The Optimization of an Electrical Accuracy of the AC Single Phase Electromechanical Meter using Box–Behnken Design

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***Abstract*—This paper presents the optimization model for an electrical accuracy of the AC single phase electromechanical meter. It is aimed to improve the electrical accuracy of the meter. Electrical accuracy of the electromechanical meter is important to the determination of electricity energy usages charged to the electricity consumers. The Response Surface Methodology, Box-Behnken Design, has been used to identify and determine the factors that affect electrical accuracy of an electromechanical meter. The experimental design starts with the identification of seven factors of interest. Eventually, four factors are proven to have effect on the electrical accuracy of an electromechanical meter. The optimal setting for each factor has been specified and the electrical accuracy has been raised to the required level.**

It's has been found that the electrical accuracy is depending on an error of meter's disk rotation speed comparing to the specified revolution of meter. Improving the electrical accuracy can be achieved by reducing the error of meter's disk rotation speed. The four identified factors are 1) the released screw distances to adjust electromagnetic fields, 2) the current coil diameter, 3) the winding cycles, and 4) the voltage coil winding cycles. The appropriate setting of these four selected factors can reduce errors of meter's disk rotation speed significantly. The optimal settings for screw position 1, 2, 3 and 4 released distance levels should be -0.3, 0.2, 1 and -1, respectively. The current coil diameter level should be set at level -1. The winding cycle level should be set at level 1 and the voltage coil winding cycle level should be set at level 0.

***Keywords*— Optimization, Electrical Accuracy, AC Single Phase Electromechanical Meter, Box-Behnken Design**

I. INTRODUCTION

Electromechanical meter has been widely used in various countries a long time ago. Electromechanical meter is known well in term of withstanding in various climates. Its lifetime is about 5 – 10 years depending on using conditions. Nowadays in Thailand this meter type is still widely used as an electricity energy meter to calculate of electricity usage charged.

The electromechanical meter design has been utilized the electromagnetic field theory to be applied. Whenever the current is supplied through current coils, this can generate an electromagnetic field around current coils (Faraday's law of induction) along with Right Thumb theory (Heinrich Lenz,'s Law). Then insert an aluminum disk through electromagnetic field, this will generate an eddy current on the disk (Heinrich Lenz,'s Law) [1]. Finally the meter disk can rotate by forces of the eddy current generated on the disk [2].

This research is related to a study of the electrical accuracy optimization of an AC electromechanical energy meter using Box-Behnken experimental design. The electrical accuracy of the energy meter is an important quality index to calculate amount of electricity usage charged for users. Generally accuracy class index of the electromechanical energy meter is class 2. It means tolerance of electrical error in this type of meter to be ±2% to ±2.5% in accordance with IEC62053-11 [3]. In production, all meter units must be tested the electrical accuracy before being delivered to customer.

Box-Behnken experimental design is an effective statistical technique to analyze a problem which has more than or equal three factors [4] for fitting response surfaces. These designs are formed by combining $2k$ factorials with incomplete block designs [5]. The objective of this techniques is to analyze the form of relationship between desired responses and factor as well as advising the best level of each factor in order to optimize responses to be desired level.

II. OBJECTIVES

The main objectives for this research are as following:

(i) To study factors that are influent to the electrical accuracy of AC single electromechanical energy meter DD862 type. The desired electrical errors are ±0.5%.

(ii) To study the best level of each factor to optimize the electrical error tolerance to be ±0.5%.

(iii) To increase sale revenue of the case study company.

III. EXPERIMENT AND METHOD

A. Introduction

Problem Identification – electrical accuracy

Response Variables – electrical errors from twelve current testing points as shown in Table I. The error of meter is comparison of the meter's disk rotation speed and the specified revolution of the meter.

TABLE I
RESPONSES FOR THE EXPERIMENTAL MODEL

Responses	Testing current (ampere)	Power factor	Voltage (Volt)
Y1	20	1	230
Y2	10	1	230
Y3	5	1	230
Y4	2.5	1	230
Y5	0.5	1	230
Y6	0.25	1	230
Y7	20	0.5	230
Y8	10	0.5	230
Y9	5	0.5	230
Y10	2.5	0.5	230
Y11	1	0.5	230
Y12	0.5	0.5	230

Identified Factors – The four identified factors are the released screw distances to adjust electromagnetic fields located in four positions inside the meter to be identified as factor A, B, C and D respectively. The other three factors are the current coil diameter and its winding cycles to be identified as factor E and F. The last factor is voltage coil winding cycles to be identified as factor G.

