Central Composite Design (CCD) for Parameters Optimization of Maximum Power Point Tracking (MPPT) by Response Surface Methodology (RSM)

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https://doi.org/10.26782/jmcms.2019.03.00025

Abstract

This paper focus on the CCD with RSM optimization of parameters. Design of Experiment (DoE) hardware was developed with P&O MPPT algorithm to measure Input A: Input Voltage (V_{IN}), Input B: Input Current (I_{IN}), Input C: Duty Cycle, Input D: Irradiance and output power. The optimization of process parameters was successfully identified from the experimental design and CCD results. The coefficient of determination of R^2 is shown 99.89% which is a good fit in the model. The adequacy prevision of 89.437 indicated an adequate signal and noise was negligible. The optimization of a set of experimental parameters and observed results were V_{IN}: 18.82 V, I_{IN}: 0.65A, Duty Cycle: 85% and Irradiance: 883.79 W/m^2. Overall, we concluded that input voltage is the most significant term influencing output power, following by input current, duty cycle and irradiance. All results were validated by experiments, simulations and theory calculation. The validation error results between predicted and experimental output power were shown that a maximum error at +3.65% and a minimum error at 0.00%, which had validated the accuracy of the prediction.

Keywords *:* Maximum Power Point Tracking (MPPT), Perturb and Observe (P&O), Central Composite Design (CCD), Response Surface Methodology (RSM), Design of Experiment (DOE) Optimization of Parameters.

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I. Introduction

There are tremendous amounts of MPPT researches, journals, thesis and papers discussing and evaluating each algorithm tracking performance, efficiency, advantages and drawback. Simulation results were shown only the total power (Ahmed. O, et al., 2017). Majority of RSM and CCD are vastly applied on chemical optimization process. However, there is very limited RSM and CCD application for MPPT. In the past, the optimization of MPPT (P&O) was the variation of step size and sampling time. (Femia, F., Petrone, G., Spagnuolo, G. and Vitelli, M. 2005). The unknown complexity relationship between input variables (input voltage, input current, duty cycle and irradiance) of MPPT with output of MPPT (output power) can be resolved by this research. The objectives of this research are to set up scaled-down Design of Experiment (DoE) P&O MPPT in acquiring the most optimized inputs, develop a comprehensive and accurate mathematical modelling equation of predicted MPPT output by providing alternate optimization process in elevating the efficiency.

II. Design of Experiment (DoE) Setup

The Design of Experiment (DoE) is the key element in designating a specific experimental setup to acquire the required data before the process of optimization as shown in Figure 1.

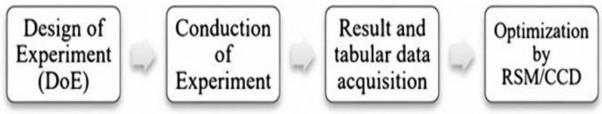

Fig. 1. Research Methodology

In a Design of Experiments (DoE), some inputs (x) will translated into one or more observable response outputs (y). RSM is a technique in predicting the effect of several input variables influencing the output responses by varying input simultaneously and conducting a series of experimental setup known as DOE. (Demirel, M. and Kayan, B., 2012). The CCD is selected to model and justify the interaction of input for the output. The Figure 2 is shown the Overall P&O MPPT DoE Hardware Setup.

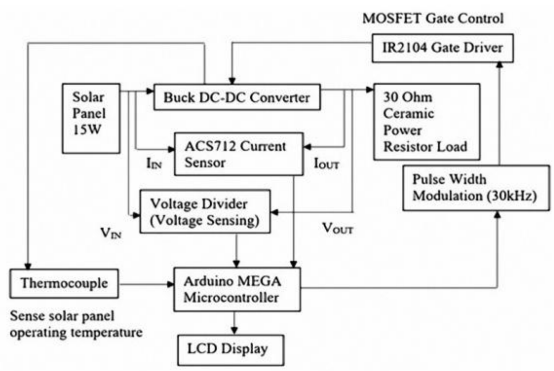

Fig. 2. P&O MPPT Block Diagram

The input power was used 15W solar panel (V_{OC}=20V, I_{SC}=1A). Based on the P&O algorithm, the programming will automatically calculate the necessary duty cycle for the PWM in controlling MOSFET to vary the output voltage and maximize output power. The PWM was set at 30 kHz (input square wave) to the MOSFET as 30 kHz (Hart, D.W., 2010). Arduino platform is used to read all parameters as data collection device. A k-type Thermocouple with MAX6675 amplifier is utilized to acquire the temperature of PV panel. Plus, the solar radiation sensor is used to measure global radiation. All the required data values were displayed via 2.4 inch MCU Friends TFT Liquid. ACS712 is used to convert the current into digital data. The IR2104 MOSFET is used as a switching gate.

