An Evaluation and Diagnosis Model for the Operating Tempo of Electric Energy Meter Auto-verification Line System based on Fuzzy Inference

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Abstract. With long-term operation of the electric energy meter auto-verification line system, any change of the operating tempo in each link may cause the decrease of the overall system efficiency. Due to the characteristics that the operating tempo change is not easy to detect and the bottleneck in system is difficult to locate, this paper proposes to take operation time $T_1$ and cycle time $T_2$ of each link as the evaluation basis of operating tempo, according to the operation characteristic of the auto-verification line system and the feasibility of time node acquisition. By analysing the timeout reasons of each link's single $T_1$ and single $T_2$, 3 indicators for evaluating operating tempo in each links are proposed. Based on fuzzy inference, the evaluation score for each link's operating tempo is calculated with the input of 3 indicators. Furthermore, the score can be used to diagnose the bottleneck in the auto-verification line system. The evaluation and diagnosis model is verified by case analysis, it can evaluate actual operating tempo of the auto-verification line system effectively, diagnose the "bottleneck" which affects the operation efficiency of the system, and provide strong support to improve the efficiency.

1. Introduction

The invention of electric energy meter auto-verification line system completely overturns the traditional verification mode of electric energy meter, and avoids a lot of repetitive and mechanical manual works[1,2]. However, due to many factors such as long-term operation, performance degradation of the system, improper handling during artificial operation and maintenance, continuous updates of software and hardware, the actual operating tempo of each link may change, which breaks the balance between each links and affects the overall efficiency of the system. The impact of this change in operating tempo on the overall efficiency is easy to be neglected because of no obvious faults, and due to the influence of each links in the auto-verification line system on each other, it is difficult to locate the "bottleneck".

With the large-scale application of auto-verification line system, the increasing of verification
quantity has put forwards to higher requests both on operation efficiency and on the level of system operation and maintenance. Some scholars have studied the operation and maintenance support technology of the system: in reference 3-5, an expert system for fault diagnosis is constructed according to the fault characteristics of auto-verification line system[3-5]; in reference 6, maintenance strategy is optimized to achieve a balance between troubleshooting and verification production according to operation status of each devices in the system[6]. The existing researches mainly focus on the fault diagnosis and maintenance strategy optimization, but pay less attention to the actual operating tempo of the auto-verification line system. Therefore, a method which can realize automatic evaluation of actual operating tempo and the bottleneck search in the system is urgently needed.

2. Evaluation principle for operating tempo of electric energy meter auto-verification line system

2.1. Design of electric energy meter auto-verification line system operating tempo

The electric energy meter auto-verification line system uses many kinds of mechanical auto-devices to connect the multi-functional verification device of electric energy meter with special device modules such as loading and unloading robots, information binding device, AC voltage testing device, appearance inspection device, etc., which achieves the whole process automation from electric energy meter packing and unpacking, loading and unloading, transmission, positioning, wiring to verification. Figure 1 is the structure diagram of a single-phase electric energy meter auto-verification line system.

Among them, the multi-functional verification device is the most critical part of the auto-verification line system, which can complete the most of items required by verification regulation automatically. In order to maximize the efficiency of the multi-functional verification device, the operating tempo of each link in the system is usually designed according to the verification time[7].

![Figure 1. Structure diagram of single-phase electric energy meter auto-verification line system.](image)

2.2. Operating tempo evaluation principle and indicator construction

Considering the operation characteristics of special device modules in the auto-verification line system and acquisition feasibility of operation time node, this paper uses each special device module’s operation time T1 and cycle time T2[8] as basis for each module and the entire system operating tempo evaluation, it involves 7 special device modules, 19 operation links, and 38 time nodes.

2.2.1. Analysis on the cause of operation time T1 timeout. Operation time T1 of each link represents the time from materials (tray/carton box) arriving at specific location, to the completion of verification or regulated tasks. (For multi-functional verification device and AC voltage testing device, collect the time node of verification completion; for other special device modules, collect the time node of material departure after completing the specified work).
In the design stage, the operating time $T_1$ of each link is usually required according to the design of system’s operating tempo. Take the system shown in Figure 1 as an example, operation time $T_1$ in each special device module should accord with the requirements in Table 1.

