Pseudo-random Dynamic Testing Signal Modeling and its Electric Energy Compressive Measurement Method

Xuewei Wang[1], Jing Yang[1], Lin Wang[1], Xiaoxuan Dong[1], Ruiming Yuan[2], Zhenyu Jiang[2]

[1]*Beijing University of Chemical Technology, Beijing, China,wangxw@mail.buct.edu.cn,008615501262388*
[2] *State Grid Jibei Electric Power Company Limited Power Research Institute, Beijing, China, ydollars@sina.com, 0086-010-56585801*

Abstract **– This paper is concerned with the problem of measuring electric energy accurately under the large power dynamic (LPD) loads (e.g. arc furnaces in the steelmaking, high-speed train) testing conditions. The m-sequence pseudo-random dynamic testing (PrDT) signal parameter model is established. Meanwhile we analyze statistical properties of the PrDT signal model to prove that the model can represent typical characters of LPD loads and the testing signal is sparse in frequency domain. Then we design a deterministic optimal measurement matrix with the minimal measuring error and a novel Compressive Measurement (CM) measuring method is proposed. The CM measuring method can solve the problem of measuring electric energy accurately under the random dynamic testing signal conditions. Using the PrDT signal model, simulation has also been carried out based on different length and period of m-sequence. The results show that the metering errors of CM measuring method are small enough to be ignored.**

Keywords – random testing signal model, compressive measurement, electric energy measurement, measurement matrix

I. INTRODUCTION

With the rapid construction of smart grid in the world, renewable energy, such as wind energy, distributed photovoltaic power, etc., and large power dynamic (LPD) load,such as arc furnaces in the steelmaking, high-speed train, etc., are widely used in electrical network. In real situation, the typical LPD loads and new energy sources are time-variant, and their current and active power signals have two typical characteristics[1]: 1) the signal envelope fluctuating fleetly and repeating in a fixed time interval; 2) the signal fundamental wave envelope random dynamic changing and obeying approximately Gaussian distribution. The complex dynamic characteristics can cause the metering errors out of tolerance for smart electricity meters, resulting economic losses in electric energy trading [2,3].

As for errors testing signal model for smart meter,two classes of periodic steady testing (PST) signal model have been proposed. The first class was periodic steady sine testing signal model, e.g. fundamental wave, which was suggested in IEC62052-11 [4], the second class was periodic steady non-sinusoidal testing signal model, e.g. the distorted signal with fundamental and harmonic wave, which was suggested in IR46 [5] and IEC62053-21 [6], etc. Until recently, deterministic dynamic testing(DDT) signal model has been proposed for dynamic errors testing of the smart meter, such as dynamic current and active power signal with a sine or trapezoidal wave envelope[7], OOK (On-Off Keying) and TASK (Ternary Amplitude Shift Keying) dynamic testing signal models which proposed in [8-10]. Unfortunately, the PST signal models cannot test dynamic errors of smart meter but steady errors, and the DDT signal models can be used to test the dynamic errors of smart meter but not the optimal models because of they cannot reflect random dynamic changing characteristic of LPD loads.

As for electric energy measurement algorithm, under the PST signal conditions, a number of measurement algorithms have been investigated in the past decades, such as synchronous measurementalgorithm[11],nonsynchronous measurementalgorithm[12], Quasi-synchronous measurement algorithm[13,14], distorted signal measurement algorithm[15-19], wavelet transform measurement algorithm[20-22], and the metering error evaluation of the algorithms[13,23-25], etc. But the proposed algorithms are suitable to accurately measure steady electric energy, cannot accurately measure electric energy under the random dynamic testing signal conditions.

As for signal detection, Compressive Sensing (CS) has been investigated as a revolutionary Compressive Signal Processing (CSP) method[26-28], which reconstructs signal from less sample values through designing measurement matrices with Restricted Isometric Property(RIP). After that, a little research about Compressive Measurement(CM) has been explored, to detect a random signal without reconstruction in literatures, including random signal estimation[29-31] and communication signal demodulating detection[32,33]. The above CM signal processing methods normally adopt Gaussian random measurement matrix, and the advantages of this matrix are universality and obeying Gaussian distribution. However, this matrix cannot measure the electric energy of random signal accurately.

