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Assessment of Energy Consumption by a Numerical Method Technique to Decide on Installing Solar Power Plants in Thailand

***Abstract**. A solar power system was designed for sustained loads; however, there was a problem when using the system for a long period of time, so it could not function as designed. This research found methods or tools to solve the problem or reduce the above problems to an acceptable level to make long-term use for loads that would continuously function. As a result, there was higher performance and reliability from the study of the tools and methods for solving the problem. It was found that numerical methods could be used to solve these problems and were responsive to the engineering applications. This paper was research on developing a model and presenting the analytical content in another form according to the research report, so to be developed in terms of energy considerations and system design to make the use of the system most efficient and beneficial. This was due to the use of solar power systems with an improper design as backup power systems. Hence, there are often problems in terms of economics and system performance involved. In addition, the size of the system must be too large in order to provide a sufficient energy supply to the energy storage system.*

***Streszczenie.** Zaprojektowano system zasilania energią słoneczną do ciągłych obciążeń; jednak wystąpił problem podczas używania systemu przez długi czas, więc nie mógł on działać zgodnie z przeznaczeniem. W ramach tych badań znaleziono metody lub narzędzia do rozwiązania problemu lub zredukowania powyższych problemów do akceptowalnego poziomu w celu długotrwałego wykorzystania obciążeń, które będą stale funkcjonować. W rezultacie uzyskano wyższą wydajność i niezawodność. Stwierdzono, że do rozwiązania tych problemów można zastosować metody numeryczne i są one przydatne w zastosowaniach inżynierskich. (**Ocena zużycia energii metodą numeryczną techniką podejmowania decyzji o instalacji elektrowni słonecznych w Tajlandii**)*

Keywords: Numerical method, Solar power plants, Correlation coefficient, Numerical integration.
Słowa kluczowe: system energetyczny zasilany energią słoneczną, optymalizacja

Introduction

Numerical methodology to analyze test data by using the correlation coefficient and the numerical integration of the numerical method has been applied for simulating the work and solar power system analysis on topics such as:

- To use in the analysis of the energy supply of solar power systems, in which there must be an installation pattern and angle of inclination in the installation with different characteristics.
- Analyze the change in the maximum power point and the maximum power transfers of the system when solar cells are connected in a series and are parallel.
- Assist in the design of the distribution of the current of the system for the loads with continuous use.
- Determine the current while charging and discharging the battery in the solar power system for a comparative analysis, etc.

Numerical analysis

After the program shows the results of the difference in the form of a graph, the program would analyze the obtained values by using numerical methods with the sequence of the steps of the analysis by utilizing the obtained values for insertion (Figure 1). This would be followed by making an estimation with the appropriate function (interpolation and approximation function), where the correct resolution would depend on the amount of information and the sampling rate of the data (sampling date) as well. After that, the program would be integrated with a numerical method (numerical integration) to find the area under the graph, that is, the amount of current, or the electrical energy at each part of the system [1-2].

Using experimental data to further calculate the obtained values, experimental values often contain values at one or more points, which may not be suitable for the calculations. Therefore, there must be a mathematical method to turn a group of points into continuous mathematical functions [3-5]. Changing data into a function can be performed in two main cases: insertion determination and estimation with the appropriate function (interpolation and approximation function). The difference between the two methods is that for interpolation, the function passes every point of the data, but the approximation function does not have to do so; that is, the function value may or may not pass through every data point, but it should be a continuous function and the value closest to every point, or it may be a graph that is best suited to a group of data. As such, there are several methods for conducting numerical analysis that could be used in both cases, but hereinafter, only a few cases that used the MATLAB programs were considered.

1) The insertion value, where the method used mainly by MATLAB was the determination of the polynomial function. This would be a connection of two adjacent points with curves or straight lines as specified. In the case of linear interpolation, linear interpolation and cubic spline interpolation would be the curve obtained from the third polynomial connected between two adjacent points. Moreover, this would provide the slope of the two curves that would meet at the data points to be equal; in other words, the curves would be flattened at the connection points.

2) Curve adjustment, the method used by MATLAB, would be the least square curve fitting, which would be the method chosen. A curve that is a polynomial with a rank, as the user wants the curve to pass through the data group, would maintain the sum of the distance from each data point to a minimum.

Building and testing a solar system simulator

Operations of the program

The calculation of the program was based on a database system of an electric current and voltage from the saved solar panel testing to analyze and calculate the values [6]. Figure 2 shows the steps to be performed in each section, and can show the working sequence of the simulator. The analysis of the solar power system is shown in Figure 3, for the simulation of a solar power system by considering the effects on the load [7], applications of the solar power system, including the rated size of the load, the load, the working voltage, etc. In the case of simulating the operation of a solar power system without considering the effect of the load [8-9], the user would only enter a specific value of the operating voltage of the system.

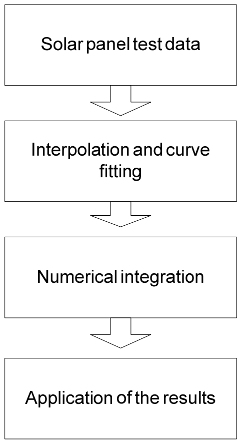

Fig. 1. Numerical method of the analysis process.