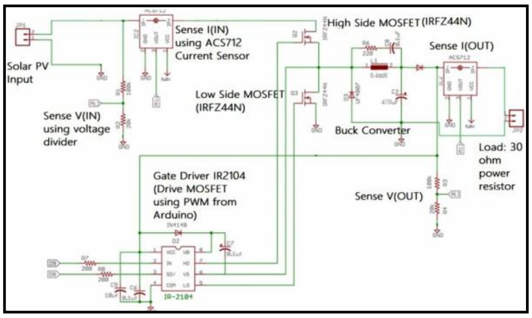

Fig. 3. P&O MPPT Circuit Schematic Drawing

Figure 3 is shown the hardware setup used in the experiment.

III. Results and Discussions

III.i. The RSM and CCD Optimization Process

The input voltage, input current, duty cycle and irradiance which have a significant effect on the power output of MPPT (response output), were selected as design variables for the RSM test. All the range for the inputs are predefined and predicted by using +alpha and –alpha method (CCD designation).

Table 1. The Range of All Input Variables

Input	Range	Mean	+ Alpha	-Alpha	
Input Voltage (V)	9-20	14.5	9	20	
Input Current (A)	0.1-1.0	0.55	0.1	1.0	
Duty Cycle (%)	60-90	75	60	90	
Irradiance (W/m2)	100-1000	550	100	1000	

The Design of Experiment (DoE) under specific controlled environment is conducted. All the data acquired from the raw data stored in the SD card: SDHC UHS-I Card. Then data was entered into Design Expert Version 10.0 by Stat-Ease software for further analysis as shown in table 2.

III.ii. Analysis of Variance (ANOVA)

Table 2. ANOVA Result

Source	Sum of Squares	Mean Square	F Value	p-value
			Prob > F	
Model	232.69	16.62	930.87	**0.0001** <0.05 (significant)
A-Input Voltage	0.28	0.28	15.67	**0.0013** <0.05 (significant)
B-Input Current	0.16	0.16	8.83	**0.0095** <0.05 (significant)
C-Duty Cycle	0.11	0.11	5.99	**0.0271** <0.05 (significant)
D-Irradiance	0.020	0.020	1.11	0.3087
AB	0.029	0.029	1.61	0.2240
AC	0.035	0.035	1.93	0.1846
AD	0.047	0.047	2.62	0.1265
BC	0.054	0.054	3.03	0.1023
BD	2.683E-003	2.683E-003	0.15	0.7037
CD	8.788E-003	8.788E-003	0.49	0.4937
A^2	0.051	0.051	2.86	0.1115
B^2	0.023	0.023	1.31	0.2703
C^2	0.015	0.015	0.81	0.3810
D^2	0.039	0.039	2.17	0.1611
Residual	0.27	0.018		
Cor Total	232.96			

The overall model's F-value (Fisher–Snedecor Value) was 930.87 implies to the model was significant since its P-value or probability value or asymptotic significance- 0.0001 was far lesser than 930.87. A model with low p-value and higher F-value indicated that the model was significant. (Prashanthi, M. and Rajakumar, S., 2016). The P-values (A, B and C) of "Prob > F" was less than 0.0500 and indicated model terms were significant. While if P-values greater than 0.1000 indicate the model terms are not significant.

Table 3. The Statistical Parameters of ANOVA

Statistical Parameters	Value
PRESS	3.01
R-Squared	0.9989
Adj R-Squared	0.9978
Pred R-Squared	0.9871
Adeq Precision	89.437

Any SNR ratio greater than 4 is desirable. This research Signal to Noise Ratio (SNR)/ Adequacy Prevision of 89.437 indicated an adequate signal i.e. signal is much more significant than noise, hence noise is negligible. (Montgomery, C.C., 2005). A small values of PRESS are desirable. In this case, the value of PRESS (Prediction Error Sum of Square) was 3.01. This model of experiment was very likely to predict new experiment output in accurate way. The Predicted R-Squared is valued at 0.9989 (99.89%), was in a reasonable agreement with the Adjusted R-Squared of 0.9978 (99.78%). The negligible difference was less than 0.2 specifically 0.11 difference. A difference with less than 0.2, which was indicated that this model was desirable. (Pant, M., Deep, K., Nagar, A. and Bansal, J.C. 2014).

