The Sampling Method and Rotation Strategy of the Smart Meter Based on the Stratified and Staged Sampling Method

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Abstract. There is a large cost during the inspection and rotation of the smart meter. In this paper, the 8-year life cycle of the smart meter is divided into 4 stages. Smart meters are sampled through a stratified and staged method, based on the qualified rate and error factors. After the final inspection in the life cycle, the rotation benefit is evaluated by the score of the state of smart meters, economic benefit, management benefit and social benefit. And the problem whether it is needed to rotate the smart meter or not can be solved based on the value of the rotation benefit.

1. Introduction

With the development of smart grid, smart meters have become a relatively important equipment in the electric energy measurement of the energy supply system. Compared with the traditional electric meter, the smart electric meter can effectively prevent the electric rate arrears. The operation parameters collection, local data processing, and remote data communication can be also realized by the smart grid, supporting the safe operation, state inspection, data record, electric price release and other works of the smart grid. Statistics indicates that there have been more than 430 million users of State Grid Corporation of China and more than 385 million smart meters have been installed up to September 2016.

When the smart meter runs for some time, there will come kinds of questions such as performance degradation and error increase [1-3]. It may not only cause economic losses to the user and the electric company, but also bring dispute between the user and the company. Therefore, it is necessary to inspect the smart meter to evaluate the operation failure and ensure that the metering equipment can be running safely and stably. A common way is on-site inspection or inspecting the randomly sampled smart meters in the laboratory. Studies on the operation, inspection, and management of the smart meter have been conducted in recent years. Yuan analysed the inspection method and plan in Chongqing [4]. Liu and Zhong designed a sampling plan based on the stratified and staged sampling method [5-6].

In this paper, we proposed an improved sampling method based on the stratified and staged sampling way and designed an evaluation model of the rotation benefit of the smart meter. The evaluation result is based on the state of smart meters, economic benefit, management benefit and social benefit. And the rotation strategy is designed based on the evaluation result.
2. Sampling Method

There are many sampling methods of the smart meter now, including simple random sampling, system sampling, stratified sampling, staged sampling and etc. So following factors need to be considered.

2.1. Estimation Accuracy
There are many smart meter manufacturers and the accuracy distribution of the smart meter of every manufacturer is independent. While using simple random sampling, it may lead to a large different accuracy distribution between the whole group and the samples. But the difference among every layer of the samples can decrease and the estimation accuracy can improve if using the stratified sampling method.

2.2. Inspection Cost
It is needed to reduce the cost because the inspection of the smart meter is destructive, unreducible, and would cost some resources. So it is needed to control the cost of the inspection work. The sample size of single sampling is large, and the sample size of multiple sampling is small. As for the sampling frequency, the sampling frequency of single sampling is small, and the sampling frequency of multiple sampling is large. In order to reduce the cost, multiple sampling is used in this paper.

2.3. The Combine of Different Sampling Methods
The question of accuracy and cost need to be considered in the inspection of the smart meter. So a combine of staged sampling, stratified sampling, and multiple sampling is proposed. It is as follows.

(1) Smart meters are widely used and have a large number. But the inspection of the smart meter is destructive and so it is needed to complete the inspection work by sampling.

(2) The smart meter of the same manufacturer is always in mass production and the quality level can be thought to be similar. And the sample from the same batch of smart meters can partly reflect the total quality level of the whole batch.

(3) On the other hand, the quality level of the smart meter produced by different manufacturers often has a certain degree of difference. So it is possible to layer the sample according to the manufacturer.

(4) The operation of the smart meter is a continuous and long process. Single sampling cannot reflect the current quality level of the whole group. But if the sampling frequency is too large, it may bring a big cost. Therefore, a multiple sampling method is used, which combines the bathtub curve and the whole life cycle of the smart meter.

3. Stratified and Staged Sampling Model
On the basis of paper [5] and considering features of the life cycle of the smart meter, we design a stratified and staged sampling model.

3.1. Sampling Period
Referring to Q/GDW 1206-2013 The Sampling Specification of Electric Meters, the following proposal sampling method is designed. The whole life cycle of the smart meter is 8 years. Fig. 1 shows the sampling procedure and it is used in the inspection of the smart meter produced by the same manufacturer and in the same mass. As shown in the Fig. 1, in the 8-year life cycle of the smart meter, the smart meter will be inspected every 2 years and need to be decided whether it will be rotated or not in the last year.