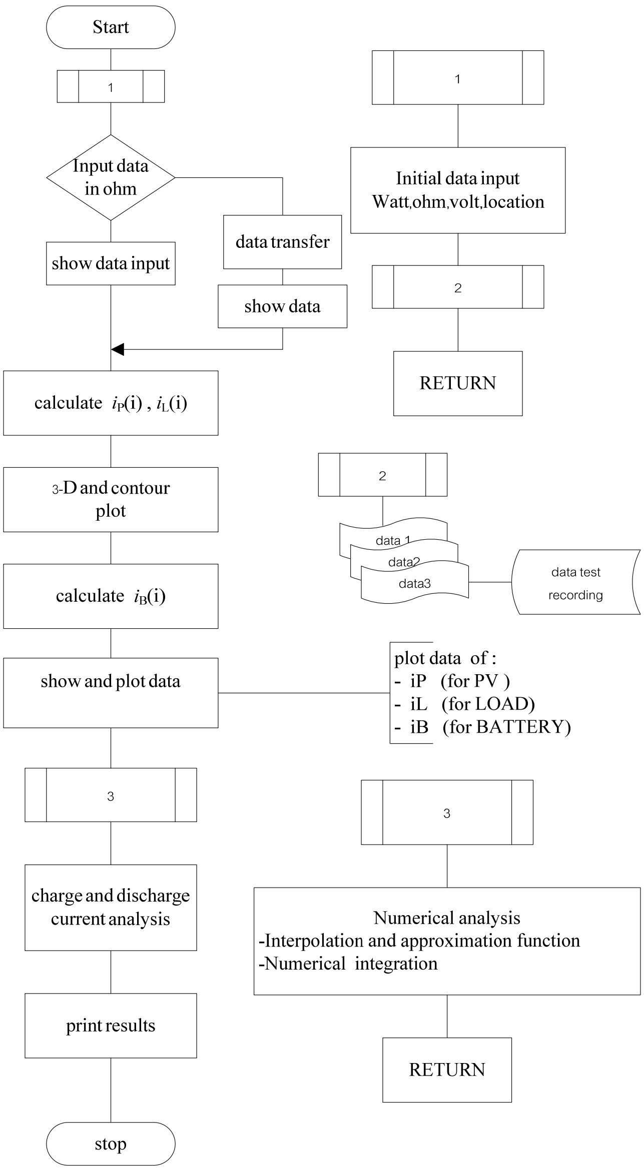

Fig. 2. Workflow of the simulator and analyzing the solar power system.

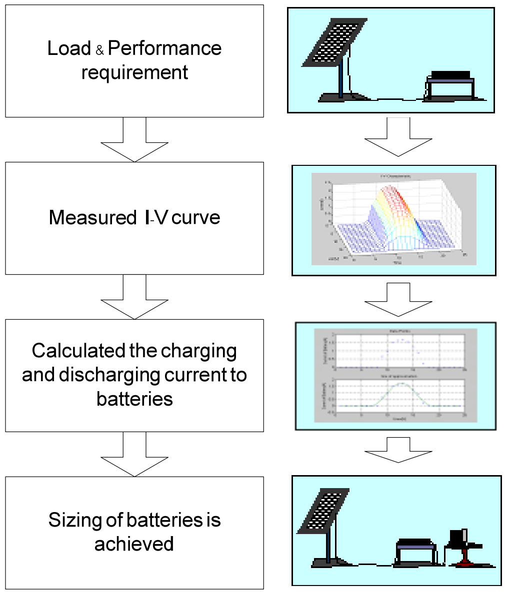

Fig. 3. Order of each part of the procedure for analyzing the solar power systems according to the proposed method.

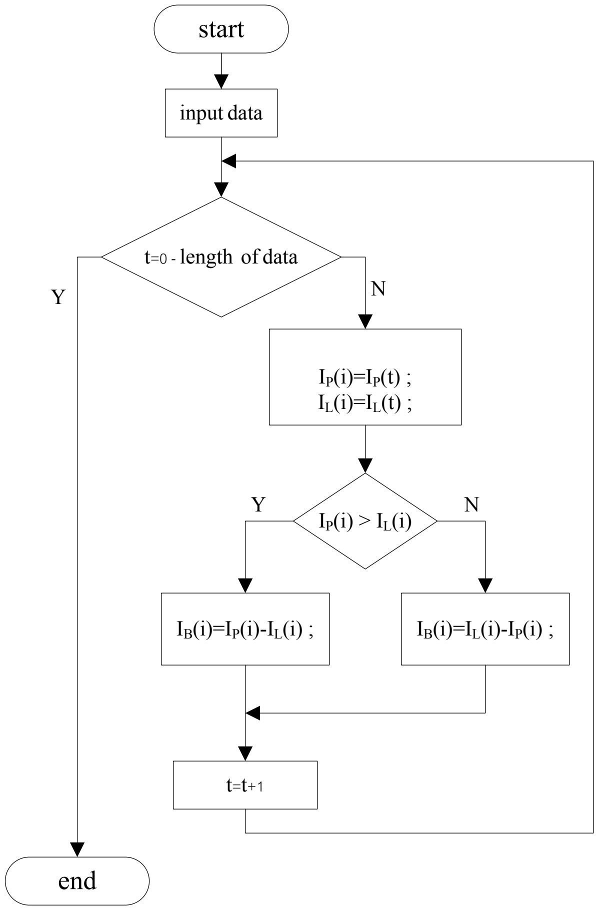

Fig. 4. Steps for calculating the current values at each section of the solar power system.

When receiving an input value for calculating the simulation of the system, the simulation program would read the data input, be ready to change the value, format it to be suitable for further calculations, and then the values would be formatted and modified. The program would calculate the solar panel current ($I_{PV(i)}$) and the load current ($I_{L(i)}$) at each value at each time period of the system's operating voltage point. This would loop the work cycle according to the amount of data that would be recorded until all periods would be completed (Figure 4), and then the program would display the data obtained from the test and store the data [10-12]. This would be shown through the screen in the form of a 3-D mesh plot and a contour plot (Figure 5).