**Table 1. Requirements for operation time of each link in single-phase electric energy meter auto-verification line system**

| Name of special device modules                  | Name of link                  | Requirement for operation time $T_1$ |
|-----------------------------------------------|-------------------------------|-------------------------------------|
| Loading stage                                 | Loading                       | $\leq 60$ s                         |
| Information binding and seal testing device   | Information binding           | $\leq 15$ s                         |
| AC voltage testing device                     | Seal testing                  | $\leq 15$ s                         |
| AC voltage testing device                     | AC voltage testing            | $\leq 2$ min                        |
| multi-functional verification device          | multi-functional verification | Related to type of electric energy meter |
| Unloading stage                               | Labeling and seal relationship binding device | $\leq 15$ s |
| Unloading robot                              | Unloading                     | $\leq 60$ s                         |
| labeling                                      | labeling                      | $\leq 15$ s                         |
| seal relationship binding                     | seal relationship binding     | $\leq 15$ s                         |
| unloading robot                               | unloading                     | $\leq 60$ s                         |

The reasons for single $T_1$ timeout in each link mainly include the performance degradation of the special device module itself and abnormal events. The timeout caused by the performance degradation of the special module itself is usually repetitive and frequent, however the timeout cause by abnormal events (such as device malfunction) is usually incidental. Special device module itself or its pre and post module’s malfunction could all cause single incidental timeout.

**2.2.2. Analysis on the cause of cycle time $T_2$ timeout.** Cycle time $T_2$ of each link represents the time from material arriving at corresponding position and completing verification or specific tasks, to next material arriving at the position again. In order to maximize multi-functional verification device’s efficiency, the cycle time of each link in the system should meet the device’s fastest verification time requirements. Taking the system shown in Figure 1 as an example, according to calculation result, the cycle time $T_2$ of each link should accord with meet the requirements in Table 2.

**Table 2. Requirements for cycle time of each link in single-phase electric energy meter auto-verification line system.**

| Name of special device modules                  | Name of link                  | Requirement for operation time $T_1$ |
|-----------------------------------------------|-------------------------------|-------------------------------------|
| Loading stage                                 | Loading                       | $\leq 70$ s                         |
| Information binding and seal testing device   | Information binding           | $\leq 28$ s                         |
| AC voltage testing device                     | Seal testing                  | $\leq 28$ s                         |
| AC voltage testing device                     | AC voltage testing            | $\leq 3.5$ min                      |
| multi-functional verification device          | multi-functional verification | /                                   |
| Unloading stage                               | Labeling and seal relationship binding device | $\leq 28$ s |
| Unloading robot                              | Unloading                     | $\leq 70$ s                         |
| labeling                                      | labeling                      | $\leq 28$ s                         |
| seal relationship binding                     | seal relationship binding     | $\leq 28$ s                         |


Besides the same reasons mentioned in Section 2.2.1, software and hardware problem on cache line which connected with special device module can also cause single cycle time $T_2$ timeout. This problem can be either incidental event such as belt damage, or frequent event caused by performance degradation, program update, improper operation and maintenance and so on.

In addition, the periodic $T_2$ timeout may be caused by the mismatching of the operating tempo of pre and post device modules, which is a normal phenomenon in the operation of the auto-verification line system. For example, the loading and unloading robots in the system shown in Figure 1 take 15 electric energy meters from one carton box and put them into several trays, or take them out of several trays and put them back into the carton. However, it’s pre and post devices (information binding & seal testing device and labeling & seal relationship binding device) perform a single round of operation on a pallet (6 electric energy meters). Based on the loading and unloading robot’s operation procedure characteristics, which is faster speed of placing or taking meter on the tray and lower speed of releasing or catching carton, there will be a quite long waiting period per 2.5 electric energy meters in information binding & seal testing device and labeling & seal relationship binding device.