![Figure 1. The life cycle of the smart meter.](image-url)
3.2. Sample Size

The sample size is decided based on the estimation accuracy and inspection cost.

At first, considering the accuracy, the accuracy of the result estimated by the sample should be bigger than the absolute error limit. In other words, the probability that the estimation failed is

$$P\{|p - p_t| > d\} = a.$$  \hspace{1cm} (1)

Where $a$ is the size of the probability $P$, $p_t$ and $p$ is the unqualified rate of the whole group and the sample, $d$ is the absolute error limit. $p$ can be approximated as a normal distribution, and then $d$ is given by

$$d = t \sqrt{\frac{n}{N-1} \frac{p(1-p)}{n}},$$  \hspace{1cm} (2)

Where $t$ is the quantile of the standard normal distribution that satisfies $t = \mu_{1-a/2}$, $N$ is the total group size, and $n$ is the sample size. Combining Eqs. (1) and (2), the sample size $n$ is given by

$$n = \frac{t^2 (1-p)}{\frac{1}{N} d^2 + \frac{1}{N} (1-p)}.$$  \hspace{1cm} (3)

Where $p$ is unknown. Referring to paper [5], we use the weighted average unqualified rate of the inspection results of last few sampling times as the estimated value of $p$.

(i). When $p \leq \text{LQL}$ (limiting quality level), the sample size is given by

$$n = \frac{N t^2 p (1-p)}{(N-1) d^2 + t^2 p (1-p)}.$$  \hspace{1cm} (4)

(ii). When $p > \text{LQL}$, the whole group of the smart meter is unqualified and will be all rotated.

3.3. Sample Model

We stratify the smart meter according to the manufacturer, and divide the 8-year total life cycle into 4 stages, sample and inspect the smart meter 4 times except the first inspection.

3.3.1. The First Stage. The sample size of each layer is equally distributed, that is, the sample size of each layer is proportional to the total size of that layer [7], in other words, the proportion of the sample size of $h$ layer $n_h$ and the total sample size $n$ is equal to the proportion of the size of $h$ layer $N_h$ and the whole group size $N$. The ratio value is $W_h$, given by

$$\frac{n_h}{n} = \frac{N_h}{N} = W_h.$$  \hspace{1cm} (5)

In the staged sampling, the wanted value can be estimated by the sample. Here, we let $\bar{y}_e$ and $\bar{y}_h$ be the wanted value and the average wanted value of $h$ layer. Then, $\bar{y}_e$ is given by

$$\bar{y}_e = \sum_{h=1}^{k} W_h \bar{y}_h = \sum_{h=1}^{k} \left( \frac{n_h}{N_h} \cdot \sum_{l=1}^{n_h} y_{hl} \right) = \sum_{h=1}^{k} \left( \frac{1}{N_h} \cdot \sum_{l=1}^{n_h} y_{hl} \right) \approx \bar{y},$$  \hspace{1cm} (6)

Where $\bar{y}$ is the true size of the wanted value, $k$ is the sampling layer, $i$ is the sample number of $h$ layer and $y_{hl}$ is the value of each sample.

3.3.2. The Second and Third Stage. The sample size of each layer is unequally distributed. Using Eq. (5), we take the qualified rate of the smart meter and power error as wanted values. When calculating
the state score of the inspected smart meter, qualified rate and power error variance both need to be considered.

At first, inspection cost $c$ is given by

$$ c = c_0 + \sum_{h=1}^{k} c_h n_h, \quad (7) $$

where $c_0$ is base cost, $c_h$ is the cost of each sample in the $h$ layer.

The sample size of this stage is given by

$$ n_h = n \frac{w_h s_h}{\sqrt{\sum_{h=1}^{k} (w_h s_h)^2}} = \frac{n N_h S_h}{\sqrt{\sum_{h=1}^{k} (N_h S_h)^2}}, \quad (8) $$

In the work of inspection, the inspection projects of every smart meter are the same and the inspection cost can be thought to be equal, that is, $n_1 = n_2 = \cdots = n_h$. Then Eq. (7) can be simplified to

$$ n_h = n \frac{w_h s_h}{\sum_{h=1}^{k} w_h s_h} = \frac{n N_h S_h}{\sum_{h=1}^{k} N_h S_h}. \quad (9) $$