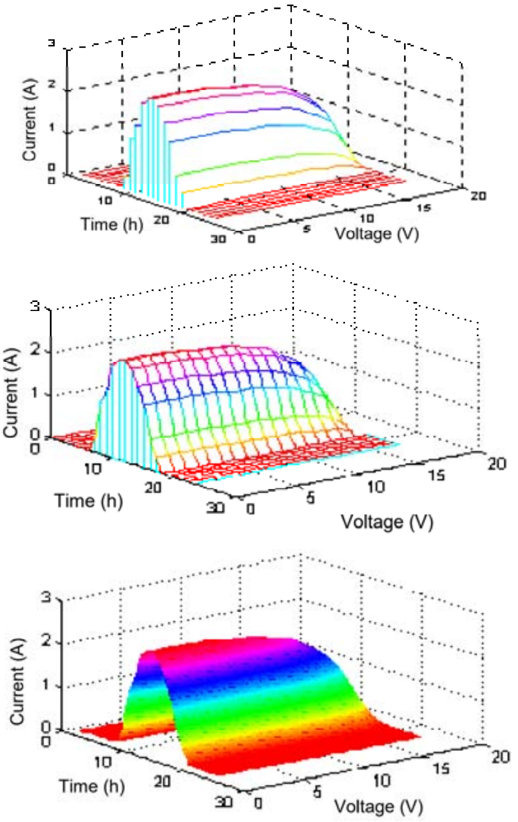

Fig. 5. The results of the three-dimensional surface shape values in various ways from the solar panel test data.

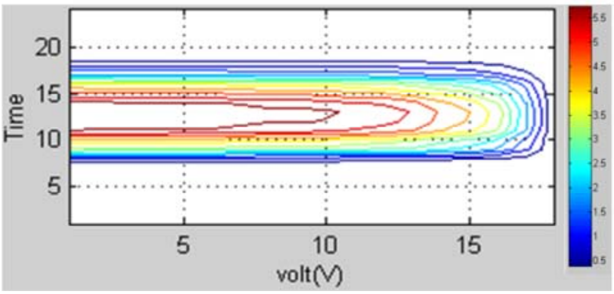

Fig. 6. Result of displaying the value in the contour plot.

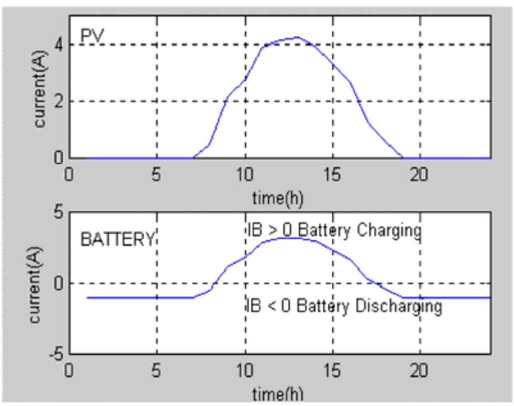

Fig. 7. The results of showing the current values at each time of the solar power system.

The user would be able to change the viewing angle and display the image at various values by setting the angle of the sweep (azimuth) for rotating the image anticlockwise (+) or clockwise (-) and set as the elevation angle (elevation) for raising the image (+) and pressing down the image (-) for plotting a mesh surface. As for plotting as a contour (Figure 6), the user could set the number of lines to view the difference at each level of the contour as well.

The program would then show the values and plot the graphs to show the different subsystem operations, including the solar panel current (I_{PV}), load current (I_L), and battery operation at different times in each time of the day (Figure 7).

Mathematical algorithm testing

The estimation between and substituting groups of data with appropriate lines.

Polynomial regression was used to determine the appropriate rank, and find the m (m^{th} order polynomial) polynomial function of the appropriate line with the method as shown in the following m^{th} degree polynomial equation:

(1) $$y = a_0 + a_1 x + a_2 x^2 + \ldots + a_m x^m + e$$

The general form:

(2) $$y = a_0 z_0 + a_1 z_1 + a_2 z_2 + \ldots + a_m z_m + e$$

where $z_0, z_1, \ldots, z_m$ is the approximation function, so rearrange Equation 2 to be:

(3)
$$y(x) = a_0 z_0(x) + a_1 z_1(x) + a_2 z_2(x) + \ldots + a_m z_m(x) + e$$
$$= \sum_{j=0}^{m} a_j z_j(x) + e$$

- The criteria to find the most suitable line: One way to find the most suitable line is to minimize the sum of the squares of the residuals (S_r), which could consider the following conditions:

(4)
$$S_r = \sum_{i=1}^{n} e_i^2$$
$$= \sum_{i=1}^{n} \left[y_i - \sum_{j=0}^{m} a_j z_j(x_i) \right]$$

Give $z_{ji} = z_j(x_i)$

(5) $$S_r = \sum_{i=1}^{n} \left[y_i - \sum_{j=o}^{m} a_j z_{ji} \right]$$

Find the minimized value:

(6) $$\frac{\partial S_r}{\partial a_j} = 0 \qquad (j = 0,1,2\ldots,m)$$
$$\sum_{i=1}^{n} \left\{ \left[y_i - \sum_{k=0}^{m} a_k z_{ki} \right] z_{ji} \right\} = 0$$

and,

(7) $$\frac{\partial S_r}{\partial a_j} = 0 \qquad (j = 0,1,2...,m)$$

$$\sum_{i=1}^{n}\left\{\left[y_i - \sum_{k=0}^{m} a_k z_{ki}\right] z_{ji}\right\} = 0$$

So,

(8) $$\sum_{i=1}^{n}\sum_{k=0}^{m} a_k z_{ki} z_{ji} = \sum_{i=1}^{n} y_i z_{ji} \qquad (j = 0,..., m)$$

Which is the "Normal Equation" for the regression coefficients $a_0 ... a_m$, where the normal equations are $\left(z^T z\right)A = z^T y$ and the normal equations can be written in a matrix form as:

(9)

$$y = \begin{bmatrix} y_1 \\ y_2 \\ . \\ . \\ . \\ y_n \end{bmatrix} \quad A = \begin{bmatrix} a_0 \\ a_1 \\ . \\ . \\ . \\ a_m \end{bmatrix} \quad z = \begin{bmatrix} z_{01} & . & . & . & z_{j1} & . & . & . & z_{m1} \\ z_{02} & & & & z_{j2} & & & & z_{m2} \\ . & & & & . & & & & . \\ . & & & & . & & & & . \\ . & & & & . & & & & . \\ z_{0n} & & & & z_{jn} & & & & z_{mn} \end{bmatrix}$$

- Standard error of the estimate ($S_{y/x}$)

(10) $$S_{y/x} = \sqrt{\frac{S_r}{n-(m+1)}}$$

where m is the rank of a polynomial function.