B. Experimental Method

This research consists of three operation steps as following:

1. Material preparation – Prepare experimental materials along with four identified factors. For the released screw distances, drive the four screws using a screw driver. For the current coil dimeter and its winding cycles, use a specific winding machine as well as the voltage coil winding, use a specific winding machine as well. Levels of each experimental factors used in experiment as summarized as shown in Table II.

TABLE II
RESPONSES FOR THE EXPERIMENTAL MODEL

Factors	Levels		
	1	2	3
A: Released screw distance 1	-1	0	1
B: Released screw distance 2	-1	0	1
C: Released screw distance 3	-1	0	1
D: Released screw distance 4	-1	0	1
E: Current coil diameter	-1	0	1
F: Current coil winding cycles	-1	0	1
G: Voltage coil winding cycles	-1	0	1

2. Box-Behnken Design – According to Box-Behnken Design for seven factors and three levels using Minitab 17, the total runs are 62 runs. All factors shown in Table I were proved that they were significant to the electrical accuracy of AC single phase electromechanical meter. The experimental design was defined alpha level (-1, 1), six center points and no replication. The experimental model was performed as shown in Fig. 1.

RunOrder	PtType	Blocks	A	B	C	D	E	F	G
1	0	1	0	0	0	0	0	0	0
2	2	1	-1	0	1	0	1	0	0
3	2	1	-1	0	0	0	0	-1	1
4	0	1	0	0	0	0	0	0	0
5	2	1	0	-1	-1	0	0	1	0
6	2	1	1	-1	0	-1	0	0	0
7	2	1	1	0	1	0	1	0	0
8	2	1	0	0	1	1	0	0	1
9	2	1	0	-1	-1	0	0	-1	0
10	2	1	0	-1	0	0	1	0	-1
11	0	1	0	0	0	0	0	0	0
12	2	1	0	0	-1	1	0	0	1
13	2	1	0	1	-1	0	0	1	0
14	0	1	0	0	0	0	0	0	0
15	2	1	0	0	-1	-1	0	0	-1
16	2	1	0	-1	1	0	0	-1	0
17	2	1	1	1	0	-1	0	0	0
18	2	1	0	0	0	-1	1	1	0
19	2	1	0	0	0	1	1	-1	0
20	2	1	0	-1	0	0	1	0	1
21	2	1	-1	0	0	0	0	1	-1
22	2	1	0	0	1	-1	0	0	-1
23	2	1	1	0	-1	0	1	0	0
24	2	1	0	0	-1	1	0	0	-1
25	2	1	0	0	-1	-1	0	0	1
26	2	1	0	0	0	-1	-1	-1	0
27	0	1	0	0	0	0	0	0	0
28	2	1	-1	-1	0	1	0	0	0
29	2	1	0	0	1	-1	0	0	1
30	2	1	1	0	0	0	0	1	-1
31	2	1	1	0	0	0	0	1	1
32	2	1	-1	0	0	0	0	1	1
33	2	1	1	1	0	1	0	0	0
34	2	1	0	1	0	0	-1	0	1
35	2	1	0	1	0	0	-1	0	-1
36	2	1	1	0	0	0	0	-1	1
37	2	1	0	-1	0	0	-1	0	1
38	2	1	1	0	-1	0	-1	0	0
39	2	1	-1	-1	0	-1	0	0	0
40	2	1	0	0	0	-1	1	-1	0
41	2	1	0	-1	0	0	-1	0	-1
42	2	1	0	0	0	1	-1	-1	0
43	2	1	0	1	1	0	0	-1	0
44	2	1	-1	0	0	0	0	-1	-1
45	0	1	0	0	0	0	0	0	0
46	2	1	-1	0	1	0	-1	0	0
47	2	1	-1	0	-1	0	1	0	0
48	2	1	0	1	-1	0	0	-1	0
49	2	1	0	0	0	-1	-1	1	0
50	2	1	0	0	0	1	-1	1	0
51	2	1	0	-1	1	0	0	1	0
52	2	1	1	0	1	0	-1	0	0
53	2	1	1	-1	0	1	0	0	0
54	2	1	0	1	0	0	1	0	1
55	2	1	1	0	0	0	0	-1	-1
56	2	1	-1	1	0	1	0	0	0
57	2	1	-1	1	0	-1	0	0	0
58	2	1	0	1	1	0	0	1	0
59	2	1	0	0	1	1	0	0	-1
60	2	1	-1	0	-1	0	-1	0	0
61	2	1	0	1	0	0	1	0	-1
62	2	1	0	0	0	1	1	1	0

Fig. 1 Experimental Plan of the Box-Behnken Design

3. Response optimization – After the experiment, the result shows that all factors are influent to the errors of specimen. Each factor has difference of significance to the errors of some current testing points. Therefore this research experiment must keep all factors in the model.