2.2.3. Indicators for evaluating operating tempo in each link. According to the process characteristics of each link, the following evaluation indicators are proposed in this paper.

a. Compliance rate of $T_1$ in each link----$X_1$

Compliance rate of $T_1$ in each link mainly evaluates whether special device module’s operation tempo is descending due to performance degradation, then affects the auto-verification line’s efficiency. Compliance rate of $T_1$ in each link can be defined as:

$$X_1(M_i) = n_1(M_i)/P(M_i)$$  \hspace{1cm} (1)

In the formula, $n_1(M_i)$ represents the cumulative operation number of times in link $M_i$ in an investigation period, $P(M_i)$ represents the cumulative operation number of times in link $M_i$ which meets the design requirements in an investigation period.

b. Compliance rate of $T_2$ in each link----$X_2$

Compliance rate of $T_2$ in each link is mainly used to diagnose whether the software and hardware on the special device module itself and cache line connected with the device have any factors affecting the efficiency of the auto-verification line system. Compliance rate of $T_2$ in each link is defined as:

$$X_2(M_i) = n_2(M_i)/P(M_i)$$  \hspace{1cm} (2)

In the formula, $n_2(M_i)$ represents the cumulative operation number of times that the $T_2$ of a link meets the requirements of the fastest verification time in an investigation period.

c. Cycle mean time under 95% cumulative distribution----$T$

Suppose $f_{M_i}(t)$ is the probability density function of $T_2$ in a link $M_i$ during an investigation period, cycle mean time under 95% cumulative distribution is defined as:

$$T(M_i) = \int_{t=0}^{t=0.95} f_{M_i}(t)dt$$  \hspace{1cm} (3)

This indicator mainly reflects the production capacity of the special device module in the non-abnormal state.

3. Evaluation and diagnosis model of operating tempo

Taking the above three indicators as input, the fuzzy reasoning method is used to evaluate whether the actual operating tempo of each link has an adverse effect on the production efficiency of the auto-verification line system. According to the operation characteristics of the auto-verification line system, the evaluation indicators of each link are divided into three states: good, warning and abnormal. In order to make the three state boundaries more flexible, membership function is used to deal with the fuzzy problem.
3.1. Construction of membership function of evaluation indicator

In this paper, the typical trapezoid and semi trapezoid distribution[9] is used to construct the membership function. In the process of constructing the membership function, the parameters need to be determined according to the specific operation characteristics of each link in the system, so as to make it more consistent with the objective facts of the evaluated object.

According to the analysis on the causes of T1 and T2 timeout of each link, the membership functions of evaluation indicators $X_1(M_i)$ and $X_2(M_i)$ of each link in the system are respectively set as shown in Figure 2(a)-Figure 2(d).

The membership functions of evaluation indicators $T(M_i)$ of each link are set as shown in Figure 2(e). Among them, $t_1$ and $t_2$ respectively represent the cycle time requirement of each link under the fastest and slowest verification time of multi-functional verification device.

![Membership function of evaluation indicator in each link](image-url)
3.2. Operating tempo evaluation and "bottleneck" diagnosis of auto-verification line system

Three states scores of each indicators are set as \( \{\lambda_1, \lambda_2, \lambda_3\} = \{\text{good (5 points), warning (3 points), abnormal (1 point)}\} \), the evaluation score for 3 indicators in each link can be expressed as:

\[
W_i = \sum_{k=1}^{3} \mu_k \lambda_k
\]  

(4)

In the formula, \( \mu_k \) represents the degree of membership for each state. And by configuring coefficient weights \( \alpha_i \) for 3 indicators, the final operating tempo evaluation score of each link can be expressed as:

\[
Y_i = \sum_{i=1}^{3} \alpha_i W_i
\]

(5)

The links that the operating tempo evaluation scores below the threshold are preliminarily determined as the "bottleneck" in the system. According to scores from low to high, the "bottleneck" links are ranked and the causes of the "abnormal" or "warning" indicators need to be analyzed in turn.