- The sum of the squares of the residuals about the mean $\bar{y}$ (S_t)

(11) $$S_t = \sum (y_i - \bar{y})^2$$

- Coefficient of determination (r^2)

(12) $$r^2 = \frac{S_t - S_r}{S_t}$$

- Correlation coefficient (r)

(13) $$r = \sqrt{\frac{S_t - S_r}{S_t}}$$

The conditions for determining the value for the most appropriate line would be $S_r = 0$, $r^2 = 1$, and $r = 1$. This would be the case that would show the line with the resulting continuous value and could represent 100% of the data.

Numerical integration

In this research, Simpson's method of numerical integrations was used to find the area under the curve of the required integrated function [13-14]. In using Simpson's method, the desired curve was approximated with small parabola segments, which would divide the required interval [a,b] from a to b evenly with an even number of intervals. As such, the form of the equation would be as follows:

(14) $$\int_a^b f(x)\, d(x) = \frac{h}{3}\{f_0 + 4\left(f_1 + f_3 + f_5 + ... + f_{2n-1}\right) + 2\left(f_2 + f_4 + ... + f_{2n-2}\right) + f_{2n}\}$$

when $h = \dfrac{(b-a)}{2n}$

and $f_i = f_{(xi)}$

Which could be written in a general form as follows:

(15) $$S_k = \frac{1}{3}\Delta x_k \left[f_a + 4\sum_{i=1}^{n-1} f_{(a+i\Delta_k)} + 2\sum_{i=2}^{n-2} f_{(a+i\Delta_k)} + f_b \right]$$

Where S_k is the area under the curve of the unknown function.

And $\Delta x_k = \dfrac{(b-a)}{2^k}$

When the appropriate algorithms and calculation methods were obtained, the next step would be to implement the algorithm and with the proposed method, test it to see the accuracy of the proposed methodology. This would be conducted by performing tests on various standard functions, which would know the exact solution, including the aforementioned algorithms to test with the actual used system.

Proper line estimation test

Using approximation with various ordinal polynomial functions and calculating the results of the estimation with the real equation (Table 1), the principle was used that the curves obtained from the estimation may not pass through all the data points. Rather, it must be a curve that would cause the least errors from the group of the tested data. Therefore, it could be considered that a line graph was appropriate, could be used to represent that group of data, and could be utilized as a substitute for the system's analysis on other issues. By considering the example of the comparison curve, the rank of the polynomial functions used in the estimation could be shown in Figure 8.

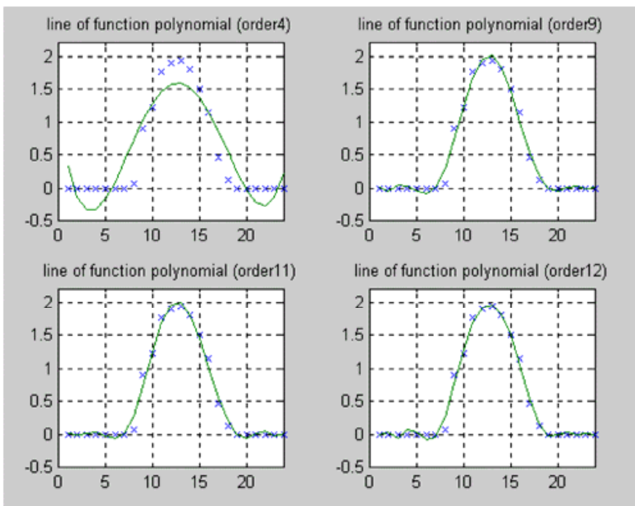

Fig. 8. Comparison of the ordinal polynomial functions for estimation of the sample data.

Table 1 shows the comparison of the calculation results when adding the order of the polynomial function. This was used to estimate more values and would result in a lower estimation error. That is, the result would be as close as possible to the actual data. However, an error should be considered in other areas, which would be a round-off error and truncation error that would consist of when appropriate algorithms and calculation methods would be obtained. The next step would be to implement the algorithm, and with the proposed method, a test to see the accuracy of the above methodology would be undertaken by doing tests with standard functions that would have known exact solutions. This would also include the aforementioned algorithms to test with the actual used system.

Table 1. Results of the calculations and comparisons with the sample functions with the known solutions.

Order of a polynomial function	Standard error of the estimate $(S_{y/x})$	Coefficient of determination (r^2)	Correlation coefficient (r)
1st order (Straight line equation)	5.7549	0.4331	0.6581
2nd order (Parabolic equation)	2.7158	0.5842	0.7643
mth order	2.8284	0.9974	0.9987

Testing of the algorithms against real solar systems

A commissioning test was performed on the solar power system to compare the proposed method with conventional energy balancing methods. After testing the algorithms used in the mathematical analysis, the information and details of the solar electric power distribution system were tested as follows:

1) Test installation location: Latitude 13.45°N, Longitude 101.32°E.
2) Solar panel: Monocrystalline silicon type; model BPTS 1255 HP; rated power 55 Wp.
3) Test load: A variable resistance load.

Tests were performed to determine suitable function models for photovoltaic applications data. The test results and comparative analysis are shown in Table 4.2. When considering the results of the estimated calculations to find suitable lines by using various ordinal polynomial functions, this would yield the different coefficients of the determination (r^2) values, and if appropriate ranks were selected, the sum of the error values would be low. This would result in a suitable graph for further data analysis.
For the polynomial results, the tenth highest coefficient of determination (r^2) yielded 0.9989, while the exponential functions yielded a coefficient of the determination (r^2) value of 0.8971, which was considered unsuitable for such system analysis because it had a higher error than the approximation with a polynomial function. From the test results and the comparison of the results using the polynomial function and exponential function (Table 2), it was found that the appropriate function for analyzing the energy supply of a solar power system was the polynomial function due to its error. From the exponential approximation results, the comparison of the difference of the polynomial function order at low and high rank values were used to estimate the solar power system in the actual installation test (Figure 10).

