An Investigation on the Total Power Loss Equation for a Large Scale PV Power Plant

Rungphet Kongnok and Boonyang Plangklang*

***Abstract*— This paper presents an investigation of the total power loss equation for a large scale PV power plant. The relation of the actual power loss and the generated power is determined to be used as the total power loss equation in this study. The actual measurement data were taken from a 6 MWp thin-film PV power plant. The determination of the total power loss equation of the PV power plant was derived from a linear fitting curve between the actual power loss and the generated power. The total power loss equation, i.e. y = 0.0597x + 3.4908, with a variance value of about 0.9463 was obtained. The comparison between the actual total loss and the calculated result of the total power loss by using the investigated equation was conducted to validate the total power loss equation. By the measurement data, the total power loss of the PV power plant was about 6.44% of the generated power. The total power loss taken from the investigated equation was less than the actual total power loss by 0.06%. The comparison result confirms the validation of the investigated equation. Therefore, the investigated total power loss equation can be used to verify the total power loss of a large scale PV power plant.*

***Keywords*— Large scale PV power plant, Total power loss, Total power loss equation.**

1. INTRODUCTION

Nowadays, renewable energy is being used extensively in the world. Examples of renewable energy are: PV, wind, biomass, and biogas [1]. Renewable energy is a valuable alternative energy source in the world because it can reduce the level of carbon dioxide emissions from traditional energy sources and has a low impact on the environmental effect [2].

Many researchers have investigated the optimal condition in the investment cost, energy management control, how to find a high efficiency of the PV power plant installation, and the effects of design and installation problems [3, 4]. The impact of PV power generation was delivered in many cases such as power soiling loss, mismatch loss, array incident loss, light-induced degradation loss, the effect of humility, aging of long-term degradation, maximum power loss, inverter loss, transformer loss, ohmic wiring loss, respectively [5, 6]. Therefore, a PV power plant needs to be designed in optimal condition to reduce the loss of the system. Many methodologies for reducing the loss of PV power plants have presented using water spray on the surface of the PV panel as a cooling technique to mprove the performance ratio (PR). Still, the operational costs are high [7-9]. The power loss data are a critical factor in designing and estimating the performance ratio of the PV power plant. However, conventionally, the system power loss data are evaluated by a simulation program to find and investigate the power loss equation of the PV power plant. Even in the present, there is still no actual data from an actual PV power plant [10]. In general, the real power loss data of the PV power plants are difficult to collect or determine the mathematical equation. Therefore, this paper aims to investigate how to manage the power loss and to investigate the total loss equation for large scale PV power plant. Furthermore, actual measurement data from a large-scale PV are collected to determine the total power loss and to develop a mathematical model.

This paper is organized as follows: Section 2 proposes the PV power plant theory. The conceptual design of the PV power plant is presented in Section 3. The PV power plant installation and measurement data of the PV power plant are shown in Section 4 and 5. Results and discussion are shown in Section 5. Finally, Section 6 presents the conclusion.

2. PV POWER PLANT THEORY

IEC 61724:1998 standard was used as a reference to investigate characteristic parameters of the PV power plant. The characteristic parameters consist of energy efficiency, specific yield factor, and performance ratio [11]. Therefore, the equations used to analyze the characteristic parameters of the PV power plant are as follows [12].

2.1 The energy efficiency of PV power plant

The energy efficiency of PV power plant is related to the electrical energy generated by the PV power plant at a certain point of time and solar energy to the position of the surface of the PV panels. If we consider a monthly energy efficiency of the PV power plant (ηM) is computed by Equation (1):

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$$\eta_M = \frac{\sum_{k=1}^{n}(E_D)i}{S \times \sum_{i=1}^{n}(G_{opt})i} \tag{1}$$

where n represents the days of a month. E_D represents the total of electrical energy generated from PV power plant in the day (Wh). G_{opt} represents a total of global solar energy falling during the day on a square meter of PV modules (Wh/m^2). S represents the total of surface area of the PV array in PV power plant (m^2).

2.2 PV plant-specific yield factor

The specific yield factor (Y_f) is related to the electrical energy generated by the PV power plant and the total PV modules installed in the PV power plant. The PV power plant specific yield can be computed by Equation (2).

$$Y_f = \frac{E_{AC,out}}{P_{\max,STC}} \tag{2}$$

where $E_{AC,out}$ represents the electrical energy generated by the PV power plant and transmitted to the power grid (Wh). $E_{max,STC}$ represents the total installed power of the PV modules (Wp).

2.3 The performance ratio of PV power plant

The performance ratio of PV power plant (PR) is related to the PV power plant specific yield factor (Y_f) of the PV plant. The reference yield (Y_R) can be calculated with the following Equation (3).[13]

$$PR = \frac{Y_f}{Y_R} \tag{3}$$

where Y_f represents the specific yield factor. Y_R is a reference yield of the PV power plant.

