Optimization Scheduling of Electric Energy Meter Automatic Testing System

Danwen Yu\textsuperscript{1,4}, Kai Sun\textsuperscript{1}, Yuhan He\textsuperscript{1}, Weixu Wang\textsuperscript{2} and Shu Liu\textsuperscript{3}

\textsuperscript{1} State Grid Shandong Electric Power Research Institute, Jinan, 250003, China
\textsuperscript{2} State Grid Shandong Electric Power Maintenance Company, Jinan, 250118, China
\textsuperscript{3} State Grid Jinan Power Supply Company, Jinan, 250012, China

\textsuperscript{4} Corresponding author: yudanwen531@163.com

Abstract. Recent years, the wide application of intelligent energy metering in smart grid leads to the increasing demand for intelligent energy meters. Automated, industrialized large-scale verification systems are widely constructed in important local power supply companies to increase the intelligent energy meter verification ability. The optimization scheduling of verification system utilizing the advanced optimization scheduling method is a necessity to improve verification efficiency. With this regard, considering the block of multi-function verification device caused by unqualified verification result, a model based on the robust optimization method is proposed to minimize the total verification time and improve the verification work efficiency. Deterministic transformation is illustrated to solve the model. The accuracy and effectiveness of the proposed optimization model are verified in simulation results and actual operation.

1. Introduction

Energy metering plays an important role in energy service, which is directly related to both the economic benefits and the social image of an enterprise [1-3]. With the promotion of intelligent energy meters and the continuous advancement of the smart grid, energy metering has entered a new stage with intensive, intelligent and automatic characteristic [4-6], which causes the great significance to improve the verification capability of metering equipment and ensure the accuracy and reliability of energy metering.

The intelligent electric energy metering automatic testing system is an intelligent automatic testing system based on automatic transmission facilities and automatic verification units [7], which is composed of loading unit, conveying unit, pressure test unit, image recognition unit, automatic connection and disconnection unit, accuracy test and multi-function unit, sealing unit, laser marking unit, labelling unit, unloading and packing unit, empty box caching unit, etc [8-9]. Each functional unit contains several test items to maintain the accuracy, stability, and measurement reliability for the electric energy meters. It is considering that as the size of the work order increases, the number of unqualified electric energy meters may increase with the same probability of failure. Therefore, limiting the number of electric energy meters verified in the automatic testing system, which is also called the scale of a work order, we can effectively reduce the possible clogging time, is necessary to study the appropriate number of electric energy meters of a work order and arrange the verification plan wisely to minimize total verification time and improve work efficiency.
The robust optimization method is widely used in recent years, which can be exploited to get the best test efficiency considering the worst possible blockages [10]. Robust optimization is a kind of uncertainty decision-making method based on interval perturbation information to achieve the optimal decision under the worst case of uncertain parameters, which is usually called the maximum and minimum decision problem [11-12]. To further optimize the verification capability of the automatic testing system and improve the verification efficiency, this paper establishes a model for the verification process of the intelligent electric energy meter on the assembly line. Then, the robust optimization method is used to find the optimal scale of a work order considering the repair time for manual operation due to the double unqualified test items of the multi-function verification device, thereby minimizing the total verification time and improving work efficiency.

The remainder of this paper is organized as follows. In Section 2, the layout and verification process of electric energy meter automatic testing system is proposed. In Section 3, the expression of the optimization model is mathematically quantified. The deterministic transformation formulation of the optimization model is also presented. In Section 4, simulation studies and discussions are given to demonstrate the accuracy and effectiveness of the proposed model. Finally, Section 5 presents the conclusions.

2. Problem Analysis

The layout of the electric energy meter automatic testing system is shown in Figure 1.

These devices labeled in Figure 1 help realize full-automatic verification. To ensure the reliability, there are parallel devices in each functional unit in actual production work for backup.