This proper method used the polynomial function from the proposed algorithm, which would result in a coefficient of determination (r^2) of 0.9989 and a correlation coefficient (r) of 0.9994; that is, the curve of the function could be used to represent 99.9% of the test data.

Table 2. Results of the Coefficient parameter (r^2) comparison of the functions used in the solar power system analysis.

Functional format used in the estimation	Approximation characteristics	Coefficient of determination (r^2)
Polynomial functions (mth - order)	1st order	0.0102
	2nd order	0.8969
	3rd order	0.9835
	4th order	0.9893
	5th order	0.9921
	6th order	0.9922
	7th order	0.9970
	8th order	0.9974
	9th order	0.9985
	10th order	0.9989
Exponential functions	$P_e(x)=ae^{bx}$	0.8971

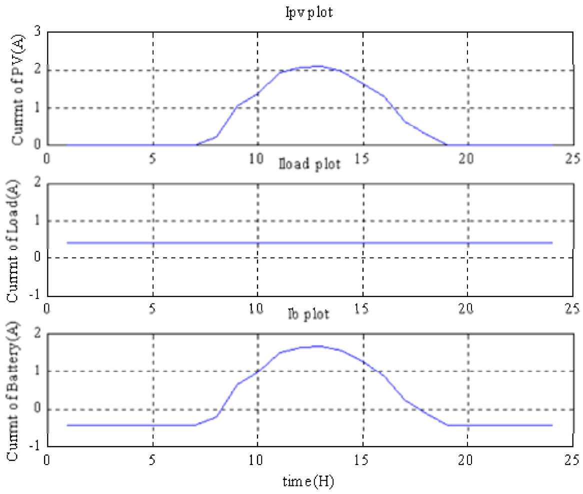

Fig. 9. Hourly diagrams of the load currents and battery currents 24 hours/day.

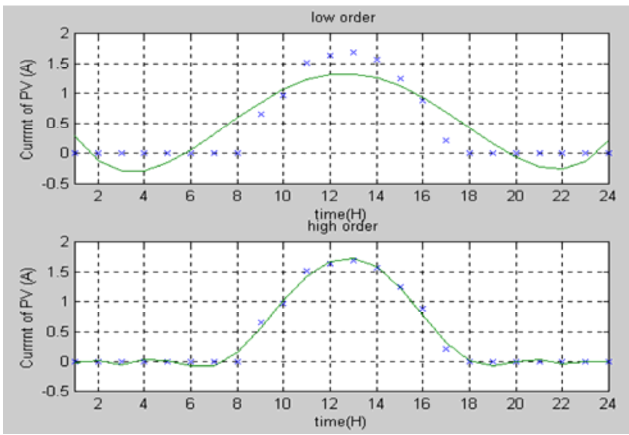

Fig. 10. Comparison of the polynomial functions at low and high order values used in the solar power system analysis.

The conditions for equilibrium between the currents at the common point of the system are shown in Figure 9, whereas the other steps are similar to those described in the numerical method section. In this case, the composite graph of the generator was derived from the combined current of the battery (discharging) and the output current of the DC-DC converter at each voltage; such as, a hyperbola curve in the I-V plane. The composite characteristics of the load would be similar to those shown in the previous section, where the intersection between the two curves would show the actual working point.

Solar power system in Thailand

Thailand is suitable for installing and using solar power systems because a tropical country receives high concentrations of solar radiation throughout the year (Figure11). For this research, the solar radiation values were plotted in Bangkok, Thailand; Latitude 13.45°N; Longitude 101.32°E.

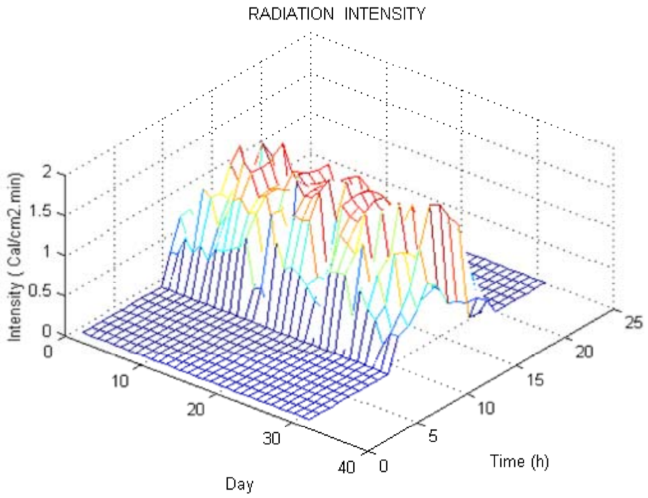

Fig. 11. Spectral irradiance distribution in July 2020 in Bangkok, Thailand.

