cox proportional hazard model', *IEEE Trans. Power Del.*, 2014, **29**, (2), pp. 951–957

[20] Wang, W.: 'An overview of the recent advances in delay-time-based maintenance modelling', *Reliab. Eng. Syst. Safe.*, 2012, **106**, pp. 165–178

[21] Sachan, S., Zhou, C., Bevan, G.*, et al.*: 'Stochastic dynamic programming approach for proactive replacement of power cables'. 24th Int. Conf. on Electricity Distribution, Helsinki, Finland, June 2016

[22] Liao, Y., Liu, H., Yuan, J.*, et al.*: 'A holistic approach to risk based maintenance scheduling for HV cables', *IEEE Access*, 2019, **7**, (1), pp: pp. 118975–118985

[23] Wang, W., Loman, J., Vassiliou, P.: 'Reliability importance of components in a complex system'. Reliability and Maintainability Symp., LA, USA, January 2004

[24] Wang, C., Xu, Z., Pan, W.*, et al.*: 'Customer interruption costs investigation method for China', *Power Syst. Technol.*, 2007, **31**, (11), pp. 58–62. (in Chinese)

[25] Li, Z., Liu, Z., Ji, X.*, et al.*: 'Evaluation on blackout-caused social loss based on social public security model', *Power Syst. Technol.*, 2014, **38**, (11), pp. 2964–2971. (in Chinese)

[26] Yu, C., Wei, Z., Zhou, X.*, et al.*: '*China electric power yearbook*' (China Electric Power Press, Beijing, China, 2018) (in Chinese)