Then use the Response Optimizer function in Minitab to optimize the significant factors in order to select the optimal condition of each identified factor to optimize the electrical errors.

4. Confirmation runs – After determining the optimal condition, five confirmation runs were perform in order to validate the result of experimental design. The result of five confirmation runs were somewhat different from the experimental result but there were still along with objectives.

IV. RESULT AND DISCUSSION

The experimental results can be divided into 4 sections as following;

1. Results from Box-Behnken Design

A. Check Model Adequacy – The residual plots were used to check the adequacy of experimental model, check normal distribution, variance stability and independence of residual in order to ensure that the experiments were accurate to be concluded.

B. Normal distribution – According to residual normality plots shown in Fig. 1. Each residual plot was distributed in straight line. Therefore the residuals can be concluded that they were all normal distributed.

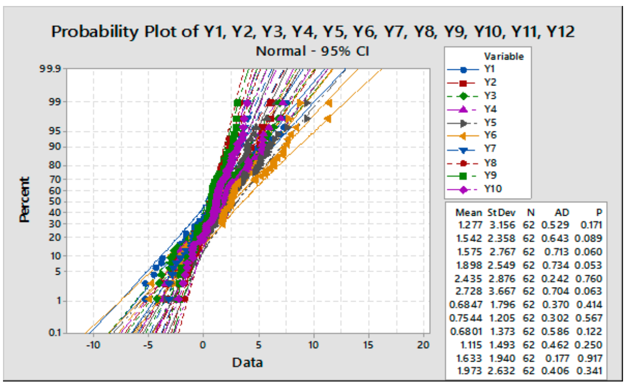

Fig. 2 Normality Plots of the residuals

For checking variance stability and independence of the residuals shown as Fig. 3 to Fig. 14 being separated by twelve responses (Y1 to Y12).