The value of the correlation coefficient (R2 =99.89%) obtained in the present study for cold water temperature was higher than (R2 adjusted=99.78%). A high R2 value illustrated good agreement between the calculated and observed results within the range of the experiment. The R2 (pre) of 99.89% was in reasonable agreement with the R2 (adj) of 99.78%. In this case A, B and C were significant model terms. Insignificant model terms, which have limited influence, such as D, AB, AC, AD, BC, BD, CD, A^2, B^2, C^2 and D^2 were excluded from the study to improve the model.

III.iii. Comparison between Experimental Results with Predicted Results for 30 Runs

The Comparison between Experimental Result and Predictive Result of Output Power for Each Run Inputs were conducted. The RSM predicted mathematical equation is extremely accurate to predict experimental result with some negligible slight difference. Conclusively, the modelling is successfully predicted the correct result which comparable with experimental result. It is easier to predict using mathematical method than repeating experiment in all times. Noted that 30 runs are recommended to ensure all range of data are included.

Noted that the error is the difference between predicted result by RSM/ CCD and experimental result, in which the error percentage was calculated by using ((Predicted Result-Experimental Result)/Experimental Result) *100%. The maximum error is limited at +3.65%, and mostly the error is below 1%, which translated into very accurate prediction by RSM and CCD. The negligible difference is due to the experimental practical factor, mathematical equation modelling negligible difference and etc.

Table 4. The Comparison between Experimental Result and Predictive Result of Output Power.

Input Variables/ Parameters (Independent Variables)				Output Response (Dependent Variables)		Error %
Input A	Input B	Input C	Input D			
V_{IN} (V)	I_{IN} (A)	Duty Cycle (%)	Solar Irradiance (W/m^2)	Pout (W) (DoE Result)	Pout (W) (Predicted by RSM)	
5.91	0.63	82.00	229.49	**2.86**	**2.83**	-1.05
14.75	0.78	89.00	673.83	**9.93**	**9.86**	-0.70
16.75	0.65	78.00	717.77	**8.17**	**8.19**	+0.24
19.75	0.60	80.00	869.14	**9.15**	**9.25**	+1.09
19.58	0.69	76.00	834.96	**9.91**	**9.87**	-1.01
19.53	0.68	77.00	839.84	**9.98**	**9.84**	-1.40
7.41	0.72	78.00	390.62	**3.95**	**3.91**	-1.01
18.95	0.62	82.00	849.61	**9.45**	**9.33**	-1.27
18.82	0.65	85.00	883.79	**9.58**	**9.93**	+3.65
6.49	0.78	81.00	302.73	**3.87**	**3.84**	-0.78
6.21	0.71	81.00	234.37	**3.36**	**3.30**	-1.79
5.82	0.71	85.00	219.73	**3.25**	**3.29**	+1.23
17.43	0.62	88.00	827.42	**9.17**	**9.07**	-1.09
5.85	0.74	87.00	220.73	**3.50**	**3.58**	+2.29
17.41	0.63	79.00	927.73	**8.34**	**8.29**	-0.60
17.41	0.65	89.00	932.62	**9.57**	**9.50**	-0.73
6.57	0.74	90.00	258.79	**4.15**	**4.18**	+0.72
17.43	0.65	86.00	826.93	**9.25**	**9.29**	+0.43
16.94	0.62	87.00	966.80	**8.81**	**8.86**	+0.57
13.42	0.63	74.00	668.95	**5.87**	**5.91**	+0.68
13.98	0.65	79.00	670.44	**6.77**	**6.82**	+0.74
16.77	0.67	75.00	708.01	**7.86**	**8.03**	+2.16
16.72	0.60	78.00	747.07	**7.64**	**7.55**	-1.18
16.43	0.61	76.00	825.20	**7.31**	**7.25**	-0.82
6.53	0.64	82.00	317.38	**3.23**	**3.26**	+0.93
6.13	0.68	82.00	231.34	**3.17**	**3.17**	0.00
5.78	0.60	87.00	214.84	**2.84**	**2.74**	-3.52
4.15	0.44	86.00	156.25	**1.44**	**1.48**	+2.78
18.82	0.61	85.00	889.31	**9.42**	**9.35**	-0.74
10.12	0.74	75.00	566.41	**5.25**	**5.28**	+0.57

III.iv. Predicted Vs Actual and Normal Plot of Residuals

The predicted output power by Design Expert (simulation result) versus the practical experimental result implies that the predicted values of output power obtained from the model from RSM/ CCD and the actual experimental data (DoE) are in good agreement. Their consistency and accuracy of tallying both results from simulation and experiment are encouraging and promising.