Summarizing the above discussion, up to now, very little effort about research has been made on both pseudo-random dynamic testing (PrDT) signal modeling and its electric energy measuring method. How to establish a PrDT signal model and explore a method of measuring electric energy of the PrDT signal accurately have become a challenging problem.

In this paper, we are motivated to establish a PrDT signal model and then investigate a novel CM method of accurately measuring electric energy of the PrDT signals, by designing a deterministic measurement matrix with minimal measuring error.

II. PSEUDO-RANDOM DYNAMIC TESTING SIGNAL MODEL

A. Parameter model of PrDT signal

The typical time-variant LPD loads have two typical characteristics as mention above: the signal envelope fluctuating fleetly and repeating with load operating station, the signal fundamental wave envelope random dynamic changing with approximately Gaussian distribution. Hence to establish a random dynamic testing signal model is suitable to both reflect the characteristics and test the errors of smart meter can be equivalent to finding a random envelope signal with the same characteristics.

The m-sequence wave as a pseudo random signal has two important properties: (1) the signal envelope fluctuating and repeating periodically; (2) envelope dynamic changing and its runs distribution compliance with Gaussian. In order to reflect the fundamental wave dynamic fluctuation for LPD loads, we establish a steady voltage signal $u_s(t)$ and a dynamic testing current signal $i_d(t)$. The dynamic testing current signal is obtained by modulating steady current signal $i_s(t)$ with the m-sequence. Firstly, by defining

$$u_s(t) = U\sin(\Omega_1 t + \varphi) \quad (1)$$

$$i_s(t) = I\sin\Omega_1 t \quad (2)$$

where $\Omega_1 = 2\pi f_1$ and f_1 is the industry frequency, and we have the m-sequence binary waveform function is expressed as follows:

$$m(t) = \sum_{k=1}^{N} m(k)g(t-kT) \quad (3)$$

Where $N = 2^n - 1$ is the length of m-sequence, n is the shift register lever, $T = 1/f_1$ is the period of $i_s(t)$, and $g(t-kT) = \begin{cases} 1 & t \in [kT,(k+1)T] \\ 0 & t \notin [kT,(k+1)T] \end{cases}$ is the window function.

Then according to the m-sequence generation theory, binary m-sequence $m(k)$ is expressed as follows:

$$m(k) = C_1 m(k-1) \oplus C_2 m(k-2) \oplus \cdots \oplus C_n m(0) = \sum_{i=1}^{n} C_i m(k-i)(\mathrm{mod}\,2) \quad (4)$$

where $C_i = 0$ or 1 , $i = 0,...n$ reflect feedback line connection state, 0: disconnect, 1: connect. The $m(k)$ modeling method is used to generate PrDT current signal $i_d(t)$,see fig.1

$$i_d(t) = m(t)i_s(t) = I[\sum_{k=1}^{N} m(k)g(t-kT)]\sin\Omega_1 t \quad (5)$$

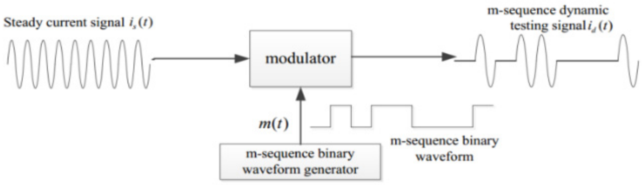

Fig. 1. PrDT signal Modeling

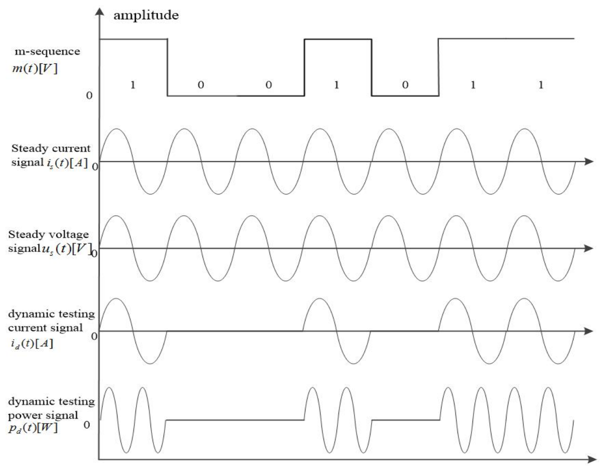

Fig. 2. Waveforms of m-sequence dynamic testing signal

So, we obtain the model of PrDT current signal and active power signal:

$$i_d(t) = I\sum_{k=1}^{N}[\sum_{i=1}^{n} C_i m(k-i)(\mathrm{mod}\,2)]g(t-kT)\sin\Omega_1 t \quad (6)$$

$$p_d(t)=u_s(t)\,i_d(t)$$
$$=p_0\sum_{k=1}^{N}[\sum_{i=1}^{n}C_i m(k-i)(\bmod 2)]g(t-kT)[\cos\varphi-\cos(2\Omega_1 t+\varphi)] \quad (7)$$

where $p_0 = UI/2$.