From the perspective of workflow, the intelligent energy meters in one same work order need to sequentially pass through several functional units on the assembly line and complete the verification items in each functional unit [13-14]. According to the logical settings, if one test item is declared unqualified, it will result in unqualified verification result of the whole unit. A warning will be displayed on the monitoring terminal held by the operation staff. At this point, Unqualified verification result will be recorded, but no manual intervention is required. When the test items certified as unqualified in a unit are more than two, the device will stop, thus causing the block of the entire automatic testing system. In this case, the manual intervention is required to recover the verification, and the verification process takes longer time.
As shown in Figure 2, the accuracy test and multi-function unit is the core of the verification. It undertakes test items such as accuracy test, electrical requirements test, functional test, communication function test, consistency test, etc. There are multiple independent parallel verification devices in one multi-function verification unit, and each verification unit contains multiple verification stations, which take the responsibility of simultaneous detection of multiple electric energy meters.

This paper assumes that the time of an intelligent energy meter spend on each verification device in the same unit is the same [15]. However, due to the principle that the accuracy test and multi-function unit will stop when there are more than two unqualified test items, manual intervention is necessary at this time. At that time, other qualified meters may fail to enter the next unit smoothly. Thus the verification time of each electric energy meter is not the same.

3. Mathematical Model

This paper describes the scheduling problem of such an automatic verification system as follow:

The average verification time of each process under normal conditions is known in advance. In the whole verification progress, the worst interference is that the qualified electric energy meters fail to end verification normally because of more than two unqualified test items. In this situation, manual maintenance will be needed to recover production and cost extra time.

3.1. Objective function.

According to the basic idea of the robust optimization method, the objective function is to minimize the maximum total verification time and optimize the number of verification groups in a work order.

\[
\min \max \sum_{c=1}^{C} \sum_{s=1}^{S} t_{s,c}
\]  

(1)

Where, \( c \) indicates the number of verification groups, \( t_{s,c} \) is the verification time of verification group \( c \) in unit \( s \), \( s \) indicates the number of units in verification system.

3.2. Constraints.

The constraints involved in the optimization model are as follows.
\[ \sum_{c=1}^{C} L_{c,x} = 1, x = 1, 2, ..., C \]  
(2)

\[ \sum_{x=1}^{C} L_{c,x} = 1, c = 1, 2, ..., C \]  
(3)

Where, \( L_{c,x} \) is a binary variable. If verification group \( c \) is in the \( x \) position of all groups, \( L_{c,x} \) is 1.

Equation (2) and equation (3) show that the position of group \( c \) in the verification process is uniquely determined, what is more, it also corresponds to the priority order.

\[ \sum_{k=1}^{K} a_{c,k} = 1, c = 1, 2, ..., C, s = 1, 2, ..., S \]  
(4)

Where, \( a_{c,k} \) is a binary variable. If verification group \( c \) is in parallel device \( k \), \( a_{c,k} \) is 1. \( K_s \) indicates the number of parallel devices in unit \( s \).

Equation (4) ensures that each verification group can only be verified on one device of a unit.

\[ e_{n,c,s} - s t_{c,s} \leq t_{x,s} \leq t_{f} + e_{n,c,s} - s t_{c,s}, c = 1, 2, ..., C, s = 1, 2, ..., S \]  
(5)

\[ e_{n,c,s} \leq s t_{c,s+1}, c = 1, 2, ..., C, s = 1, 2, ..., S - 1 \]  
(6)

Where, \( e_{n,c,s} \) is the completion time of verification group \( c \) in unit \( s \), \( s t_{c,s} \) is the start time of verification group \( c \) in unit \( s \), \( t_f \) is the repair time for manual operation due to more than two unqualified test items.

Equation (5) represents the relationship between the start time and the completion time of the same verification unit. Equation (6) represents the relationship between two successively linked verification units.

\[ \sum_{c=1}^{C} a_{c,k} \cdot e_{n,c,s} \leq \sum_{c=1}^{C} a_{c,k} \cdot s t_{c,s}, c_1, c_2 = 1, 2, ..., C, c_1 \leq c_2, s = 1, 2, ..., S, k = 1, 2, ..., K \]  
(7)

\[ \sum_{c=1}^{C} L_{c,x} \cdot s t_{c,x} \leq \sum_{x=1}^{C} L_{c,x+1} \cdot s t_{c,x}, x = 1, 2, ..., C - 1, s = 1, 2, ..., S \]  
(8)

Equation (7) represents that in each unit, verification group \( c \) will be verified in order. Equation (8) emphasizes that on a device in a certain unit, the group verifies in order.