4. Case Analysis

Taking the auto-verification line system in Figure 1 as an example, operating tempo of the auto-verification line is evaluated on a daily basis. Based on time nodes collected by the auto-verification line system, the calculation results of 3 evaluation indicators are shown in Table 3. Considering the production ability of special device module in non-abnormal state is the key factor of impacting operating tempo of the auto-verification line, the weight coefficient of \( T(M_i) \) is increased. The weight for \( X_1(M_i), X_2(M_i), T(M_i) \) are set as 0.2, 0.3, 0.5 respectively, and the evaluation scores of operating tempo of the auto-verification line system are shown in Table 4.

According to the result of operating tempo evaluation scores, the link “AC voltage testing 1” needs to cause a warning, and considering other operating tempo evaluation results are relatively good, the link “AC voltage testing 1” can be taken as the “bottleneck” link of the system on that day. And based on the evaluation results, there are abnormalities in indicator X2 and indicator T, however, the score of indicator X1 is relatively high, which means that the reason why this link becomes the "bottleneck" should have nothing to do with the testing capability of the device itself, and it is necessary to comprehensively consider whether software and hardware on the cache line connected with the device have any factors affecting the efficiency of the auto-verification line system. Being analyzed by the operation management personnel, the problems of the cache logic of AC voltage testing are found. By optimizing the cache control program of AC voltage testing link, the operation efficiency of the whole auto-verification line system is increased significantly from 85 minutes to 80 minutes per batch.

| Link name               | Operation time coincidence rate | Cycle time coincidence rate | Average cycle time in 95% probability distribution/s |
|-------------------------|---------------------------------|-----------------------------|------------------------------------------------------|
| Material loading        | 77%                             | 75%                         | 66.31                                                |
| Information binding     | 99.9%                           | 59%                         | 25.79                                                |
| Seal inspection         | 99.8%                           | 59%                         | 25.12                                                |
| AC voltage testing 1    | 98.9%                           | 30%                         | 300.56                                               |
| AC voltage testing 2    | 99.2%                           | 86%                         | 193.13                                               |
| Appearance inspection   | 100%                            | 81%                         | 20.89                                                |
| Multi-functional        |                                 |                             |                                                      |
| verification            |                                 |                             |                                                      |
| Labeling                | 100%                            | 62%                         | 25.09                                                |
| Seal relationship binding| 99.6%                           | 61%                         | 25.22                                                |
| Material unloading      | 75%                             | 80%                         | 66.83                                                |
Table 4 The evaluation scores of operating tempo of the auto-verification line system.

| Link name                  | Operation time coincidence rate | Cycle time coincidence rate | Average cycle time in 95% probability distribution | Link score |
|----------------------------|---------------------------------|-----------------------------|-----------------------------------------------------|------------|
| Material loading           | 4.54                            | 4.42                        | 5                                                   | 4.73       |
| Information binding        | 5                               | 4.8                         | 5                                                   | 4.94       |
| Seal inspection            | 5                               | 5                           | 4.8                                                 | 4.94       |
| AC voltage testing 1       | 4.99                            | 2.4                         | 1                                                   | 2.20       |
| AC voltage testing 2       | 5                               | 5                           | 5                                                   | 5          |
| Appearance inspection      | 5                               | 5                           | 5                                                   | 5          |
| Multi-functional verification| 4.89                           | /                           | /                                                   | 4.89       |
| Labeling                   | 5                               | 5                           | 5                                                   | 5          |
| Seal relationship binding  | 5                               | 5                           | 5                                                   | 5          |
| Material unloading         | 4.5                             | 4.72                        | 5                                                   | 4.82       |

5. Conclusion
This paper builds an evaluation and diagnosis model for the operation tempo of the electric energy meter auto-verification line system and bottleneck link based on fuzzy diagnosis to increase the system’s operation efficiency and maintenance level. Based on the time nodes collected by the auto-verification line, this model constructs three evaluation indicators, and finds out the bottlenecks that affect the operation efficiency by scoring indicators of each link. The model makes up the experience deficiency of operation and maintenance personnel to some extent, changes the situation that operation tempo variation reducing efficiency is being neglected, and strengthens the management and control of the electric energy meter auto-verification line system.

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