Optimization of Inspection Plan for Transformer Verification Line Under Uninterrupted State

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Abstract. At present, transformer verification line of metering centre adopts fixed cycle inspection method manually. This method requires downtime for detection, which costs a lot of time and cost. Moreover, the inspection cycle is determined based on experience and lacks rigorous basis. To solve this problem, a hybrid delivery of inspection devices is proposed to realize non-stop detection and reduce the cost of inspection time. Considering impact of cost and false detection risk on inspection cycle, a multi-objective optimization model of inspection cycle based on inspection and false detection cost is proposed. Based on NSGA-II algorithm, perturbation population is introduced to enhance the global search ability, which aims to minimize the cost of inspection and false detection. Taking the verification line’s inspection plan of the metering centre as an example. It is solved by ENSGA-II algorithm, and feasibility of hybrid delivery mode is verified, which reduced downtime by 14.58%. A more reasonable inspection cycle is obtained, inspection cost is reduced by 29.57%, and false detection cost is reduced by 6.34%. It provides a reference for the formulation of inspection plan in the actual production process.

1. Introduction
Since 2010, the State Grid Corporation of China has vigorously promoted the construction of low-voltage current transformer verification line. At present, 27 provinces and cities have built low-voltage current transformer verification line [1,2]. The health status monitoring of verification line mainly depends on inspection. The inspection is regular or quantitative [3]. However, with the rapid growth of power demand in recent years, the long-term full load operation of the verification line makes the health status of equipment change rapidly [4], improving monitoring quality and adopting a more flexible inspection method has gradually attracted attention.

Reasonable formulation of the inspection plan can reduce inspection cost and false detection cost. Aiming at the problem of inspection plan, Jingshu Liu proposed variable control inspection method and applied to the inspection of electric energy measurement standard equipment. The inspection cycle and frequency are considered in the proposed inspection method, but these are still based on the status of verified equipments and the experience of metering personnel [5]. Bo Gao studied the monitoring method of the three-phase watt hour meter verification line, and proposed a monitoring method combining inspection and verification. Where inspection cycle adjust appropriately according to the
number of tasks and the stability of equipment [6]. Libin Wang integrated the reliability and importance of equipment, proposed the concept of maintenance priority coefficient. And an optimal maintenance frequency model of verification line equipment based on the maintenance priority coefficient was established [7].

On the inspection issue of verification line, fewer personnel in the power measurement industry have studied the inspection cycle in the process of inspection. However, it has not been found to study the inspection problem from the delivery mode, delivery quantity and experimental times of the inspection device. Based on the analysis of the verification line’s workflow, a hybrid delivery strategy of putting the inspection device and transformer into the line together is proposed. The model with optimization objectives of inspection cost and false detection cost is established. And solved by NSGA-II algorithm (ENSGA-II) with disturbance population.

2. Problem description and related strategy

2.1. Problem description
The body of low-voltage current transformer verification line is composed of a series of standard devices. Under long-term full load operation, the standard devices will have different degrees of faults [8]. Failure of standard device will lead to false detection. In order to monitor the health status of the line, the method of inspection is generally adopted. The inspection task brings costs. In the process of inspection, if it is found that the health status of the equipment does not meet the requirements, it is necessary to recover all the inspected transformers between this inspection and the last inspection, and re-verify them after the problems are eliminated. This process will produce recovery, re-inspection costs and maintenance costs. The composition of cost is shown in Figure 1.

![Figure 1. Composition of the inspection cost](image)

Cost in the optimization problem of inspection plan is affected by cycle, quantity and experiment times of inspection devices. Short inspection cycle can reduce the probability of false detection, but the inspection cost will increase. Therefore, the inspection plan optimization problem aims to minimize various costs and study the impact of the above factors.

2.2. Hybrid delivery strategy
Traditional inspection method manually put the inspection device into each warehouse for experiment after shutdown. In this case, when a multi-functional verification warehouse performs inspection tasks, the other multi-functional verification warehouses are affected and generally do not work. In order to reduce the impact of daily tasks, an inspection device with higher accuracy is developed according to relevant verification regulations, which accuracy level is 0.05s. The hybrid delivery strategy as shown in Figure 2 is proposed.
In the hybrid delivery strategy, after inspection device information is entered into the system, loading is completed by the manipulator together with the transformer. On the verification line, the inspection device enters each multi-functional verification warehouse in turn, and the other processes are the same as transformer. In the hybrid delivery scheme, it is not necessary to stop the normal task. It is only necessary to obtain the experimental data of inspection device and draw the quality control chart to meet the needs of line health status evaluation.