3.3. Deterministic Transformation

Considering the objective function of the optimization model is \( \min_{\mathbf{x}} \), it is necessary to translate the worst case constraints to deterministic expression based on robust optimization theory. Therefore, equation (5) can be rewritten as equation (9)

\[ t_{c,s} = u s t_{f} + e_{n,c,s} - s t_{c,s}, c = 1, 2, ..., C, s = 1, 2, ..., S \]  
(9)

Where, \( u_s \) is a binary variable. If verification group \( c \) suffers more than two unqualified items in unit \( s \), \( u_s \) is 1.

Based on the transformation of equation (9), the objective function can be rewritten as equation (10).

\[ \min \sum_{c=1}^{C} \sum_{s=1}^{S} t_{c,s} \]  
(10)

After deterministic transformation, the optimization model can be easily solved as a certain problem.

4. Simulation Results
This section analyzes the validity of the proposed model. The model is solved by GAMS (general algebraic modeling system) software CPLEX solver. The computer configuration is Intel Core i5-6500 CPU, the main frequency is 3.2GHz, and the RAM is 8G.

4.1. Introduction to the study
Take an electric energy meter verification system in a certain province as example. The number of each functional unit is shown in Table 1.

| No. | Units                  | Number of Parallel Devices | Verification Time(s) | Unqualified probability(%) |
|-----|------------------------|----------------------------|-----------------------|-----------------------------|
| 1   | Image Recognition      | 6                          | 60                    | 0.8                         |
| 2   | Pressure Test          | 6                          | 130                   | 1.3                         |
| 3   | Accuracy Test and Multi-function | 20          | 4500                  | 2.1                         |
| 4   | Laser Marking          | 3                          | 28                    | 0.7                         |
| 5   | Labelling              | 6                          | 40                    | 1.1                         |

The dates shown in Table 1 are obtained from the actual historical data of an electric energy meter automatic testing system. The verification time is counted for a single electric energy meter. The repair time $t_f$ is 10 minutes. The unqualified probability shown in Table 1 represents double qualification in specific.

4.2. The relationship between the group number and verification time
In order to explain the relationship between the change of the group number, the verification time of each unit and the total verification time, the simulation results are shown in Table 2.

| Group Number | Verification Time of Each Unit (s) | Minimum total Verification Time (s) |
|--------------|------------------------------------|-------------------------------------|
| 7            | Unit1 49, Unit2 125, Unit3 4532, Unit4 24, Unit5 43 | 4773 |
| 8            | Unit1 48, Unit2 128, Unit3 4550, Unit4 25, Unit5 44 | 4795 |
| 9            | Unit1 55, Unit2 135, Unit3 4564, Unit4 34, Unit5 56 | 4844 |
| 10           | Unit1 73, Unit2 156, Unit3 4588, Unit4 56, Unit5 63 | 4936 |
| 11           | Unit1 82, Unit2 167, Unit3 4594, Unit4 59, Unit5 66 | 4958 |
| 12           | Unit1 62, Unit2 142, Unit3 4585, Unit4 48, Unit5 60 | 4945 |
| 13           | Unit1 73, Unit2 144, Unit3 4592, Unit4 55, Unit5 67 | 4946 |

As shown in Table 2, the total verification time increases as the group number increases, and the relationship between them is not linear. Through analysis, when there are 10 groups in a work order, the minimum total verification time is 4936s. Compared with 9 groups and 4844s, the group number increases by 11.11%, and the minimum total verification time only increases by 1.90%. Therefore, the growth rate of minimum total verification time is within the acceptable range to complete the maximum number of verifications in the shortest amount of time.

4.3. sensitivity analysis
Based on the analysis of Table 1, this section will analyze the parameters that affect the simulation results of the proposed model. Since the electric energy meters spend the longest verification time in the accuracy test and multi-function unit (unit3), reducing the unqualified probability of this unit and shortening the unit's average troubleshooting time is of great significance for shortening the overall verification time. During the operation of electric energy meter automatic testing system, the unqualified probability of each unit can be reduced by checking during the period and replacing the consumable parts in time. The troubleshooting time can be shortened by improving personnel quality and providing spare consumables.

When the group number is 10, the above two key parameters change, which leads to the result as shown Figure 3 and Figure 4.