Meanwhile, the PV power plant reference yield is computed by using Equation (4) as follows:

$$Y_R = \frac{G_{opt}}{1000}\frac{\left(Wh/m^2\right)}{\left(W/m^2\right)} \tag{4}$$

where G_{opt} represents the total global solar energy falling on PV modules per one square meter in the PV power plant.

Generally, the PV power plant is related to the system performance with total losses that result from degradation, pollution, from environmental and physicality of the system (wires, inverter, loss on conductor and loss on transformer)

2.4 Mean absolute percentage error (MAPE)

The MAPE is adapted to solve the difference between the investigated formula model and real measurement data. The difference in real measurement data and the investigation formula model is a problematic discussion in the proposed methodology. The MAPE needs to be minimal and close to zero so that it explains a little data change or close to the real data estimation as Equation (5) [14].

$$MAPE(\%) = \frac{1}{n} \times \sum_{t=1}^{n}\left|\frac{A_t - F_t}{A_t}\right| \times 100 \tag{5}$$

where, A_t represents the base case, F_t represents the data from the test case, and n represents the number of test data.

3. CONCEPTUAL DESIGN OF PV POWER PLANT

Design of the large-scale PV farm power plant needs to find the capacity of PV sizing installation and all components such as the PV type, the inverter type, the power rating of step-up power transformer in the PV power plant, and the location of the PV power plant. Then, the pre-designed PV power plant is selected by using the PVsyst program for simulation, as shown in Fig. 1 [15].

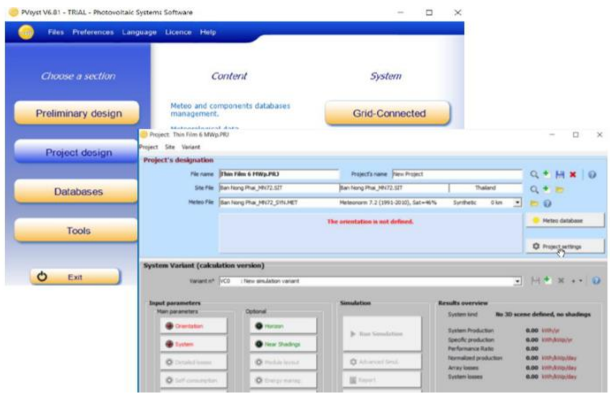

Fig. 1. The PV simulation software.

The details of the PVsyst software and the input menu for the PV power plant design are shown in Fig.1. This project was a design of the 6 MWp PV power plant with six substations. Each substation consisted of one step-up transformer and two inverters. The rated power of each substation was approximately 1 MWp. An overhead power cable and an XLPE high voltage underground cable were used to transfer the generated power to the main substation via a control unit using medium-sized switchgear.

The simulation results via the PVsyst software are illustrated in Fig. 1. The total generated energy of 9441.7 MWh/year was obtained from the simulation result. The 892.7 MWh in March was the maximum generated energy, while the 690.5 MWh in September was the minimum generated electricity. The average yearly performance ratio of the PV power plant is 0.845. Also, the simulation results were used to investigate the equation of the generated power of the installed PV panels.

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Grid-Connected System: Simulation parameters

Project : **Thin Film 6 MWp**

Geographical Site **Ban Nong Phai** Country **Thailand**

Situation Latitude 13.90° N Longitude 101.50° E

Time defined as Legal Time Time zone UT+7 Altitude 11 m

Albedo 0.20

Meteo data: **Ban Nong Phai** Meteonorm 7.2 (1991-2010), Sat=46% - Synthetic

Simulation variant : **New simulation variant**

Simulation date 17/06/19 00h24

Simulation parameters System type **No 3D scene defined, no shadings**

Collector Plane Orientation Tilt 17° Azimuth 0°

Models used Transposition Perez Diffuse Perez, Meteonorm

Horizon Free Horizon

Near Shadings No Shadings

User's needs : Unlimited load (grid)

PV Arrays Characteristics (6 kinds of array defined)

Sub-array "Sub-array #1" uCSi-aSi:H Model **NA-E125L5**
Original PVsyst database Manufacturer Sharp Corporation
Number of PV modules In series 16 modules In parallel 500 strings
Total number of PV modules Nb. modules 8000 Unit Nom. Power 125 Wp
Array global power Nominal (STC) **1000 kWp** At operating cond. 938 kWp (50°C)
Array operating characteristics (50°C) U mpp 682 V I mpp 1375 A

Sub-array "Sub-array #2" uCSi-aSi:H Model **NA-E125L5**
Original PVsyst database Manufacturer Sharp Corporation
Number of PV modules In series 16 modules In parallel 500 strings
Total number of PV modules Nb. modules 8000 Unit Nom. Power 125 Wp
Array global power Nominal (STC) **1000 kWp** At operating cond. 938 kWp (50°C)
Array operating characteristics (50°C) U mpp 682 V I mpp 1375 A