In contrast, the Normal Plot of Residuals graph implies that the data is normally distributed. Generally, the normal probability plot is a graphical method to identify any departures from normality which includes any outliers, skewness, a need for transformations and mixtures.

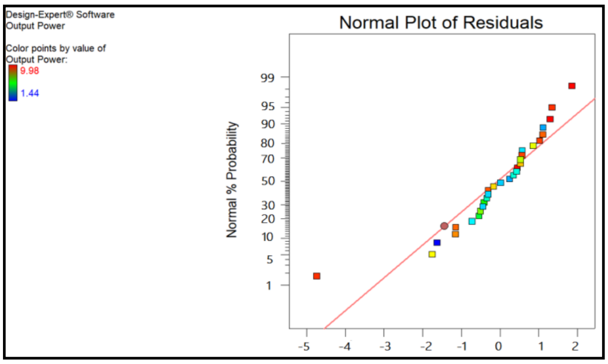

Fig. 4. The Normal Plot of Residuals graph shown that there are minimal departures from normality. Majority of data are within straight line i.e. data plotted exhibits normal behavior.

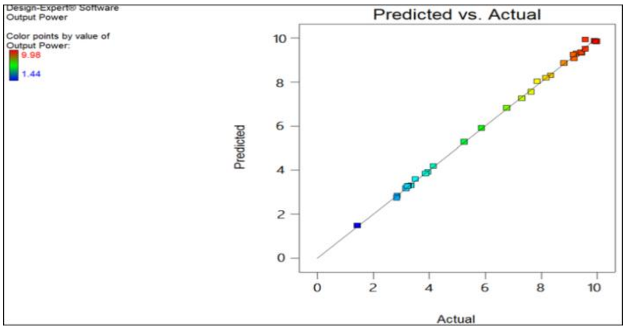

Fig. 5. The predicted output power by Design Expert (simulation result) versus the practical experimental result from Design of Experiment.

III.v. The Most Optimized Input Parameters

The most optimized input variables or parameters for maximum output power extraction from P&O MPPT. Noted that the figure 6 is readjusted/ reconfigured ranges (lower bound and upper bound) are now set according to the experimental data.

Table 5. The most optimized inputs for maximum power

A: V_{IN}	B: I_{IN}	C: Duty Cycle	D: Irradiance
18.82 V	0.65A	85%	883.79 W/m^2

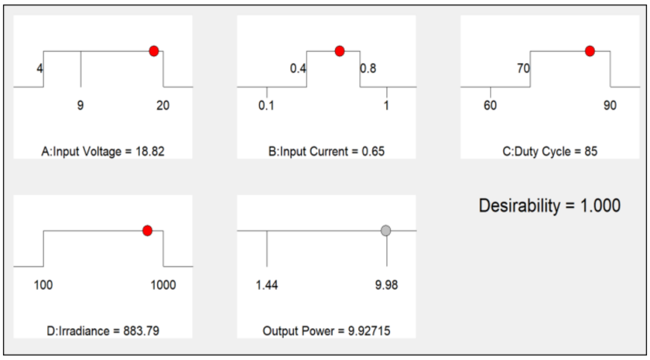

Fig. 6. The most optimized input variables are all within the predicted range.