From Figure 3 and Figure 4, the effect of unqualified probability is more significant than the effect of average troubleshooting time on the total verification time. Therefore, through the simulation results, the model can provide a reference for determining the key improvement direction of the automatic testing system and have practical significance in guiding actual production.

5. Conclusions
This paper builds the model of electric energy meter verification system. The intelligent electric energy meter in one work order is reasonably grouped according to the number of parallel verification devices. The physical and logical associations between the functional units are also comprehensively considered to construct an optimization model. Using the basic concept of the robust optimization method, the disturbance caused by the unqualified verification items in the accuracy test and multi-function unit is regarded as major disturbances to the verification process. In the proposed model, the objective function is set to minimize the worst disturbance while minimizing the total verification time in the worst case. Then, the deterministic transformation of the established model is illustrated to find the optimal solution in the worst case of the optimization model. In order to test the validity and practicability of the proposed model, this paper takes a single-phase intelligent electric energy meter verification system of an anonymous provinces as example. In actual practice, the optimal solution of proposed model is referred to arrange the work plan and the verification process, which directly leads to a better production pace and higher efficiency. Then, we analyze the parameters including unqualified probability and average troubleshooting time that affect the simulation results. In general, the model proposed in this paper can improve the large-scale verification efficiency of intelligent energy meter and provide a guarantee for wide application of intelligent measuring equipment in the power grid.

References
[1] Palensky P, Dietrich D. Demand Side Management: Demand Response, Intelligent Energy Systems, and Smart Loads[J]. IEEE Transactions on Industrial Informatics, 2011, 7(3):381-388.
[2] Jain S, Pradish M, Paventhan A, et al. Smart Energy Metering Using LPWAN IoT Technology[M]// ISGW 2017: Compendium of Technical Papers. 2018.

[3] O'Driscoll E, O'Donnell G E. Industrial power and energy metering – a state-of-the-art review[J]. Journal of Cleaner Production, 2013, 41(Complete):53-64.

[4] Sun Q, Li H, Ma Z, et al. A Comprehensive Review of Smart Energy Meters in Intelligent Energy Networks[J]. IEEE Internet of Things Journal, 2016, 3(4):464-479.

[5] Cheng X, Yu M, Liu M, et al. Research on Comprehensive Performance Evaluation Method of Smart Energy Meter[C]// 2018 3rd International Conference on Mechanical, Control and Computer Engineering (ICMCCE). IEEE Computer Society, 2018.

[6] Chen X, Huang R, Shen L, et al. Research on the full life cycle management system of smart electric energy meter[J]. IOP Conference Series: Earth and Environmental Science, 2018, 113:012193-.

[7] Zhai X H, Liu H G. Design and Realization of Automatic Verification Pipeline System for Intelligent Electric Energy Meters[J]. Shandong Electric Power, 2014, 41, 6, 36-38.

[8] Zhang Y, Huang J J. Research and Application of Intelligent Verification Line System for Electric Energy Meter[J]. Electrical Measurement and Instrumentation, 2009, 2:496-499.

[9] Zhou L. Application Research of Auto-verification Pipeline System for Single-phase Energy Meters[J]. Electrical Engineering, 2014, 15(02):59-63.

[10] Ben-Tal A, El Ghaoui L, Nemirovski A. Robust optimization[M]. New Jersey: Princeton University Press Princeton, 2009: xxii+542.

[11] Bertsimas D, Sim M. The Price of Robustness[J]. Operations Research, 2004, 52(1):35-53.

[12] Li Z, Floudas C A. Robust counterpart optimization: Uncertainty sets, formulations and probabilistic guarantees[C]//Proceedings of the 6th conference on Foundations of Computer-Aided Process Operations, Savannah (Georgia). 2012.

[13] Xu Y, Wang L. Differential evolution algorithm for hybrid flow-shop scheduling problem[J]. Journal of Systems Engineering and Electronics, 2011, 22 (5): 794-798.

[14] Lee T S. A review of scheduling problem and resolution methods in flexible flow shop[J]. International Journal of Industrial Engineering Computations, 2019:67-88.

[15] Zhang C S, Ouyang D T, Ning J X. An artificial bee colony approach for clustering[J]. Expert Systems with Applications, 2010, 37(7): 4761-4767.