There are two issues of a solar power plant. The first is the area that is used for the project installation [1-2]. Currently, the area used for construction per one megawatt is about 10-12 rai of land with improved technology (formerly, 15-20 rai of land was used in the first phase of the electricity sales project using solar energy). Nevertheless, there is still a problem regarding the use of large areas for solar power plant projects because it is necessary to find a place that is large enough for the generation of electricity under the power purchase agreement, and it should be land that is not far from the transmission line that would be used to connect to the system to distribute the electricity in the system. For the worthiness of the project and the area investment around the project area, there should not be any high buildings or tall trees that would overshadow the power generation panel because this would cause a decrease in the generation efficiency. Additionally, this type of solar power plant must depend on nature and the seasons. This is a problem because for the location of the project in each area of the country, the intensity of the sunlight received to generate electricity is not equal, together with the cold season, hot season, and the time of the light to generate the electrical power are also not equal. The second point is the understanding of the local people regarding solar electricity generation technology. There are still some villagers who have a misunderstanding that this type of power plant causes agricultural produce to not be as desired or causes it to fall unevenly according to the season. The solar research projects in Bangkok and the vicinity have used integrated research methodology combining quantitative research and qualitative research [15-16] with the topic studied being the establishment of a juristic person registered with the Department of Business Development, Ministry of Commerce. The sample included executives/managers of the establishments. The sample size was calculated using the formula of Yamane for 400 people by use of the specific selection method [17-18]. Questionnaires were utilised to collect the data, and for the qualitative research, in-depth interviews of the key informants who were nine academics involved in solar electricity systems were used. The tool used was an interview form. The statistics used for data analysis were descriptive statistics and reference statistics, which consisted of the percentage, average, standard deviation, and multiple regression analysis. The objectives of this research were to study: 1) The acceptance and decision-making process for solar energy use of an establishment, 2) performance of an establishment that chooses solar energy, and 3) examination of the decision model for choosing the solar workplaces of the establishment. The results indicated that, when considering the multiple correlation coefficient with step-by-step techniques, S.E. = 0.380. Prediction standards from 10 predictive variables showed that six variables entered the equation by prioritizing as follows: possibility to buy in the future (β = 0.227), state policy (β = 0.192), product attention (β = 0.174), expectation of use (β = 0.172), product knowledge (β = 0.137), and social influence (β = 0.117), which together could predict the variance of the performance of the enterprises in Bangkok and the vicinity at 76.50% with a statistically significant level of 0.05 (R2 = 0.765).

Application of the solar system to prevent corrosion by the cathodic protection method

To prevent corrosion by cathodic protection (CP), the metal required to prevent corrosion was converted to the cathode instead of an anode, which would cause corrosion. This could be done in two ways:

1) Sacrificial Anode

This was done using other metals that had the ability to attract electrons. An electromotive force or lower emf was attached to the metal to be protected. Thus, to complete the cycle, the protected metal would be the cathode, and the metal next to it would be the anode.

2) Impressed Current

This used an external electric current forcing the metal to be protected into the cathode. The electric current would have to be high enough to overcome the potential difference of the metal in order to provide the system to prevent corrosion and have a long service life.

Impressed current corrosion protection

In this research, solar power systems were designed for impressed current corrosion protection, which would use an external current to provide cathode-protected construction. There would have to be a direct current source or a rectifier to convert AC power to a direct current. The anode used must either be buried in the soil or in water to complete the cycle. The structure or work piece connected to the negative electrode anode would be connected to the anode. The type of anode used would depend on the amount of current that would be required; such as, cheap iron scraps, rapidly corroding and requiring large quantities. Graphite would be used as a bar using a current of 0.1 amps/sq m; if more, it would swell. Fifteen percent of silicon steel mixed with molybdenum or 3% of chromium, brittle, would use 0.4-0.5 amps/square meter, and platinum-plated titanium would use 5-10 amps/square meter. The system voltage required for the impressed current corrosion protection can be calculated as follows:

$$E = Io*(Ra + Rw) + Ew \tag{16}$$

where: E = O/P voltage required (volts); Io = Max. operating current (amp); Ra = Earthing resistance of the groundbed (ohms); Rw = Resistance of wiring (Max = 0.2 ohms); Ew = Anode/pipe back voltage (2.0 volts); Ip = Protective current (amp).

For the design of the impressed current corrosion protection system, the following conditions must be considered:

- Size and the surface of the pipe.
- Installation characteristics of the work pieces; such as, buried pipes, underwater pipes, etc.
- Nearby buildings metal.
- Electrical systems available at that location.

When knowing the parameters of the various elements, and then collecting information about the pipe system to be protected and to design the system, the following conditions would need to be noted:

- Impressed current corrosion protection design
  - Metal pipe diameter = 10.16 cm.
  - Length of pipe = 1 meter
  - The pipe is under the ground = 0.5 m.

Fig. 12. The 10.16-cm diameter metal pipe required to prevent corrosion.

Determination of the electric current that the system would need to prevent corrosion as the impressed current.

1) Design conditions:
   - Number of years for protection = 20 years
   - Current density = 134.712 mA/sq m.
   - Soil resistivity = 750 ohms - centimeter

2) The current required by the system:

(17) $$Ir = \frac{Average\ \ Current\ \ Density*\ \ Pipe\ \ Surface\ \ Area}{1000}$$

$$Ir = \frac{134.712\ *0.3192}{1000}$$

$$Ir = 0.043 \text{ Ampere}$$

Putting the pipe parameters into Equation17, the required system current would be (Ir) = 0.043 amperes.

3) The weight and number of the anode rods used, and the calculation of the weight of the anode rods can be shown as follows:

(18) $$W = \frac{Ir*C*Y}{U}$$

where: W Is the weight of the anode rod used; ; Ir Is the current used in the system that is equal to 0.043 amperes; C Is that the corrosion rate of the anode rod is equal to 8 kg/amp per year; Y Is the number of years of protection is equal to 20 years; U Is the utilization factor value that is equal to 0.85.

Therefore, the weight of the anode rod would be:

$$W = \frac{0.043*20*8}{0.85}$$

$$W = 8.094 \quad \text{kg}$$

The calculation of the number of anode rods used can be shown as follows:

(19)

$$Quantity\ of\ \ Anode = \frac{AnodeWeight\ (kg)}{Anode\ Weight\ \ per\ \ \ each\ (kg\ /\ each)}$$

- Anode weight is the calculated anode weight equal to 8.094 kg.
- Anode weight per each is the anode weight per rod, which would be equal to 4.25 kg per piece.

When the weight of one anode rod is 4.25 kg and the system would require an 8.094 kg anode, 1.90 usable anode rods could be determined, that is, two anodes would be sufficient for such a system. The anodes used would be magnesium anodes.