3.3.3. The Fourth Stage. In this stage, it will be decided whether the smart meter needs to be rotated or not. Because this stage is the last year of the 8-year life cycle, the probability that the smart meter happens accidents will increase largely. And we increase the sample size of this stage appropriately. Let the total sample size of $j$ stage be $n^{(j)}$ and the sample size of this stage is given by

$$ n^{(4)} = \alpha \cdot n_{max}^{(j)} \quad (1 \leq j \leq 4), \quad (10) $$

Where $n^{(4)}$ is calculated from Eq. (9) and $\alpha$ is the gain parameter, bigger than 1. The biggest sample size of all stages $n_{max}^{(j)}$ and the whole group size $N$ need to be considered when determining the size of $\alpha$. But the size of $\alpha$ should not be too big, or the cost will increase greatly and a large number of smart meters will be destroyed.

3.4. Qualified Rate and Power Error
We get the qualified rate and power error information of the smart meter in every layer through several kinds of tests and then give the state score of the smart meter $S_h$.

3.4.1. Qualified Rate. Referring to papers [5] and [8], the test projects include: direct test (D), start-up test (SU), creep test (CR), constant test (CO), insulation and withstand voltage test (I&WV), daily timing error test (DTE) and etc. Set the weight of each test and the average qualified rate $Z$ is given by

$$ Z = \omega_1 \cdot q_1 + \omega_2 \cdot q_2 + \omega_3 \cdot q_3 + \omega_4 \cdot q_4 + \omega_5 \cdot q_5 + \omega_6 \cdot q_6, \quad (11) $$

Where $q_1$-$q_6$ are the qualified rates of each test, and $\omega_1$-$\omega_6$ are the weights, whose sum is 1.

3.4.2. Power Error. The error is one of the most important parameters to measure the current state of the smart meter. We measure the error of the smart meter at 8 power points, as shown in Tab. 1.

| Table 1. Inspected points of the smart meter. |
|------------------------------------------------|
| $\cos \varphi = 1$ | $\cos \varphi = 0.5L$ |
| $I_{max}$ | $I_b$ | $0.5I_b$ | $0.1I_b$ | $I_{max}$ | $I_b$ | $0.5I_b$ | $0.2I_b$ |

Because the power error level of each layer differs from each other, we use the power error variance to describe the error feature of each layer.
4. Rotation
After the 8-year life cycle, it will be determined whether the smart meter needs to be rotated or not. However, the rotation is a large work and has a big cost, so besides the inspection result and state score, other factors are also necessary to consider.

In this paper, we consider state score, economic benefit, management benefit and social benefit of the smart meter. We set the weight of each factor and finally, the rotation benefit \( E \) is given by

\[
E = \omega_1' \cdot e_1 + \omega_2' \cdot e_2 + \omega_3' \cdot e_3 + \omega_4' \cdot e_4,
\]

(12)

Where \( e_1 \sim e_4 \) and \( \omega_1' \sim \omega_4' \) are the values and weights of state score, economic benefit, management benefit and social benefit.

Then, let the threshold value of the rotation benefit be \( E_{\text{ts}} \) and the rotation strategy is shown in Tab. 2.

| \( E \geq E_{\text{ts}} \) | \( E < E_{\text{ts}} \) |
|----------------|----------------|
| delay the rotation | rotate at once |

Referring to Q/GDW 1206-2013 The Sampling Specification of Electric Meters, the smart meter that continues to work after 8-year life cycle needs to be inspected every 1 year.

5. Experiments
The first batch of smart meters in Chongqing city are put into use in 2010 and now, their 8-year life cycle has not completely ended. It is difficult to sample and inspect all these smart meters. Referring to papers [5], [6] and [8], we select 50000 smart meters installed in 2010 to verify the proposal method. Among the 50000 smart meters, 28000 are produced by manufacturer A and 22000 are produced by manufacturer B. Referring to GB/T 2828.2-2008 Sampling Procedures for Inspection by Attributes-Part 2: Sampling Plans Indexed by Limiting Quality (LQ) for Isolated Lot Inspection, let LQL be 5%, the initial unqualified rate \( (\tilde{p})_0 \) be 0.3%, the failed estimation probability \( a \) be 5%, that is, \( t = 1.96 \), and the absolute error limit \( d \) be 0.004, then the total sample size

\[
n^{(1)} = \frac{N t^2 p^{(1)} (1 - p^{(1)})}{(N - 1) d^2 + t^2 p^{(1)} (1 - p^{(1)})} = 708
\]

