Research on parallel inspection model and key technology of distribution transformer

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Abstract. In this paper, a parallel inspection model based on pipeline and multitask is designed innovatively for the large-scale sampling inspection of distribution transformer before putting into operation. According to the characteristics of inspection resource sharing, the key technologies such as resource allocation and task scheduling are optimized, and the resource optimization allocation method and task parallel scheduling algorithm are proposed. Compared with the former, the optimized parallel inspection model improves the inspection efficiency and resource utilization to a large extent, and has important application value in the modern factory inspection mode.

1. Introduction
As an important electrical equipment, distribution transformer is widely used in power system, mainly used for voltage and current transformation and power transmission of distribution network under 35kV. With the large-scale transformation and upgrading of China’s distribution network construction, the quality and performance of distribution transformers become more and more important.

However, due to the high cost of transformer, in order to save the production cost, some manufacturers have Jerry built and rough technology in the manufacturing process, which leads to the quality problems such as fire, explosion and burning in the operation of distribution transformer [1], seriously affecting the safe and stable operation of power system and the reliability of power supply. In recent years, in order to enhance the quality, State Grid Corporation of China has vigorously carried out sampling inspection of power supply materials such as distribution transformers. Last year, thousands of distribution transformers were sampled and tested in a province in the east of China alone. It is imperative to carry out large-scale batch inspection of distribution transformers.

The traditional distribution transformer inspection is mainly based on manual inspection and manual judgment in the whole process. The inspection efficiency is low, the labor cost is high, and the inspection results are easy to be affected by manual misjudgment. In recent years, with the development of integrated inspection device [2]-[3] and the use of automatic transportation equipment [4]-[5], the labor cost and transportation cost have been greatly reduced, and the precondition for large-scale batch inspection of distribution transformer has been met. However, with the application of the above integrated inspection device and automatic transportation equipment, there are still a lot of problems in the utilization rate of inspection resources and transit time.

The current research on distribution transformer inspection includes: research and analysis of on-site inspection technology of distribution transformer [6]; research on intelligent test platform of transformer [7]; research on Optimization of on-line monitoring technology of distribution transformer...
[8]. At present, there is no research on the model of batch inspection, nor on the optimization of inspection efficiency and resource utilization in batch inspection.

In this paper, based on the research of large-scale batch inspection of distribution transformer, a parallel inspection model based on pipeline and multi task is proposed innovatively, and the key technologies are optimized, and the inspection resource optimization allocation method and task parallel scheduling algorithm are proposed. The results show that the inspection efficiency and resource utilization of the optimized parallel inspection model are greatly improved compared with those before optimization.

2. Parallel inspection model
Firstly, the concept of "intelligent inspection factory" is put forward. Based on the pattern of intelligent inspection factory, pipeline is used to realize fine-grained parallelism, and multitask is used to realize coarse-grained parallelism. The parallel inspection model is composed of intelligent inspection factory, pipeline and multitask.

2.1 Intelligent inspection factory
Based on the integrated inspection device and automatic transportation system, the unmanned intelligent inspection factory has been applied in part of the State Grid system. The intelligent inspection factory mainly includes four functional modules, as shown in Figure 1.

2.1.1 Central control system. The central control system realizes the unified management of intelligent inspection factory, including task scheduling, warehousing, test status query, exception handling, report generation and other functions. The host computer of the central control system and the slave computer of each subsystem are interconnected through wireless network to realize the real-time transmission of control flow and data flow.

2.1.2 Storage system. The storage system includes automatic three-dimensional warehouse and ground buffer area. Based on the wireless network, the automatic warehouse receives the in and out order from the central control system, and automatically addresses the target samples through the stacker. A buffer zone is set up on the ground for temporary storage of samples, reducing the flow of samples between the inspection station and the warehouse, and saving transportation time.

2.1.3 Transportation system. The transportation system mainly includes AGV vehicle and docking platform. AGV car receives the instruction, automatically transports and docks from the source address to the target address, and realizes the sample flow. The target address can be divided into three types: inspection station, buffer area and automatic three-dimensional warehouse. The docking platform is convenient for automatic docking of AGV vehicles.