3. Optimization model of inspection plan

The inspection plan optimization model improves the inspection scheme at the level of production plan formulation, so as to reduce the impact on normal tasks and various costs without reducing the monitoring quality.

3.1. Assumptions

Based on above analysis, the basic assumptions of the model are as follows.

- verification/inspection time of transformers with different ratios is the same
- at the same time, a multi-functional verification warehouse can only verify the same batch of transformers
- in the process of verification/inspection, the time for the transformer/inspection device to enter and leave the station shall be considered within the transportation time
- inspection cannot be interrupted, and the inspection device can enter any station in any multi-functional verification warehouse
- when inspection device and transformer are in the same multi-functional verification warehouse, experiment of inspection device shall be completed first. After inspection device experiment is completed, inspection device and transformer shall enter next link at the same time.
- control center can control different stations of the multi-functional verification warehouse, but the tested equipment can be out of the warehouse together only after the experiments on all stations in the warehouse are completed.

3.2. Objective function and constraint

In this section, the mathematical formula of the problem will be described. Table 1 illustrates the symbols used in the optimization model of inspection plan.
Table 1. Notations used in models.

| notations | significance |
|------------|--------------|
| Parameters |              |
| \( I \)    | total working days of the year designed |
| \( J \)    | number of inspections in a year |
| \( T \)    | inspection cycle |
| \( H \)    | number of inspection devices placed each time |
| \( X \)    | whether there is inspection on that day, 0/1 variable |
| \( S \)    | number of stations in the multi-functional verification warehouse of the verification line |
| \( M \)    | indicates the delivery strategy of the inspection device, 0/1 variable |
| \( Cap \)  | characterize production related capabilities |
| \( t \)    | time spent on different experiments |
| \( c \)    | cost of different experiments |
| Subscript  |              |
| \( ins \)  | inspection related |
| \( ver \)  | verification related |
| \( mt \)   | maintenance related |
| \( l \)    | task batch |

(1) Inspection cost: cost of performing experiments by the inspection device during the inspection process and cost caused by the loss of capacity. The objective is to minimize the cost of inspection.

\[
F_1 = \min \left( \sum_{i=1}^{I} \sum_{j=1}^{J} H_j \ast X_i \ast (n \ast c_{\text{ins}} + (S - H_j) \ast \frac{t_{\text{ins}}}{t_{\text{ver}}} \ast c_{\text{ver}} \ast M_m) \right) \tag{1}
\]

(2) False detection cost: failure of the standard device in the verification line but not found in time, after it is found in the next inspection process, all the last batch of transformers verified by the station shall be recovered and the equipment shall be repaired. The objective function is to minimize the false detection cost.

\[
F_2 = \min \left( \sum_{s=1}^{S} f_b(t) \ast f(H_j) \ast \frac{Cap_a}{T} \ast f_{rel}(n) \ast c_{2} + \frac{t_{mt}}{t_{ver}} \ast c_{3} \right) \tag{2}
\]

Constraints

\[
J = \text{floor}\left( \frac{f}{T} \right) \tag{3}
\]

\[
f_b(t) = m \left( \frac{t}{\eta} \right)^{m-1} \tag{4}
\]

\[
Cap_a = Cap_d - \sum_{i=1}^{I} \sum_{j=1}^{J} H_j \ast X_i \ast n \ast \frac{t_{\text{cer}}}{t_{\text{ver}}} \tag{5}
\]

\[
f_{rel}(n) = k_{rel} \ln(pn + q) + o \tag{6}
\]

\[
\max((e_{t,s} + t_{j,s}) \ast \sigma_{i,s}) \leq b_{t+1} \tag{7}
\]

\[
e_t = b_t + \max(t_{\text{cer}}, t_{\text{ver}}) \tag{8}
\]

Formula (3) represents the determination of annual inspection times; Formula (4) is the equipment failure probability based on Weibull distribution on station \( s \); Formula (5) describes the relationship between \( Cap_a \) (actual production capacity) and \( Cap_d \) (design capacity) of verification line; Formula (6) is to verify the relationship between the times of experiment execution and the reliability of experimental
results, which is fitted based on historical empirical data; Formulas (7) and (8) indicate that the next batch of tasks can be carried out only after the prerequisite inspection is completed.