Fig.2 shows the waveform of PrDT signal which is given by the parameter model.

B. Statistical properties of the model

Pseudo-random signal is a long period signal (i.e. m-sequence of n=17, N=131071 bits). It is a random binary signal within a period, otherwise is a periodic signal. In this section, we research statistical properties of the PrDT current signal $i_d(t)$ during a period T_m. T_m is the period of m-sequence and $T_m = T \times N$.

According to $i_d(t) = m(t)i_s(t)$, we can deduce the mathematical expectation $E[i_d(t)]$, variance $\mathrm{var}[i_d(t)]$, autocorrelation function $R_d(\tau)$ of $i_d(t)$. And it is not difficult to know that $m(k)$ and $m(t)$ have the same statistical properties. Thus:

$$E[i_d(t)] = i_s(t)\cdot E[m(k)]=(I\sin\Omega_1 t)E[m(k)] \quad (8)$$

$$\mathrm{var}[i_d(t)] = \mathrm{var}[m(k)\cdot i_s(t)] = i_s^2(t)\,\mathrm{var}[m(k)] = (I^2\sin^2\Omega_1 t)\,\mathrm{var}[m(k)] \quad (9)$$

$$R_d(\tau) = E[i_d(t)i_d(t+\tau)]=E[m(t)i_s(t)m(t+\tau)i_s(t+\tau)] = i_s(t)i_s(t+\tau)E[m(t)m(t+\tau)] = i_s(t)i_s(t+\tau)R_m(\tau) \quad (10)$$

We need to deduce $E[m(k)]$, $\mathrm{var}[m(k)]$, $R_m(\tau)$. Based on the balance property of m-sequence: The number of "1" is one more than that of "0" in a period:

$$P(m=1) = \frac{2^{n-1}}{2^n-1},\ P(m=0) = \frac{2^{n-1}-1}{2^n-1}$$

according to the binomial distribution, we can calculate out:

$$E[m(k)] = 1\cdot P(m=1) + (0)\cdot P(m=0) = \frac{1}{2} + \frac{1}{2(2^n-1)} \quad (11)$$

$$\mathrm{var}[m(k)] = E[m^2(k)] - E^2[m(k)] = \frac{1}{4} - \frac{1}{4(2^n-1)^2} \quad (12)$$

And $m(t)$ is a stationary random process during T_m, its autocorrelation function is expressed as follows:

$$R_m(\tau) = \frac{1}{T_m}\int_0^{T_m} m(t)m(t+\tau)dt = \begin{cases} \frac{1}{2}[(1+\frac{1}{N}) - \frac{|\tau|(N+1)}{2NT}] & |\tau| \le T \\ \frac{1}{4}(1+\frac{1}{N}) & T \le |\tau| \le (N-1)T \end{cases} \quad (13)$$

Denote $n = 17$, $N = 2^n - 1$

$$E[m(k)] = \frac{1}{2} + \frac{1}{2(2^n-1)} = \frac{1}{2} + \delta_1 \quad (14)$$

$$\mathrm{var}[m(k)] = \frac{1}{4} - \frac{1}{4(2^n-1)^2} = \frac{1}{4} + \delta_2 \quad (15)$$

$$R_m(\tau) = \begin{cases} (\frac{1}{2} - \frac{|\tau|}{4T})(1+\delta_3) & |\tau| \le T \\ \frac{1}{4}(1+\delta_3) & T \le |\tau| \le (N-1)T \end{cases} \quad (16)$$

where $T_m = T \times N$ is the period of m-sequence. $|\delta_1| \le 3.8\times10^{-6}$, $|\delta_2| \le 1.5\times10^{-11}$, $|\delta_3| \le 7.6\times10^{-6}$ is small enough to be ignored. We can obtain:

$$E[i_d(t)] = \frac{I}{2}\sin\Omega_1 t \quad (17)$$

$$\mathrm{var}[i_d(t)] = \frac{I^2}{4}\sin^2\Omega_1 t \quad (18)$$

$$R_d(\tau) = \begin{cases} \frac{I^2}{4}[\cos\Omega_1\tau - \cos(2\Omega_1 t + \Omega_1\tau)][(1-\frac{|\tau|}{2T})] & |\tau| \le T \\ \frac{I^2}{8}[\cos\Omega_1\tau - \cos(2\Omega_1 t + \Omega_1\tau)] & T \le |\tau| \le (N-1)T \end{cases} \quad (19)$$

In the dynamic load conditions, we take T (the period of $i_s(t)$) as time variable to calculate the statistical properties of $i_d(t)$. Denote $t = k_1T + t_0$, $\tau = k_2T$, $k_1, k_2 = 0,1\ldots N-1$, $t_0 < T$ and t_0 is constant, then:

$$E[i_d(k_1T + t_0)] = \frac{I}{2}\sin\Omega_1 t_0 \quad (20)$$

$$\mathrm{var}[i_d(k_1T)] = \frac{I^2}{4}\sin^2\Omega_1(k_1T + t_0) = \frac{I^2}{4}\sin^2\Omega_1 t_0 \quad (21)$$

$$R_d(k_2T) = \frac{I^2}{8}(1-\cos 2\Omega_1 t_0) \quad (22)$$

Now we calculate the mean time of $i_d(t)$ when $t = k_1T + t_0$. Denote $N = 2^n - 1$, thus:

$$\langle i_d(k_1T+t_0)\rangle = \lim_{N\to\infty}\frac{1}{N}\sum_{k_1=1}^{N} m(k_1T+t_0)i_s(k_1T+t_0) = \lim_{n\to\infty}\frac{2^{n-1}}{2^n-1}I\sin\Omega_1(k_1T+t_0) = \frac{I}{2}\sin\Omega_1 t_0 \quad (23)$$

In the same way, according to the shift and add property of m-sequence: $m(k_1T)m(k_1T + k_2T) = -m(k_1T + lT)$, $(l = 0,1\cdots N-1)$, the time autocorrelation function of $i_d(t)$ is:

$$\langle \overline{i_d(k_1T + k_2T + t_0)\cdot i_d(k_1T + t_0)}\rangle = \lim_{N\to\infty}\frac{I^2}{2N}\sum_{k_1=1}^{N} m(k_1T + t_0)m(k_1T + t_0 + k_2T)\cdot[1-\cos(2\Omega_1k_1T + 2\Omega_1t_0 + \Omega_1k_2T)] = \frac{I^2}{8}(1-\cos 2\Omega_1 t_0) \quad (24)$$

Thus, $i_d(t)$ is a stationary random signal during T_m, and is ergodic when $t = k_1 T + t_0$ ($k_1 = 0,1\ldots, N-1; t_0 < T$ and t_0 is constant). According to the Winner–Khintchine theorem, the power spectral density of $i_d(t)$ is:

$$S_d = \mathrm{F}\,[R_d(k_2 T)] = \frac{I^2\pi}{4}(1-\cos\frac{4\pi}{T}t_0)\delta(\Omega) \tag{25}$$

Equation (25) shows that $i_d(t)$ has a discrete frequency component only at $\Omega = 0$, and also indicates that $i_d(t)$ is sparse in frequency domain. And CM method can be used to measure the electric energy of PrDT signal.

III. CM METHOD FOR MEASURING THE ELECTRIC ENERGY OF PRDT MODEL

Section II indicates that m-sequence dynamic testing (PrDT) signal is sparse in frequency domain, we can adopt CM method to establish a PrDT power signal model without reconstruction. And then we calculate the electric energy of the PrDT power signal.

This Section gives scope for explaining the used methods and algorithms.