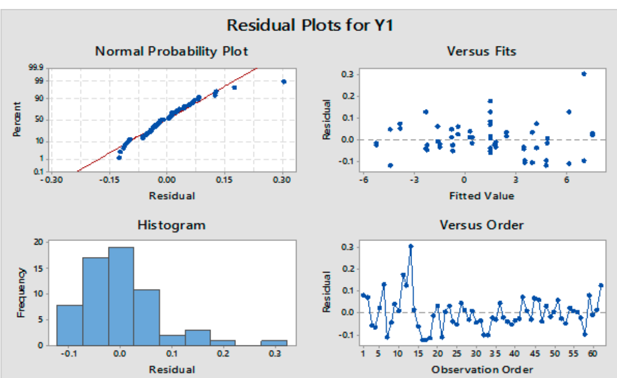

Fig. 3 Residual Plots for Y1

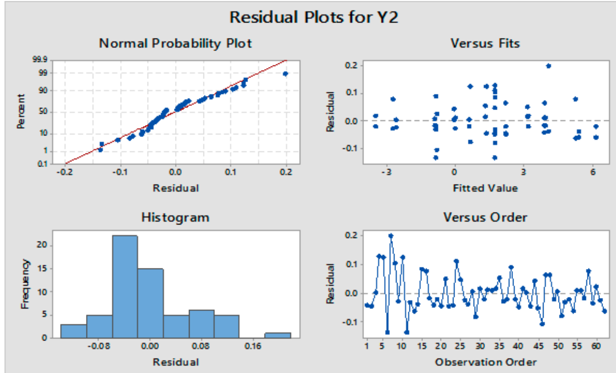

Fig. 4 Residual Plots for Y2

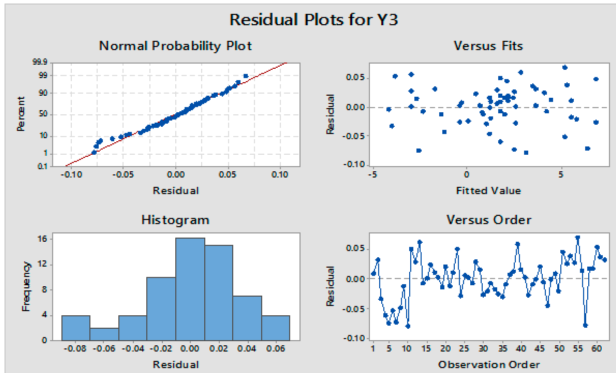

Fig. 5 Residual Plots for Y3

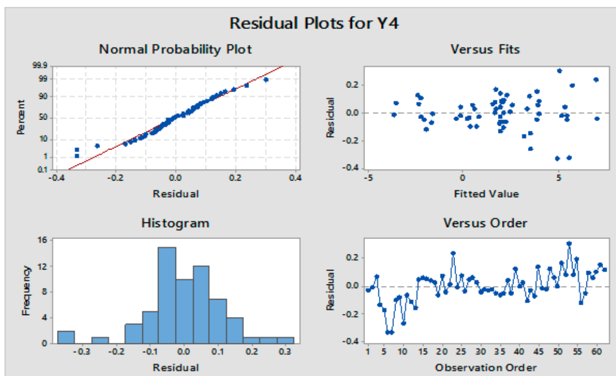

Fig. 6 Residual Plots for Y4

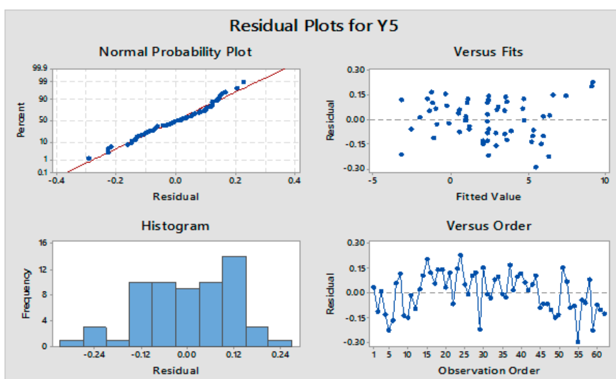

Fig. 7 Residual Plots for Y5

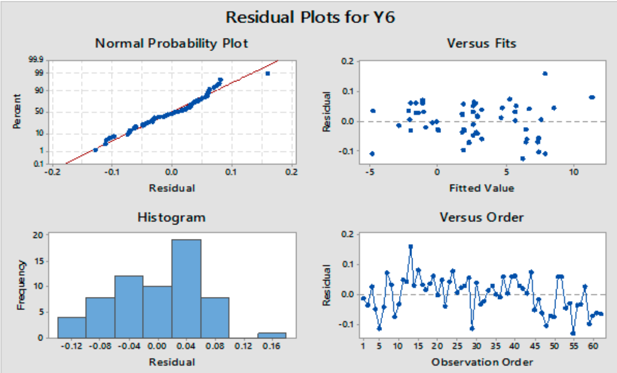

Fig. 8 Residual Plots for Y6

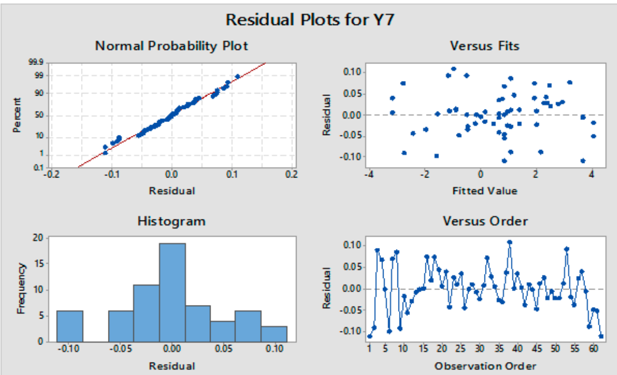

Fig. 9 Residual Plots for Y7

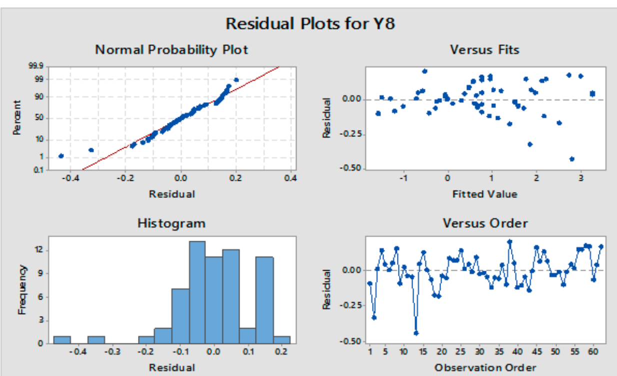

Fig. 10 Residual Plots for Y8

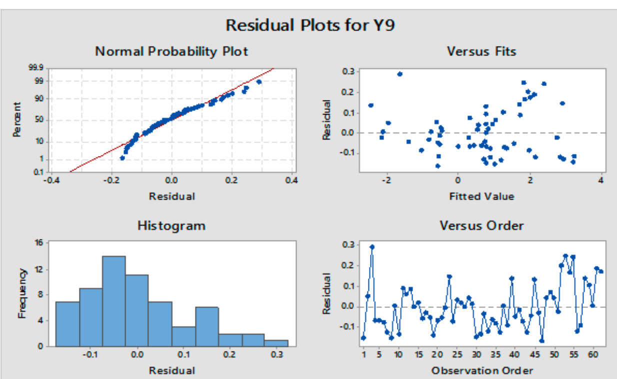

Fig. 11 Residual Plots for Y9

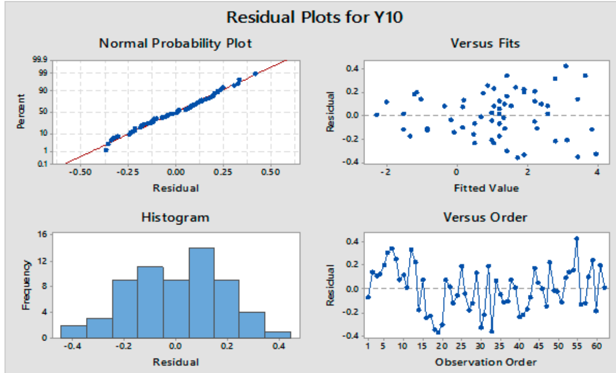