4. ENSGA-II algorithm
The inspection optimization problem is essentially an assembly line production scheduling problem, which belongs to NP-hard problem. It has the characteristics of computational complexity, multi-objective, multi-constraint and discreteness [9]. To solve the problem, the fast non dominated sorting genetic algorithm based on elite strategy (NSGA-II) is effective [10]. In the inspection plan optimization model, solution space of the model is discontinuous, resulting in the use of NSGA-II algorithm, which is easy to produce many identical individuals. This is not conducive to the gene exchange and evolution of the population, also easy to fall into local optimization. Therefore, the disturbed population is introduced to improve the diversity of the population and avoid the algorithm falling into local optimization [11]. Schematic diagram of the algorithm is shown in Figure 3.

![Figure 3. Flowchart of NSGA-II that coupled with disturbed population](image)

When genetic composition of the population is relatively simple, the same individuals are easy to appear in the process of evolution, which leads to the decline of population quality and premature entry into the state of local convergence. In order to avoid the adverse effects of the same individual on population diversity, the concept of disturbed population is introduced to avoid decline of search ability. Introduction and operation process of disturbed population is shown as Figure 3 and steps 1 to 4.

1. In the population $P_i$ after completing the genetic operation, the individual $S_i$ with exactly the same gene is selected and the same individual is deleted;
2. A certain number of individuals are randomly selected from the disturbed population $D_i$ and supplemented to the population $P_i$ excluding the same individuals, so as to restore the population to its original size and obtain the offspring population $R_i$;
3. Whether there are still the same individuals in the population $R_i$. If so, repeat steps 1 to 3 until there are no same individuals in the population.
6

(4) Each figure should have a brief caption describing it and, if necessary, a key to interpret the various lines and symbols on the figure.

5. Case Study
The case is selected from the laboratory of a metering center. This laboratory has built a set of low-voltage current transformer verification line compatible with through core and multiple turn current transformers. The system is equipped with one appearance inspection bin, two insulation and withstand voltage bins and three multi-functional verification warehouse, with a total of 36 multi-functional verification stations and a design annual verification capacity of 200000 low-voltage current transformers.

5.1. Result and analysis
Based on the proposed optimization model and solution method, taking the verification line of low-voltage current transformer in a metering center as the object. NSGA-II and ENSGA-II are used respectively, combined with the separate delivery and hybrid delivery strategy of inspection device. The pareto front solutions obtained experimentally are shown in Fig. 4 and Fig.5 respectively.

In the Pareto frontier distribution of two algorithms, scheme using hybrid delivery method obtains better solutions on the two objectives. Which shows that compared with the separate delivery strategy of the inspection device, the hybrid delivery strategy can better reduce the cost in all aspects. In order to verify the effect of introducing disturbed population, the proposed ENSGA-II is compared with the original NSGA-II. In the evaluation indicators, IGD, Spacing, Pareto solution mean PC_ave and program execution time mean t_ave are selected. Results are shown in Table 2.

|                      | IGD  | Spacing | PC_ave | t_ave/s |
|----------------------|------|---------|--------|---------|
| ENSGA-II             | 50.55| 94.76   | 37.46  | 15.12   |
| NSGA-II              | 506.89| 113.29  | 26.81  | 11.12   |

It can be seen from table 2 that ENSGA-II is better than NSGA-II in the convergence and diversity index IGD of pareto solution, indicating that the convergence and diversity of the algorithm have been greatly improved after the introduction of disturbed population. In the solution set uniformity index Spacing and number mean index PC_ave, ENSGA-II can not only obtain more leading-edge solutions, but also have a more uniform distribution of solutions. However, after the introduction of disturbed
population, the steps of finding, deleting duplicate individuals and adding new individuals are added on the basis of the process of NSGA-II, which increases the time complexity of algorithm execution.