A. CM detection system model for the electric energy of PrDT signal

We first consider the discretization of $p_d(t)$ with sampling frequency $f_s = N_s/T$ can be expressed as follows:

$$p_d(n') = \frac{UI}{2}\sum_{k=1}^{N}[\sum_{i=1}^{n} C_i m(k-i)(\mathrm{mod}\,2)]g(n'-kT)[\cos\varphi - \cos(2\omega_1 n' + \varphi)]$$

where $\omega_1 = \Omega_1/f_s = 2\pi/N_s$, N_s is the number of sampling points during T, n' is the sampling number of the signal. Denote the vector form $\boldsymbol{p_d} = [p_d(1), p_d(2), \cdots p_d(N_m),]^T$, where $N_m = N \cdot N_s$ is the sample points number during T_m.

According to the model in Fig.3, we regard p_d as CM original signal and obtain the electric energy E of p_d by measurement matrix Φ. The mathematical model as follows:

$$\boldsymbol{E} = \Phi \times \boldsymbol{p_d} \tag{26}$$

where $\Phi \in R^{1\times N_m}$.

Equation (26) denotes an I/O relationship of CM detection system, $\boldsymbol{p_d}$ is the input and measurement variable, E is the output and Φ is the system state matrix.

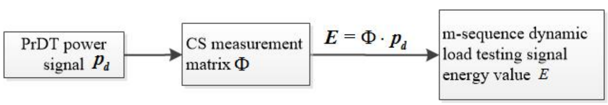

Fig.3. CM detection system model for PrDT signal

We should build the optimal measurement matrix Φ to make the relative error δ of E and the electric energy theoretical value E_0 is minimal.

$$\left|\frac{\Phi \cdot p_d - E_0}{E_0}\right| = \delta_{\min} \tag{27}$$

B. Design of CM matrix

According to the CM detection system model(Fig.3.), we adopt the steady optimization method to obtain CM matrix Φ.

Denote $m(k) = 1$, $p_d(n')$ is the steady input signal, and we can obtain the system steady quantity $\boldsymbol{h}_{1\times N_s}$ .Denote:

$$\boldsymbol{h}_{1\times N_s} = [h(n')] \quad , \quad \boldsymbol{p}_{dN_s\times 1} = [p_d(n')]^T$$

According to Equation (26), we establish the relationship:

$$E = \max(\boldsymbol{p_d}^{T}{}_{N_s\times 1} \times \boldsymbol{h}_{1\times N_s}) = \boldsymbol{\Phi}_{1\times N_s} \times \boldsymbol{p}_{d\,N_s\times 1} \tag{28}$$

Equation (26) (27) (28) show that we should find out $\boldsymbol{h}_{1\times N_s}$, which can deduce $E = E_0 = N_s p_0 \cos\varphi$, then we calculate out the deterministic measurement matrix of CM by Equation (28):

$$\Phi_{1\times N_s} = [\phi(n)] = [h(N_s - n + 1)] \tag{29}$$

through Fourier transform:

$$\begin{aligned} P_d(\omega) &= DTFT[p_d(n')] = \sum_{n'=1}^{N_s} p_d(n')e^{-j\omega n'} \\ &= \frac{IU}{2}[2\pi\cos\varphi\sum_{i=-\infty}^{+\infty}\delta(\omega - 2\pi i) - \pi e^{-j\varphi}\sum_{i=-\infty}^{+\infty}\delta(\omega + 2\omega_1 - 2\pi i) \\ &\quad - \pi e^{j\varphi}\sum_{i=-\infty}^{+\infty}\delta(\omega - 2\omega_1 - 2\pi i)] \end{aligned} \tag{30}$$

$$H(\omega) = DTFT[h(n')] = \sum_{n'=1}^{N_s} h(n')e^{-j\omega n'} \tag{31}$$

Thus, the I/O relationship of the measurement system in frequency domain can be expressed:

$$E(\omega) = P_d(\omega)H(\omega) \tag{32}$$

According to the steady optimization method, we can know the performance indicators and constraint conditions in frequency domain:

$$\min J = \min\{C_1\sum_{n'=1}^{N_s}[E(\omega) - E_0(\omega)] + C_2\sum_{n'=1}^{N_s}H^2(\omega)\} \tag{33}$$