Fig. 12 Residual Plots for Y10

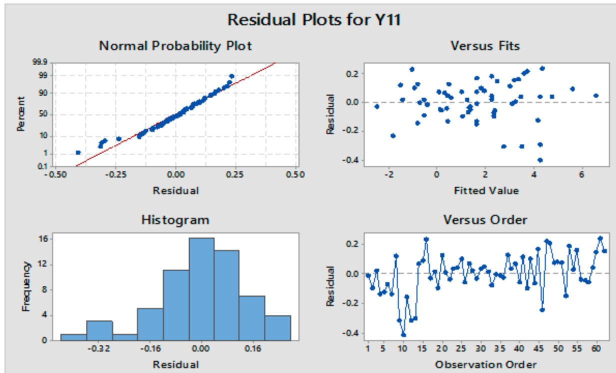

Fig. 13 Residual Plots for Y11

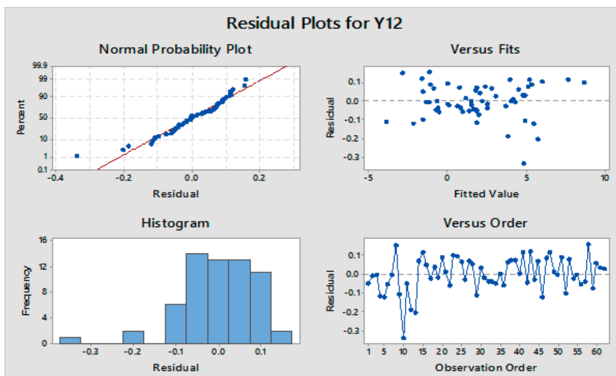

Fig. 14 Residual Plots for Y12

C. Variance Stability – According to versus fits in the residual plots as shown in Fig. 2 to Fig. 13, all versus fitted values of the residuals were distributed randomly without any particular shape, the variance stability of all residuals can be concluded that they were constant.

D. Independence of the residuals – According to versus order in the residual plots as shown in Fig. 2 to Fig. 13, all residuals were distributed without any particular pattern, the independence of the residuals can be concluded that they were independent.