Table 3. Costs of different methods

| Algorithm | Delivery mode | Cycle/d | Inspection device quantity | Inspection time/h | Inspection cost | False detection cost |
|-----------|---------------|---------|----------------------------|-------------------|----------------|----------------------|
| ENSGA-II  | Separate      | 67      | [8,12,10,11]               | 192               | 24900          | 17130                |
| ENSGA-II  | Hybrid        | 70      | [10,12,9]                  | 93                | 25100          | 15680                |
| NSGA-II   | Separate      | 54      | [11,12,9,12]              | 192               | 25200          | 17630                |
| NSGA-II   | Hybrid        | 66      | [11,10,11,9]              | 164               | 24500          | 16130                |
| Manual    |               | 60      | [12,12,12,12]             | 216               | 35640          | 16742                |

The selected solutions obtained by different algorithms are compared with traditional method. The cost and relevant data are shown in Table 3. Compared with the traditional method, system under the hybrid strategy does not need to shut down and inspection time is reduced by 28 hours, a 14.58% drop. On the other hand that using algorithm with different delivery methods can achieve a large degree of inspection cost reduction on the basis of small fluctuation of false detection cost. A more reasonable inspection cycle is obtained, which inspection cost is reduced from 35640 to 25100, about 29.57%, and false detection cost is reduced from 16742 to 15680, about 6.34%.

In order to analyze the impact inspection cycle on the cost of inspection plan, the pareto solution obtained by using ENSGA-II algorithm and hybrid delivery scheme is shown in Figure 6.

As Figure 6 shows, with the increase of cycle, cost of inspection will continue to decrease, but the cost of false detection will increase. The main reason is that in case of false detection, a large number of transformers verified in the previous batch need to be recovered, resulting in a large increase in cost. However, when the system is in better working condition, the probability of false detection of the system is lower. By appropriately increasing the inspection time interval, a better inspection cost reduction effect can be obtained.

6. Conclusion
Firstly, a hybrid delivery strategy of inspection device and transformer is proposed in this paper to optimize the inspection plan. Automation of inspection process is improved through the application
of high-precision inspection device. On this basis, inspection cycle is taken as the main influencing factor. In order to minimize the cost of inspection and false detection, an optimization model of verification plan is established.

Secondly, the ENSGA-II is used to solve the problem and verified it can effectively solve the inspection optimization problem. Experimental results show that the hybrid delivery strategy has a better cost reduction effect and realized inspection under uninterrupted state.

Finally, inspection cycle plays a decisive role in the process of optimize inspection plan. Under different working states of the system, selecting an appropriate inspection cycle can effectively reduce costs.

The optimization model and algorithm of inspection plan proposed in this paper can provide theoretical basis and reference for the establishment and implementation of inspection plan. In the follow-up research, preventive maintenance based on equipment health status will be introduced into the influencing factors of inspection plan optimization to enter a deeper discussion.

References
[1] Lijun D, Enguo Z, Qian Z, et al.(2015) Design and application of site calibration system for automatic verification pipeline. 52(17): 118-123.
[2] Guishan L, Lei L, Ying L, et al.(2013) Research on Auto-Verification and Intelligent Storage System for Smart Watt-Hour Meter. 50(05): 95-100.
[3] (2014) Q/GDW11278-2014 Calibration specification for 0.4kV metering current transformer automatic testing system. Place of publication unknown.
[4] Haibin C, Shunan Y, Liwen C, et al.(2021) Research on current transformer error testing technology based on field signal simulation technology. 58(02):133-138.
[5] Jingshu L, Fei L, Lei Z.(2014) A Period Verification Method for Standard Electrical Energy Measuring Equipment. (06): 33-34.
[6] Bo G, Zhenming Z, Hongwu Z, et al.(2019) Application Research on Quality Monitoring of Automatic Verification Production Line of Three-phase Intelligent Watt-hour Meter.47(04): 37-40.
[7] Libin W, Hongying W, Chao Z.(2017) Research on the optimal maintenance frequency of automatic verification pipeline equipment in electric energy meter.54(08): 89-92.
[8] Lihua Z, Zhaoxin D.(2015) Verification quality monitoring of metering low-voltage current transformer automatic verification line. 52(19):43-48.
[9] Youhua J, Jinwan Y, Le Z, et al.(2021) Optimal Scheduling Strategy for Limited Electricity in Multiple Parks in the Absence of Power Supply from Grid .42(01):105-116.
[10] DEB K, PRATAP A, AGARWAL S, et al.(2002) A fast and elitist multiobjective genetic algorithm: NSGA-II.6(2): 182-97.
[11] Zhenzhen Z, Xingshi H, Qinglin Y, et al.(2021) Computer Engineering and Applications: 1-13[2021-07-09]. http://kns.cnki.net/kcms/detail/11.2127.TP.20210428.1801.021.html.