4) Resistance value, when the piping is vertical:

(20)

$$Ra = \frac{0.00521\rho}{NL}[\,2.3\log\frac{8L}{d} - 1 + (\,\frac{2L}{s}*2.3\log 0.656N)]$$

where: Ra : Resistance value when the piping is vertical (Ohm); ρ : Soil resistivity = 659.30 ohm – cm; N : Number of anodes connected in parallel (number of the anode) = 2 pcs; L : Anode length = 15 cm; d : Diameter of the anode rod (diameter of the anode) = 6 cm; S : Twice depth of the anode = 100 cm.
Therefore, resistance is obtained when piping is horizontal as: Ra = 0.2188 ohms.

The selection of the battery size would be calculated from the power applied to the corrosion protection system of the metal pipes. The battery used would be 7.5 amps/hour at a voltage of 12 volts, when the battery loses 1.032 amps of current per day, so solar panels would be required. This could charge at least 1.032 amps per day from the calculation of the amount of current that the battery would need to be supplied to the metal tube corrosion protection unit. The current would be 1.032 amp/day. In addition, the solar panel would have to recharge the battery of 4.128 amps/hour after the allowance. To be sufficient for use in the future, there would need to be a reserve in case of a possible system failure. This would need to calculate the size of a solar panel, and the voltage to be supplied to the system from the statistics of the average sunlight length in Thailand that could be used for a solar power system for approximately five hours per day. This would be considered in conjunction with the average daily and average sunlight length for the year [19]. Therefore, the amount of current that the solar panel would have to supply to the battery would be 0.825 amps when charging the factors and allowances, of the solar panel. Then, it would be used to select a silicon monocrystalline solar panel with the following coordinates:

- Rated power 13.59 watts
- Normal voltage 16.45 volts
- Open circuit voltage 21.46 volts
- Typical current 0.83 ampere
- Short circuit current 0.92 ampere

The measurement for soil resistivity of the distance between the conductors would be 60 cm, and the depth of the plant would be 20 cm, so when measuring the meter, it would read 1.5 ohms.

(21) $$\rho = \frac{4\pi AR}{[(1+\frac{2A}{\sqrt{A^2+4B^2}}-\frac{A}{\sqrt{A^2+B^2}})]}$$

By ρ Is the specific resistance.
A Is the distance between the conductors (cm).
B Is the depth of the conductors pinned into the ground (cm).
R Is the test resistance (ohms).

In the design, soil resistivity equal to 659.30 ohms-centimeter was chosen.

- Determination of the current density could show the results of the calculation as follows:
  - Current reading = 43 mA.
  - Pipe diameter = 10.16 cm.
  - The pipe length = 1 meter.
  - Area of the metal pipe to be protected = $\pi * D * L$

Current density per area is 134.712 mA./square meter.

Actual system testing for use with the metal pipe corrosion protection system

In this topic, the authors discussed the applications of the methods that were presented with the actual applied load with a continuous usage period of 24 hours to view the results of the analysis. This was compared with the actual test. The load that was tested was selected as a cathodic protection system for the corrosion protection of metal pipes because the system was in accordance with the conditions of use of the proposed methods with a 24-hour power consumption. The system also required high system reliability. This was because if such a system was continually discontinued for some time, it would result in an imbalance of the metal pipe that would need to be prevented [20], which would cause the metal pipe to corrode. Corroding in the proposed method would therefore be suitable for determining such a system.

1) Design conditions

A solar system assembly consisting of a battery and various controllers was the main supply unit that supplied the power to the corrosion protection system of the metal pipes with the electricity system of the utilities as a backup source in the event that the solar power system was damaged and unable to supply power [21]. This would be due to the requirement of the metal pipe corrosion protection system to have an external power supply for the system at all times. Otherwise, the metal pipe would corrode and rust.

2) Test equipment preparation

The required experimental equipment for the corrosion protection system of the metal pipes in the power supply unit and the load would be as follows:

2.1) The load unit is detailed as follows:

(1) The metal pipes are as shown in Figure 13.
- The metal pipe diameter is 10.16 cm.
- The pipe is 1 meter long.
- Buried 0.5 m below the ground.

When calculating the electric power demand of the load, the following results were obtained: operating voltage at 12 volts, current demand of 43 milliamps, and 24-hour power needed.

(2) Anode set for metal pipe corrosion protection system (Figure 14).
- The anode rod is magnesium metal.
- Weight is 0.8 kg.
- Number of rods is 1 stick.

Fig. 13. The metal pipe used for the impressed current corrosion protection test.

Fig. 14. The magnesium-type anode used in the impressed current metal pipe corrosion protection unit.

2.2) Power supply unit
- Single silicon crystal type of solar panel; rated power is 13.59 watts.
- The battery is sealed lead acid, which has a capacity of 7.5 ampere-hours; operating voltage is 12 volts.
- Control unit for charging the battery is a charge controller for the battery that has protection against overcharging, and prevents a reverse current from the system.
- Automatic transfer switch (ATS) is a device that controls the work during the power supply system of the solar power system and the electrical system of the electricity in the event that the solar power system could not be used to stabilize the system and prevent damage to the load.
- The electricity system of the backup power supply unit is an AC power system with a voltage of 220 volts and frequency of 50 Hz, supplied through a rectifier to generate DC power at a voltage of 12 volts to supply to the load.

The electrical system connection for testing would connect the devices together for further installation and commissioning (Figure 15).

Data analysis

To test the implementation of the entire system to check its performance and the stability of the system by keeping a record of the data in the usage conditions mentioned above, the protection effect was measured with reference to the requirements of the NACE Standard RP- 0169-92 specified by the National Association of Corrosion Engineers (NACC) of the metal pipe as follows:

1) The difference in potential was negative by more than 850 millivolts when measured through an electric solution. Electrolyte compared with copper/copper sulphate (Cu/CuSo4), excluding the resulting difference in the voltage drop (IR drops) was measured with an instant off state.

2) The difference in potential was negative by more than 850 millivolts compared with copper/copper sulfate (Cu/CuSo4) in the instant on state.

3) The difference of the change in the potential difference (polarization) during the instant off state and the natural potential must not be less than 100 millivolts.