2.1.4 Inspection system. Inspection system is the core component of intelligent inspection factory, mainly including inspection stations and inspection personnel. The inspection station is equipped with integrated inspection device and independent control software, which is used to carry out specific inspection tasks and complete various test items. The slave computer of the inspection station is interconnected with the host computer through wireless communication. Note that the integrated inspection devices on each inspection station can be the same or can be configured differently.
2.2 Inspection pipeline

Based on the above intelligent inspection factory, large-scale batch inspection of distribution transformer can be realized. In order to improve the efficiency of inspection, the idea of pipeline is adopted. The test equipment of each inspection station in the inspection system is configured differently, and the whole inspection process is divided into several stages, thus forming the inspection pipeline. According to the characteristics of each test item of distribution transformer, the test stations are divided into four categories: routine station, shielding station, temperature rise station and impact station. The specific test items and classification basis of each station are shown in Table 1.

| Station type | Test item | Classification basis |
|--------------|-----------|----------------------|
| routine      | Insulation resistance, absorption ratio, dielectric loss, capacitance, DC resistance, transformation ratio, no-load loss and no-load current, no-load loss and no-load current at 90% and 110% rated voltage, induced withstand voltage, short-circuit impedance and load loss, zero sequence impedance test | The time consumption of each project is short, the volume of test equipment is small, and the test current used is similar |
| shielding    | Partial discharge measurement, sound level measurement | All need to be done in the shielding room |
| temperature rise | Temperature rise test, short-time overload test | It takes a long time and a large current |
| impact       | Lightning impulse test, power frequency withstand voltage test | High voltage required |

After the classification of inspection stations, the above four types of stations are taken as the four stages of the inspection pipeline, which are respectively represented by P₁, P₂, P₃ and P₄. Similar to the five-level flow of computer instructions, the distribution transformer can complete all test items by successively carrying out four stages: routine item (P₁), shielding item (P₂), temperature rise item (P₃) and impact item (P₄).

Let's first assume an ideal situation, that is, each stage of the pipeline takes the same time. Figure 2 shows how the eight inspection tasks achieve fine-grained parallelism through the pipeline.
In order to measure the pipeline performance, two concepts are introduced here: pipeline throughput $T$ and pipeline efficiency $E$. The throughput of pipeline is equal to the number of inspection tasks completed in unit time, which is used to measure the pipeline inspection capability. The efficiency of pipeline is equal to the working time-space area divided by the total time-space area of pipeline, which is used to measure the resource utilization of pipeline.

$$T = \frac{n}{l \Delta t}$$
$$E = \frac{n \times m}{s}$$

Where, $n$ is the total number of tasks, $l$ is the total number of cycles, $\Delta t$ is the time of each cycle, $m$ is the number of pipeline segments, and $s$ is the total number of space-time areas.

Without pipeline, it takes 32 cycles to complete 8 inspection tasks. Using pipeline, it can be seen from Figure 2 that only 11 cycles are needed to complete all inspection tasks, greatly improving inspection efficiency. Suppose $\Delta t = 1$, then $T_{pipeline} = 8/11$, $E_{pipeline} = 4/11$.

### 2.3 Concurrent execution of tasks

In addition to pipeline, the concept of multi-core in computer science is further introduced to expand the number of inspection resources, so that multiple pipelines can be executed concurrently, so as to achieve coarse-grained parallelism between tasks and further improve inspection efficiency. Ideally, assuming that each inspection station doubles at the same time, the concurrent execution pipeline is shown in Figure 3.

At this time, it only needs 7 cycles to complete all 8 inspection tasks. $T_{parallel} = 8/7$, $E_{parallel} = 4/7$. Compared with a single pipeline, both $T$ and $E$ are significantly improved.

However, all the above conclusions are drawn in the ideal situation, while the actual situation is much more complicated.

First of all, the time required for each inspection stage ($P_1$, $P_2$, $P_3$, $P_4$) is not the same. Each test item has corresponding test standard, which specifies the time required for the item, for example, temperature rise item takes a long time.

Secondly, not every inspection task has to go through four stages. Which test items to do depends on the user's requirements, and often does not need to carry out all the test items. According to experience, conventional test items and temperature rise test items need more, while shielding and impact items are relatively less.
Therefore, in practice, all kinds of inspection stations do not need to be configured in the same proportion, which will cause resource waste and reduce resource utilization. We need to further explore how to optimize the allocation of inspection resources so that the throughput and utilization are better.

3. Optimal allocation strategy of inspection resources

3.1 Resource allocation proportion

The core of rational allocation of resources is to allocate inspection resources according to the degree of use, and the more you use, the more you allocate. From the analysis of pipeline time-space graph, we can see that the utilization degree of inspection resources in each stage of pipeline depends on: first, the frequency of this stage on the time-space graph; second, the time needed in this stage. Considering these two factors, the optimal allocation method of inspection resources is obtained.