S.t. $DTFT[E] = E_0\sum_{n'=1}^{N_s}e^{-j\omega n'} = N_s p_0 \cos\varphi\sum_{n'=1}^{N_s}e^{-j\omega n'}$

where C_1, C_2 are constant, we obtain:

$$\begin{aligned} H(\omega) &= CP_d(\omega) \\ &= C[2\pi\sum_{i=-\infty}^{+\infty}\delta(\omega - 2\pi i) - \pi\sum_{i=-\infty}^{+\infty}\delta(\omega + 2\omega_1 - 2\pi i) \\ &\quad - \pi\sum_{i=-\infty}^{+\infty}\delta(\omega - 2\omega_1 - 2\pi i)] \\ &= C\sum_{n'=1}^{N_s}(1 - \cos 2\omega_1 n')e^{-j\omega n'} \end{aligned} \tag{34}$$

where $C = -C_1 IU/4C_2$ is constant, hence:

$$h(n') = IDTFT[H(\omega)] = C[1 - \cos(2\omega_1 n')] \tag{35}$$

and

$$\phi(n') = h(N_s - n' + 1) = C\{1 - \cos[2\omega_1(n' - 1)]\} \quad (36)$$

Combining Equation (36) to $\boldsymbol{\Phi}_{1\times N_s} = [\phi(n')]$, we can get the optimal measurement matrix in CM detection system.

IV. RESULTS AND DISCUSSIONS

To verify the CM method to measure the electric energy of PrDT signal model, which is established in section II, we adopt different length of m-sequence to modulate steady signal, $f_1 = 50Hz$, $f_s = 2500Hz$. We obtain the discrete dynamic testing current signal, see Fig.4.

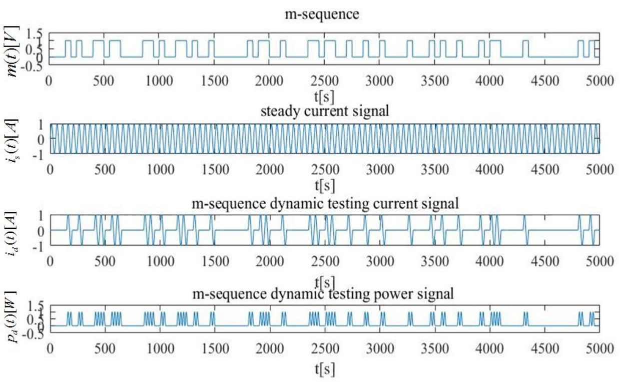

Fig. 4. Experimental simulation of PrDT signal

Then we adopt different primitive polynomial coefficients to produce different length and the same period of PrDT signals. Using CM method which we proposed, to measure electric energy of the PrDT model and calculate the measurement error δ. The errors are less than 1×10^{-14} that small enough to be ignored.

Table 1. The relative errors of single periodic PrDT signals

number	primitive polynomial coefficients and length	power factor	error δ (10^{-14})
1	101110001 (511bit)	1.0	7.03
2	110101001 (511bit)	1.0	6.48
3	101101001 (511 bit)	1.0	7.12
4	101100101 (511bit)	1.0	6.94
5	11000001 (255 bit)	1.0	1.74
6	10010001 (255 bit)	1.0	0.59
7	1000100001(1023 bit)	1.0	1.22
8	1101100001(1023 bit)	1.0	6.28

We adopt the same primitive polynomial coefficient (101110001, 511bit) and different periods of PrDT signals. Using the same CM method to measure electric energy of the PrDT model and calculate the measurement error δ (Table 2). The measurement errors δ are less than 1×10^{-14} that small enough to be ignored, too.

Table 2. The relative errors of multiple periodic PrDT signals

number	period	power factor	error δ (10^{-14})
1	1	1.0	7.03
2	2	1.0	3.55
3	4	1.0	7.62
4	2	0.5	32.9
5	4	0.5	12.1

V. CONCLUSIONS

1) A novel method of random dynamic testing signal modeling and an m-sequence dynamic testing (PrDT) signal parameter model have been proposed, and the model is suitable to both express two characteristics of the typical LPD loads and test the errors of smart meter.
2) A deterministic optimal CM measurement matrix with the minimal measuring errors has been designed, and a novel CM method has been proposed for measuring the electric energy of PrDT signal. The method can solve the problem of measuring electric energy accurately under the random dynamic testing signal condition.
3) Simulation results have been given to prove that the metering errors of CM measuring method are small enough to be ignored under the conditions of the PrDT signal and different model parameters.

VI. ACKNOWLEDGMENT

This work is supported by the National Natural Science Foundation of China (No. NSFC-51577006) and State Grid Jibei Electric Power Company Limited Research Program (No.52018K14001W).

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