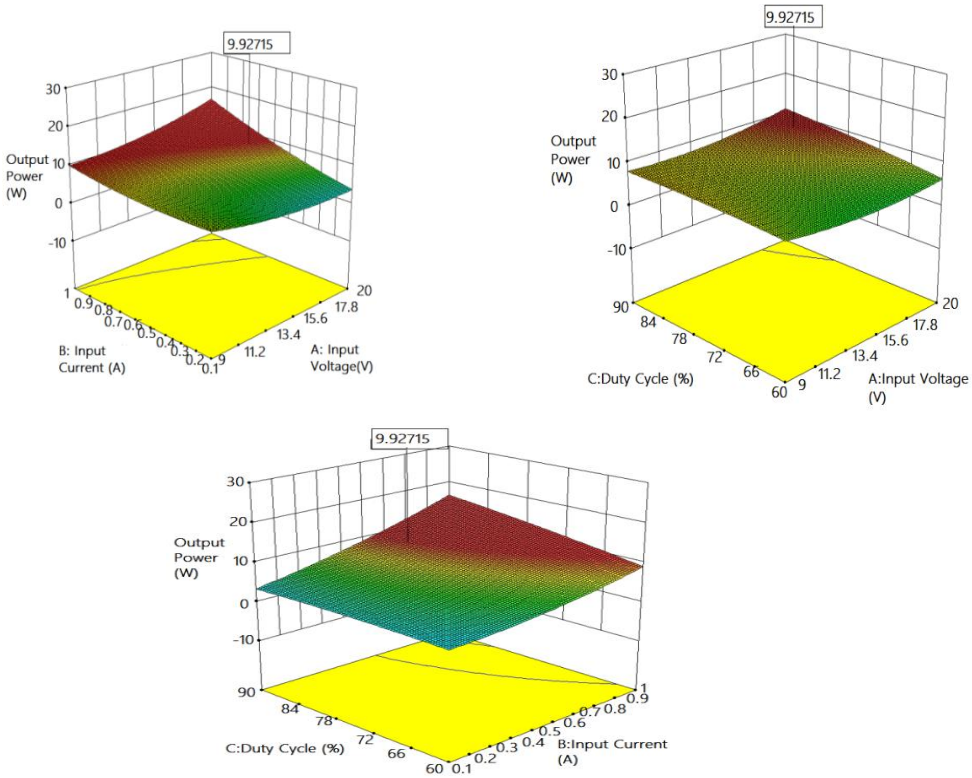

Fig. 7. The 3-Dimensional Response Surface Graph which indicates that the higher

the input voltage, input current and duty cycle, the higher the output power in mathematical relation. The P=VI governs the direct proportional relationship between

P and V/I. When the duty cycle of buck converter increases, the output voltage will also increase. It is impossible and impractical to have maximum voltage, current and duty cycle at one time, because PV solar has a limited power rating and $V_{OpenCircuit(MAX)}$ and $I_{ShortCircuit(MAX)}$ cannot be simultaneously achieved. Duty cycle of above 90% is also inefficient. So, due to PV practical restriction and V-I curve characteristic, the software will optimally find the balance between all inputs instead of maximizes all.

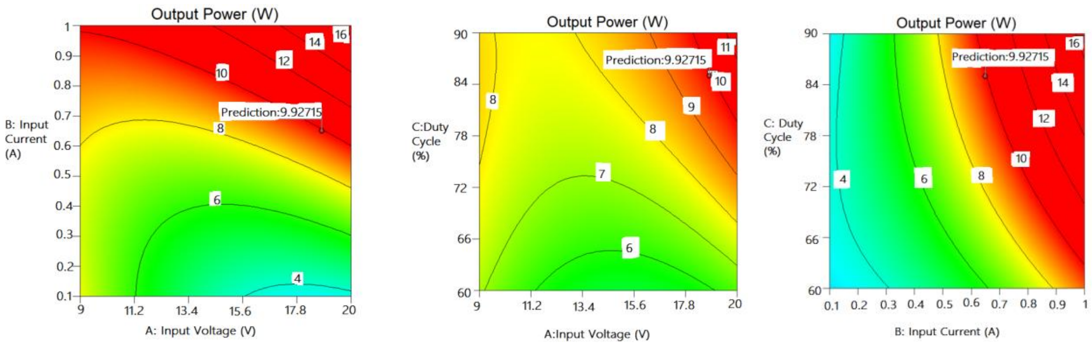

Fig. 8. The 2-Dimensional Contour Graphs are the alternate representative of 3D Response Surface Graph.

III.vi. Mathematical Modelling

All the data inputted into Design Expert is translated into a mathematical modelling equation, in term of all inputs whereby A=Input Voltage, B=Input Current, C=Duty Cycle and D=Irradiance as shown in equation 1. This enabled easier prediction by any substitution of inputs. By using this mathematical equation, it is more efficient and time-saving to predict multiple set of inputs, comparing with conventional method through changing one factor per time and fixing other factors. (Lichtfouse, E., Schwarzbauer, J. and Robert, D. 2013).

$$\text{Output Power} = 5.90817 - 1.32562A - 29.71404B + 0.099268C + 0.016738D + 1.06913AB + 0.012071AC - 0.00172471AD + 0.27119BC - 0.00696180BD - 0.000104986CD + 0.047002A^2 + 5.34370B^2 - 0.00172190C^2 + 0.0000150914D^2 \quad [1]$$