2. Response Surface Methodology (RSM)

A. Box-Behnken Design

Results from Minitab for Box-Behnken Design, at significant level (α) 0.05, P-value of each main factor and 2-way interaction was lower than 0.05 in some current testing points hence all main factors cannot be eliminated from the experimental model. Therefore, the factors effect to the electrical errors of AC single phase mechanical meter DD862 type were released screw distance 1, released screw distance 2, released screw distance 3, released screw distance 4, current coil diameter, current coil winding cycles, voltage coil winding cycles and the other 2-ways interaction at a significant level 0.05 to be the final conclusion.

B. Response Optimizer

In order to optimize the level of each significant factors, response optimizer function in Minitab was performed which target is zero point for all responses. The optimal condition of all significant factors were obtained using optimization plot as shown in Fig. 14.

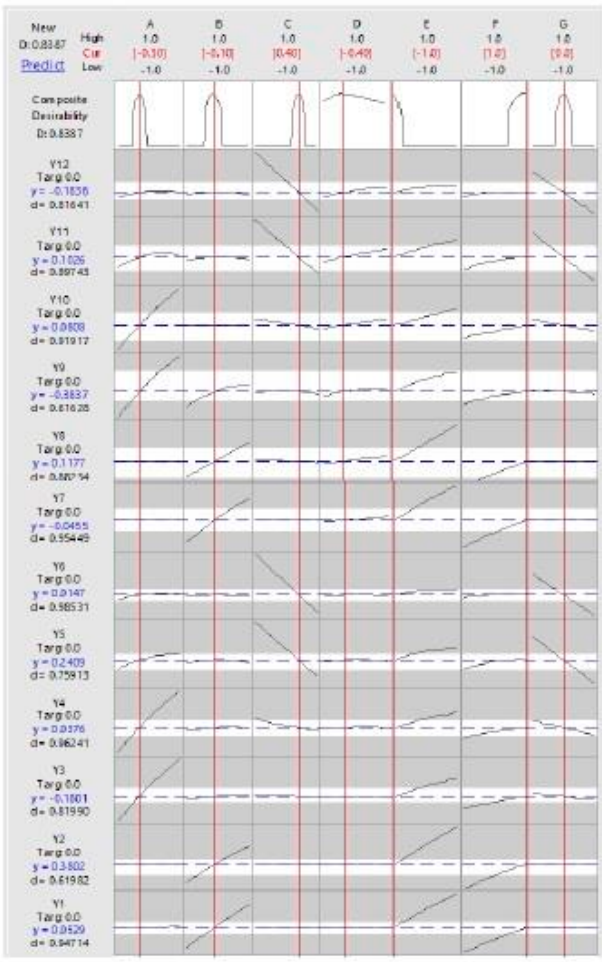

Fig. 14 Optimization plots for of factors for all responses

According to Fig. 6, the optimal condition of seven factors to minimize the electrical errors of AC single phase electromechanical meter are released screw distance 1 level to be -0.3, released screw distance 2 level to be 0.2, released screw distance 3 level to be 1, released screw distance 4 level to be -1, current coil diameter level to be -1, current coil winding cycle level to be 1 and voltage coil winding cycle level to be 0, can be summarized as shown per Table III.

TABLE III
OPTIMIZED LEVEL OF SEVEN FACTORS

Factors	Optimized level
A	-0.3
B	0.2
C	1
D	-1
E	-1
F	1
G	0

The results of optimal conditions of twelve responses were obtained as shown in Table IV.

TABLE IV
OPTIMIZED CONDITION FOR THE TWELVE RESPONSES

Responses	Electrical errors (%)
Y1	0.05
Y2	0.38
Y3	-0.18
Y4	0.03
Y5	0.24
Y6	0.01
Y7	-0.04
Y8	0.11
Y9	-0.38
Y10	0.08
Y11	0.10
Y12	-0.18

3. Confirmation runs

The results of five confirmation runs were obtained as shown in Table V.