Can be calculated. So the sample size of each layer in the first stage \( n_A^{(1)} \) and \( n_B^{(1)} \) is 396 and 312. The qualified rate of each test project is shown in Tab. 3.

| project | D | SU | CR | CO | I&WV | DTE |
|---------|---|----|----|----|------|-----|
| A       | 0.999 | 1   | 0.999 | 0.998 | 0.998 | 1   |
| B       | 0.999 | 0.999 | 1   | 0.998 | 0.996 | 0.999 |

According to Eq. (11), let the weight of direct test \( \omega_1 \) be 0.25 and the weight of others be 0.15, then the qualified rate of each layer \( Z_A^{(1)} \) and \( Z_B^{(1)} \) is 0.999 and 0.99855.

The power error inspection is shown in Tab. 4 and the standard deviation factor of each layer is 0.256 and 0.405.
Table 4. The result of each inspected point.

| inspection point | cos φ = 1 | cos φ = 0.5L |
|------------------|-----------|--------------|
|                  | l<sub>max</sub> | l<sub>b</sub> | 0.5 l<sub>b</sub> | 0.1 l<sub>b</sub> | l<sub>max</sub> | l<sub>b</sub> | 0.5 l<sub>b</sub> | 0.2 l<sub>b</sub> |
| A                | 0.220     | 0.189       | 0.125           | 0.149           | 0.171     | 0.139       | 0.154           | 0.090           |
| B                | 0.155     | 0.208       | 0.167           | 0.183           | 0.200     | 0.061       | 0.091           | 0.078           |

The evaluation standard of the state score is shown in Tab. 5.

Table 5. The evaluation standard.

| score | qualified rate | error level |
|-------|----------------|-------------|
| 5     | (0.999, 1]     | [0, 0.46)   |
| 4     | (0.998, 0.999] | [0.46, 0.62) |
| 3     | (0.997, 0.998] | [0.62, 0.78) |
| 2     | (0.996, 0.997] | [0.78, 0.93) |
| 1     | [0, 0.996]     | [0.93, +∞)  |

Let the weight of the qualified rate factor and the power error level factor be 0.6 and 0.4, then the state score of each layer is

\[ S^{(1)}_A = 0.6 \times 5 + 0.4 \times 5 = 5, \quad S^{(1)}_B = 0.6 \times 4 + 0.4 \times 5 = 4.4. \]

The unqualified rate of next stage is given by

\[ n^{(2)} = \frac{N t^2 p^{(2)} (1-p^{(2)})}{(N-1) d^2 + r^2 p^{(2)} (1-p^{(2)})} = 286, \]

Where the sample size \( n^{(2)}_A \) and \( n^{(2)}_B \) is 160 and 126.

As for smart meters in the remaining life cycle, sample and inspect them through the same way and finally, get the state score in the fourth stage \( S^{(4)}_A = 3.4 \) and \( S^{(4)}_B = 3 \).

According to Eq. (12), calculate the rotation benefit and let the weight \( \omega'_1 - \omega'_4 \) to 0.4, 0.3, 0.2 and 0.1. The statistics of Chongqing Electric Power Research Institute shows that the smart meter produced by manufacturer A is almost distributed in urban areas and the one produced by manufacturer B is mostly distributed in some remote areas. So let the economic benefit, management benefit and social benefit of A be 5, 4, 4 and let the ones of B be 2, 3, 4. Then, get

\[ E_A = 0.4 \times 3.4 + 0.3 \times 5 + 0.2 \times 4 + 0.1 \times 4 = 3.76, \]
\[ E_B = 0.4 \times 3 + 0.3 \times 2 + 0.2 \times 3 + 0.1 \times 4 = 2.8. \]

In this paper, we let the threshold value \( E_{ts} \) be 3. Because of \( E_A > E_{ts}, E_B < E_{ts} \), only the smart meter produced by manufacturer B needs to be rotated.

6. Conclusion

According to the qualified rate and the power error information, we proposed an improved stratified and staged sampling method and designed an evaluation model of the rotation benefit. It helps to improve the efficiency in the management of the smart meter and save time and economic cost in the rotation work. Finally, we used the data of the smart meter in Chongqing to verify our proposal method.
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