By comparing with Standard Quadratic Equation Model:

$$Y = \beta_0 + \sum_{j=1}^{k} \beta_j X_j + \sum_{i} \sum_{<j=2}^{k} \beta_{ij} X_i X_j + \sum_{j=1}^{k} \beta_{jj} X_j^2 + e_i \quad (2)$$

Whereby Y is the response; X_i and X_j are the variables; β_0 is a constant coefficient; β_j, β_{jj}, and β_{ij} are the interaction coefficients of linear, quadratic and second-order terms, respectively; k is the number of studied factors; and e_i is the error. (Carré, A. and Mittal, K.L., 2011).

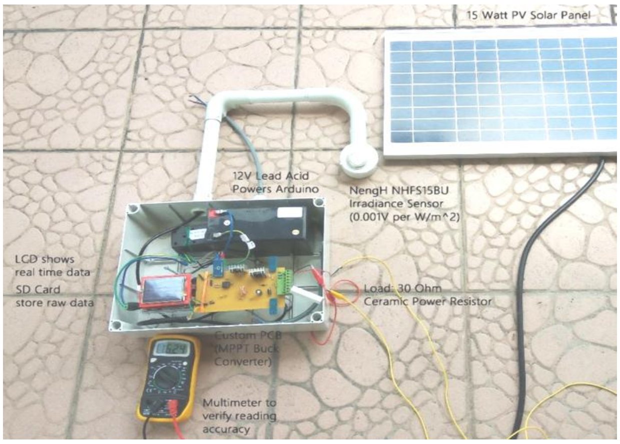

Fig .9. The Data Acquisition process under Design of Experiment (DoE) in a constantly controlled environment.

III.vii. Comparison between Experimental, Simulation and Mathematical Results

To double confirm the model's adequacy for predicting the maximum power output of MPPT, an optimized input condition new experiment was conducted

In contrast, the simulation result was acquired by Design Expert software in which the software automatically predicted the output power by using RSM and CCD technique. The mathematical result was acquired by substituting the most optimized input value into the mathematical model generated by software.

There is a good agreement between the predictive (simulation), mathematical modelling and experimental results at the optimum levels, implying it is a high validity of the model. (Sarrai, A.E., Hanini, S., Merzouk, N.K., Tassalit, D., Sazbo, T., Hernadi, K. and Nagy, L., 2016). Generally, all three results are very close to each other as shown in Table 6. By using the equation stated in mathematical modelling, all the recommended optimized inputs were substituted, we have 9.93W from mathematical results:

Table 6. The comparison between all output powers.

Experimental Result acquired from DoE	Predicted Simulation Result from RSM	Mathematical Modelling by RSM
9.58 Watt	9.92715 Watt	9.927774706 Watt

IV. Conclusions

Overall, we concluded that input voltage is the most significant term influencing output power, following by input current, duty cycle and irradiance. The efficiency of P&O MPPT is around 80%. A universal equation modelling for the MPPT output was derived for any value of input condition. Hence, we are able to theoretically utilize the developed equation to predict the output easily. All the results are validated by experimental, simulation and mathematical approaches, proven by ANOVA, graphs, various evaluations and analysis. A universal equation modelling for the MPPT output was derived for any value of input condition. Hence, we are able to theoretically utilize the developed equation to model, predict and acquire the output easily. (Othman, A.M., Elsayed, M.A., Elshafei, A.M. and Hassan, M.M., 2017).

Overall, the optimization was successfully executed. This research methodology can be similar for larger MPPT PV power generation. The software embedded inside the MPPT hardware may programme under RSM and CCD methods, with adaptive learning technology. (Hussain Mutlag, A., Mohamed, A. and Shareef, H., 2016). Plus, the RSM and CCD process can be incorporating with MPPT algorithm, alongside with Artificial Intelligence (AI)-enabled deep learning. By constantly driving the input parameter to the proximity of optimized magnitude, the efficiency of MPPT and whole solar system will be greatly improving dramatically.

V. Acknowledgment

The authors would like to thank the financial, technical and supervisory support of the UCSI University, Centre of Excellence for Research, Value Innovation and Entrepreneurship (CERVIE). The research project code are Proj-In-FETBE-027 and Proj-In-FETBE-036 and the software support (Design Expert by Stat-Ease) from UTAR University.

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