In the second chapter, for the convenience of display, it is assumed that the time consumption of each stage of the pipeline is the same. In fact, the inspection time of P1, P2, P3 and P4 is different. The actual inspection time of P1, P2, P3 and P4 is about 4h, 3h, 8h and 2h respectively. The frequency of each stage can be calculated according to the test items of the sample. Assume that the frequency of each stage is \( r_1, r_2, r_3, r_4 \). In theory, the quantity ratio of the four stations should be:

\[
\frac{n(P_1)}{n(P_2)} : \frac{n(P_3)}{n(P_4)} = 4r_1 : 3r_2 : 8r_3 : 2r_4
\]  

(3) rounded according to the actual situation.

The above method calculates the theoretical ratio. In the actual operation process, due to the abnormal conditions such as communication loss, equipment failure, transportation failure and manual misoperation, it is difficult to steadily advance the pipeline in each stage according to the theoretical value, and there are some inspection resources in some stations that are occupied for a long time and cannot be released.

3.2 Competition for shared resources

Furthermore, due to the concurrent execution of multiple tasks, each inspection station becomes a shared resource, which can be used by any task. At the same time, when the number of idle inspection stations is less than the number of tasks, some tasks cannot continue due to lack of resources, and tasks are temporarily suspended, as shown in Figure 4.

![Figure 4. Task temporarily suspended](image)

Four parallel tasks A, B, C and D have completed routine test items, and shielding test will be carried out. At this time, the number of idle shielding stations is 3, which is less than the number of tasks. Task A, B and C enter the next station smoothly and release the current station. Task D cannot find an idle target station, so it can only be suspended first. At this time, the fourth routine station will be occupied by task D for a long time. Therefore, when scheduling tasks under the parallel inspection
model, these problems need to be considered comprehensively to ensure the overall efficient and smooth operation.

4. Task parallel scheduling algorithm
Aiming at the above problems, this chapter optimizes the traditional pipeline scheduling strategy and proposes a parallel scheduling algorithm based on buffer and state queue.

4.1 Set up a buffer
A buffer is set up to temporarily store samples of suspending tasks and release inspection resources. As shown in Figure 4, the fourth routine station is occupied by task D for a long time. In order to avoid resource waste, first suspend task D and transport the sample of D out of the fourth routine station, so as to release the fourth routine station.

4.2 Planning the shortest path
In addition to pipeline efficiency, transportation efficiency is another key factor to determine the overall inspection efficiency. When a task is issued, the target station is locked and the transportation system starts to work. Each stage of the pipeline is completed, the test sample will be transported, so the transportation time cannot be ignored. The transportation process can be divided into three situations, as shown in Table 2. It can be seen that the transportation time from the warehouse to the station is significantly longer than that from the buffer to the station and from the station to the station. Through the establishment of buffer, the transportation path can be effectively shortened, so as to effectively improve the overall inspection efficiency.

| Scenario                  | Time (min) |
|---------------------------|------------|
| warehouse to the station   | 5          |
| buffer to the station      | 3          |
| station to the station     | 2          |

4.3 Task scheduling based on three state queues
In order to optimize the task scheduling under the parallel inspection model, ensure the efficient operation of the pipeline and save the transportation time, this section designs and implements a task scheduling algorithm based on three state queues.

The data structure of "inspection task" is designed, including three elements: sample information, test items and task status. The "sample information" includes the sample parameters and the current location of the sample; "test item" includes all the test items required for the sample and the currently executing test items; "task status" includes three states: new, running and pending.

Three task queues are designed, which are new queue, run queue and suspend queue. The corresponding task states are new, run, and pending. Three queues are used to schedule tasks in parallel, and buffer is used to pre-transport samples.

The scheduling diagram is shown in Figure 5. The core idea of scheduling is as follows:

a. First, put all tasks that can be performed into the execution queue, and all tasks that cannot be run into the suspended queue, and the new queue will be cleared quickly;

b. When all stations are busy, the scheduling is suspended. When a station is released, the scheduling is activated;

c. When a task is suspended, it enters the suspended queue, and the corresponding samples are also transported to the sample buffer;

d. After a station completes the current task, the scheduling system is responsible for judging the next target location of the sample in the station;

e. After a task is completed, it is deleted from the execution queue. When all tasks are deleted, the scheduling ends.
Figure 5. Parallel task scheduling diagram

The specific algorithm is shown in Table 3.