TABLE V
RESULT OF FIVE CONFIRMATION RUNS

Responses	Electrical errors (%)				
	Meter 1	Meter 2	Meter 3	Meter 4	Meter 5
Y1	0.21	0.14	0.09	0.14	0.12
Y2	0.38	0.41	0.42	0.32	0.39
Y3	-0.38	-0.20	-0.18	-0.24	-0.27
Y4	0.19	0.24	0.11	0.19	0.20
Y5	0.42	0.31	0.22	0.37	0.34
Y6	0.22	0.15	0.05	0.16	0.33
Y7	-0.16	-0.10	-0.15	-0.22	-0.18
Y8	0.13	0.21	0.03	0.18	0.28
Y9	-0.24	-0.13	-0.42	-0.26	-0.33
Y10	0.15	0.21	0.28	0.24	0.18
Y11	0.09	0.18	0.27	0.17	0.23
Y12	-0.23	-0.18	-0.34	-0.22	-0.25

The results of five confirmation runs showed that all electrical errors were under 0.5% along with objective. Therefore the initial conclusion was the optimized level of seven factors can be used to optimize the AC single phase electromechanical meter. Then the results must be checked the model adequacy before concluding the result of the research.

Normality check - The optimized level at -0.3 of released screw distance 1, 0.2 of released screw distance 2, 1 of released screw distance 3, -1 released screw distance 4, -1 of current coil diameter, 1 of current coil winding cycles and 0 of voltage coil winding cycles were tested without replication. The result of normality test was conducted using probability plots and found that all data are normal distributed as their p-value is all higher than 0.05 as shown per Fig. 15

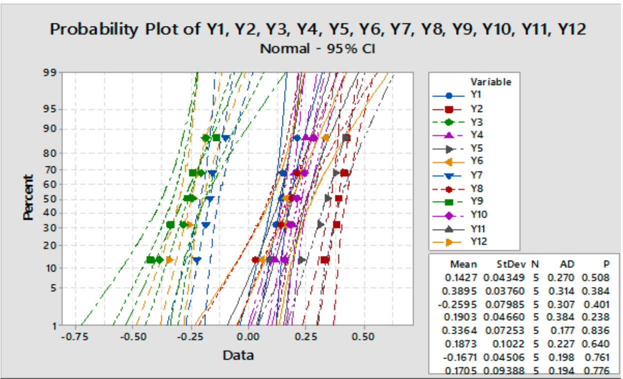

Fig. 15 Probability Plots for Confirmation Runs

V. CONCLUSION

Box-Behken Design and Minitab were performed in this research and found that released screw distance 1, released screw distance 2, released screw distance 3, released screw distance 4, current coil diameter, current coil winding cycles and voltage coil winding cycles were influent to the electrical errors.

The optimal condition of seven factors was summarize as following:

1. Released screw distance 1 set at level -0.3
2. Released screw distance 2 set at level 0.2
3. Released screw distance 3 set at level 1
4. Released screw distance 4 set at level -1
5. Current coil diameter level to be -1
6. Current coil winding cycle level to be 1
7. Voltage coil winding cycle level to be 0

Confirmation runs were performed using optimal condition of each factor to validate the results of experimental model analysis which showed the electrical errors of each testing current point shown as Table IV. The results of five confirmation runs showed that all electrical errors of five AC specimens were under 0.5% as expected in objectives. Therefore, the results of the confirmation runs were not different from the experimental model analysis.

VI. SUGGESTION

This research is for improving the electrical accuracy of the AC single phase electromechanical meter in current rate of 5(20) A. only. In case of improving the electrical accuracy of the AC single phase electromechanical meter in different current rates, needs to be reinvestigated the optimal condition of the testing current points are different. Nevertheless the methods in this research can be a guideline. There are other several factors effect to electrical accuracy of the AC single phase electromechanical meter, to investigate more factors probably used to minimize the electrical errors to be closed to zero as an ideal case.

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REFERENCES

[1] K. Siha, W. Ramanggoon, and S. Phannongsaen, “The Design and Built of the Aluminium Separator using Eddy Current Theory,” B. Eng. thesis, Khon Kaen University, Khon Kaen, Thailand, 2009.

[2] Assumption University Alumni Association, “The truth of Electricity Energy Meter,” 2013. [Online]. Available:http://www.ac108.com/forum_thai/index.php?topic=769.

[3] Thailand Industrial Standard Institute (TSI), “Electricity Metering Equipment (AC) – Particular Requirements – Electromechanical Meter For Active Energy Meter (Class 0.5, 1 and 2),” TIS2336-2552.

[4] P. Sudasana Na Ayudthaya and P. Luangpaiboon, *Design and Analysis of Experiments*. Bangkok, Thailand: Top, 2008.

[5] D. C. Montgomery, *Design and Analysis of Experiments*, 8th ed. Hoboken, NJ: Wiley, 2012.