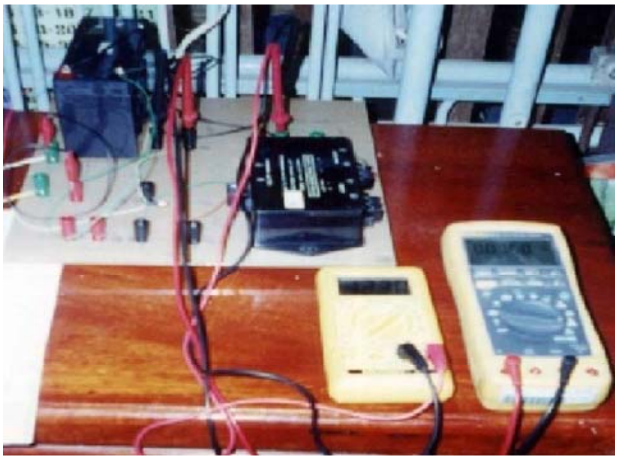

Fig. 15. An electrical system connection for testing the impressed current corrosion protection of the metal pipes.

For the test results of the anti-corrosion system of the metal pipes in a practical installation, when installed, the operating conditions were simulated in the event that the photovoltaic system would be unable to power the load. It was tested for seven days of loading and recharging the battery, then simulated the lack of the power condition of the system to see the performance of the system for five days, and then measured the corrosion protection effect of the metal pipes according to the standard. The measurement of the NACE Standard RP 0169-92 was conducted at the beginning of the installation. The measurement results were obtained after cutting, setting and using a Cu/CuSo 4 probe (Figure 16) and taking measurements in accordance with the steps specified in the standard (Table 3). In addition to displaying the results of the various measurements, the operating voltage, current at the load, and the power used at each time were also recorded throughout the period of testing the corrosion protection system of the metal pipes. The results of the comparison of the structural characteristics of the corrosion-protected metal pipe can be shown with the metal pipes without anti-corrosion protection in Figure 16.

Fig. 16. The Cu/CuSo 4 probe for measuring the anti-corrosion performance of the metal pipes.

The data analysis and functional testing to determine the validity of the proposed methods and algorithms provided accurate results and a function model, which was suitable for the power distribution analysis and solar power system design. This resulted in the calculation that was accurate and closest to the actual use of the system. It also increased the reliability of the cathodic protection system.

- Calculation with the traditional power balance method yields 4.15 amps/hours.
- From the calculation with the proposed method, the result is 3.05 amps/hours.
- The amount of current capacity from the actual measurement is 2.84 amps/hours.

Table 3. Measurement of the corrosion protection effect of the metal pipes with Cu/CuSo 4 probe.

Comparison of parameters	The results of the proposed methods	The results of the actual measurement of the testing plant
Load power (W)	3.00	3.00
Average charging voltage (V)	12.00	12.26
Average voltage at discharge (V)	12.00	11.26
Average charging current (A)	1.42	1.19
Average discharge current (A)	0.25	0.23
Electric energy while charging (W-h)	119.28	113.70
Electric energy while discharging (W-h)	39.00	36.51

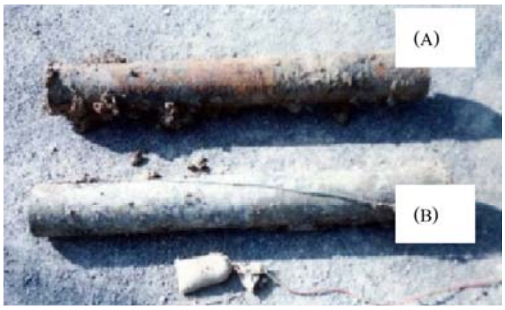

Fig. 17. Results of the structural comparison of the non-corrosion-protected pipes (A) with the impressed current corrosion protection metal pipes (B).

The results obtained from the proposed calculations were approximately 26% different from the energy balance method and 7.3% from the actual test data. When it was used to determine the capacity of the collector, this was sufficiently sized and sufficient to store the energy produced by the solar cells, and could be used to continuously supply the load. When installed to test the corrosion protection of the impressed current metal piping, the protective effect was measured in accordance with the requirements of the NACE standard RP 0169-1992, both before and after installation for seven days. As shown in Table 3, this was compliant with the requirements of the NACE standard RP 0169-1992, and when considering the structural characteristics of the pipes from the results of the comparison between the non-corrosion-proof buried metal pipes tested in soil and impressed current corrosion protection metal pipes, this showed that the system was completely able to prevent corrosion of the test installation metal pipes. Figure 16 shows that nonprevention would cause significant corrosion and rust on the surface of the pipe. Therefore, this was a good indication of the positive properties of the corrosion protection system for metal pipes from the methods and procedures listed above. In addition, the method could be applied to prevent corrosion of steel structures or other metal materials as with metal pipes; such as, building foundation systems, marine vessels, etc.

Conclusion

This article demonstrated the numerical method technique for a solar power system analysis. The results of the approximation calculations to find the appropriate line from the sample function used a polynomial function with proper estimation order, in which the sum of the error values was low. Additionally, the appropriate line used in the estimation could be used as a 100% representation of information. In the case of the estimation to find the appropriate line from the real system data, a polynomial function was used with the ranks in the estimation. Furthermore, a suitable estimate could be used to represent more than 90% of the data, but error values should be considered in other areas. For the round-off error and truncation error for this research, the authors only discussed the curve fitting and interpolation methods. However, for readers who would implement these topics, it must be noted that the resulting information may be inaccurate; such as, the data obtained from the experiment. Thus, a suitable method would be a method of using curving and polynomial estimation because the data obtained from the experiment would show that there would be no measurement errors. Therefore, the resulting graph would not have to go through all the data points, but rather the line that would cause the least amount of the overall data error. Three numerical integrations showed the results of the computational accuracy differed; for example, using the trapezoidal function would require more integrating points. In addition, quad8 and quad8 use could be achieved with a lower tolerance by the function. The quad and quad8 preliminary would be 0.001.

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