Table 3: A parallel task scheduling algorithm based on three queues

| Step | Content |
|------|---------|
| 1    | The new task enters the task queue, the scheduling system starts, and enter step 2 |
| 2    | Traverse the task queue, move the tasks that can be executed (i.e. there are idle target stations) to the execution queue, and mark them as the execution status; move the tasks that cannot be executed to the suspension queue, and mark them as the suspension status, and send the corresponding samples to the buffer zone; start the test at the inspection station, and enter step 3 |
| 3    | After the task is dispatched (at this time, the task queue is empty), start traversing the suspended queue and enter step 4 |
| 4    | Traverse the suspended queue. When one of the tasks can be executed, move the task to the execution queue, mark it as execution status, and send the sample to the target station. If none of the tasks can be executed, go to step 5 |
| 5    | After the completion of the suspended queue traversal, if it is still not empty, or if the suspended queue is empty and the execution queue is not empty, the scheduling system will pause and enter step 6; if the suspended queue is empty, the execution queue will also be empty, enter step 9 |
| 6    | Wait. When a station is released, the scheduling system is activated. Start scheduling from the current task of the station, and enter step 7 |
| 7    | If the task has been completed, delete the task from the execution queue, store the sample in the warehouse, and the scheduling system will start to traverse from the suspended queue to step 4 |
| 8    | If the task is not completed, move it to the head of the suspended queue, traverse the suspended queue from the beginning, and enter step 4 |
| 9    | All tasks are completed, and the scheduling system is shut down |
5. Experiment

5.1 Setup
This experiment was carried out in Shandong electric power material quality inspection center. The experimental site meets the requirements of intelligent inspection factory, including multiple sets of inspection stations based on integrated inspection device, two AGV vehicles, seven-layer three-dimensional warehouse and central control system. The central control system and each subsystem are interconnected through wireless network. A total of 40 distribution transformer samples are selected, 20 of which need to be fully tested, and the other 20 only need to carry out routine and temperature rise tests. Limited by the site, only 16 sets of stations can be arranged on site at most.

According to the setting of test items, the frequency of routine, shielding, temperature rise and impact items can be calculated as follows: \( r_1 = 40/40 = 1 \), \( r_2 = 20/40 = 0.5 \), \( r_3 = 40/40 = 1 \), \( r_4 = 20/40 = 0.5 \). Before optimization, the number of inspection stations is equal, which is \( n(P_1) = n(P_2) = n(P_3) = n(P_4) = 4 \). According to formula 3, the optimized ratio of the number of inspection stations should meet the requirements of \( n(P_1):n(P_2):n(P_3):n(P_4) = 4r_1:3r_2:8r_3:2r_4 = 4:1.5:8:1 \). Restricted by the site, after rounding, \( n(P_1) = 4 \), \( n(P_2) = 2 \), \( n(P_3) = 8 \), \( n(P_4) = 2 \). Since the initial concurrency level is 4( \( n(P_1)=4 \)), the number of buffers is also set to 4. See Table 4 for the condition difference before and after optimization of parallel inspection model.

![Table 4](image)

5.2 Results and analysis
The resource utilization (i.e. pipeline efficiency) of each inspection station before and after optimization is shown in Table 5.

![Table 5](image)
The transportation time before and after optimization is $T_1 = 40.5h$, $T_2 = 24.6h$. The total time of completing all inspection tasks before and after optimization is $T_1 = 122h$, $T_2 = 96h$. See Table 6 for performance comparison of parallel inspection models before and after optimization.

|                       | Before optimization | After optimization | Improvement |
|-----------------------|---------------------|--------------------|-------------|
| Utilization(%)        | 62.2                | 79.3               | 27.5%       |
| Transportation time    | 40.5                | 24.6               | 39.3%       |
| Total time             | 122                 | 96                 | 21.3%       |

The results show that after optimization, the utilization rate of inspection station is increased by 27.5%, the transportation time is saved by 39.3%, that is, the effective transportation distance is shortened, which conforms to the idea of the shortest path. The total time to complete all inspection tasks is reduced by 21.3%, while the overall inspection efficiency is increased by 27.1%.

6. Conclusion
In this paper, a parallel inspection model of distribution transformer based on pipeline and multitask is proposed. Then, the resource allocation and scheduling algorithms are optimized according to the characteristics of shared resources.

Compared with the model before optimization, the difference between the model after optimization is: there is no resource sharing before optimization, there is no buffer before optimization, there is after optimization; the conventional pipeline scheduling algorithm before optimization, the parallel scheduling algorithm after optimization.

Results show that the optimized parallel inspection model has a great improvement in the utilization rate of inspection resources, the total transportation distance and the overall inspection efficiency, and has an important application value in the scene of modern intelligent inspection factory.

In the next step, the switch integrated inspection device is considered to be incorporated into the parallel inspection model to further enrich its application scenarios.

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