Sub-array "Sub-array #3" uCSi-aSi:H Model **NA-E125L5**
Original PVsyst database Manufacturer Sharp Corporation
Number of PV modules In series 16 modules In parallel 500 strings
Total number of PV modules Nb. modules 8000 Unit Nom. Power 125 Wp
Array global power Nominal (STC) **1000 kWp** At operating cond. 938 kWp (50°C)
Array operating characteristics (50°C) U mpp 682 V I mpp 1375 A

Sub-array "Sub-array #4" uCSi-aSi:H Model **NA-E130L5**
Original PVsyst database Manufacturer Sharp Corporation
Number of PV modules In series 16 modules In parallel 481 strings
Total number of PV modules Nb. modules 7696 Unit Nom. Power 130 Wp
Array global power Nominal (STC) **1000 kWp** At operating cond. 939 kWp (50°C)
Array operating characteristics (50°C) U mpp 695 V I mpp 1352 A

Sub-array "Sub-array #5" uCSi-aSi:H Model **NA-E130L5**
Original PVsyst database Manufacturer Sharp Corporation
Number of PV modules In series 16 modules In parallel 481 strings
Total number of PV modules Nb. modules 7696 Unit Nom. Power 130 Wp
Array global power Nominal (STC) **1000 kWp** At operating cond. 939 kWp (50°C)
Array operating characteristics (50°C) U mpp 695 V I mpp 1352 A

Sub-array "Sub-array #6" uCSi-aSi:H Model **NA-E130L5**
Original PVsyst database Manufacturer Sharp Corporation
Number of PV modules In series 16 modules In parallel 481 strings
Total number of PV modules Nb. modules 7696 Unit Nom. Power 130 Wp
Array global power Nominal (STC) **1000 kWp** At operating cond. 939 kWp (50°C)
Array operating characteristics (50°C) U mpp 695 V I mpp 1352 A

Total Arrays global power Nominal (STC) **6001 kWp** Total 47088 modules
Module area **66083 m²**

Inverter Model **SG500MX**
Original PVsyst database Manufacturer Sungrow
Characteristics Operating Voltage 460-850 V Unit Nom. Power 500 kWac

Sub-array "Sub-array #1" Nb. of inverters 2 units Total Power 1000 kWac
Pnom ratio 1.00
Sub-array "Sub-array #2" Nb. of inverters 2 units Total Power 1000 kWac
Pnom ratio 1.00
Sub-array "Sub-array #3" Nb. of inverters 2 units Total Power 1000 kWac
Pnom ratio 1.00
Sub-array "Sub-array #4" Nb. of inverters 2 units Total Power 1000 kWac
Pnom ratio 1.00
Sub-array "Sub-array #5" Nb. of inverters 2 units Total Power 1000 kWac
Pnom ratio 1.00
Sub-array "Sub-array #6" Nb. of inverters 2 units Total Power 1000 kWac
Pnom ratio 1.00

Total Nb. of inverters 12 Total Power 6000 kWac

New simulation variant

Balances and main results

	GlobHor kWh/m²	DiffHor kWh/m²	T_Amb °C	GlobInc kWh/m²	GlobEff kWh/m²	EArray MWh	E_Grid MWh	PR
January	149.7	61.40	25.78	174.0	169.1	889.7	879.2	0.842
February	140.1	67.10	27.57	153.6	149.1	785.3	776.1	0.842
March	170.5	81.80	29.63	177.2	172.0	903.3	892.7	0.839
April	170.6	88.30	30.37	166.9	161.5	850.7	840.3	0.839
May	155.7	94.70	30.09	153.6	147.9	786.6	777.0	0.843
June	155.2	94.80	29.25	142.0	136.7	731.6	722.4	0.848
July	156.5	87.50	28.98	144.5	139.3	745.7	735.9	0.849
August	142.6	96.10	28.55	136.9	132.1	711.3	701.9	0.854
September	133.6	76.90	27.39	134.6	130.1	699.6	690.5	0.855
October	139.1	76.60	27.78	147.7	143.3	763.5	753.5	0.850
November	138.9	59.20	26.61	157.9	153.6	810.2	799.9	0.844
December	145.5	52.70	25.85	172.6	168.0	882.8	872.2	0.842
Year	1808.1	907.10	28.15	1861.5	1802.6	9560.0	9441.7	0.845

Legends: GlobHor Horizontal global irradiation; DiffHor Horizontal diffuse irradiation; T_Amb Ambient Temperature; GlobInc Global incident in coll. plane; GlobEff Effective Global, corr. for IAM and shadings; EArray Effective energy at the output of the array; E_Grid Energy injected into grid; PR Performance Ratio

Fig. 2. A data report from the PV simulation software.

4. PV POWER PLANT INSTALLATION

The 6 MWp thin-film type PV farm was considered as the large-scale PV power plant in this study. The PV power plant was located at Hua Wa, Si Maha Phot District, Prachin Buri province, Thailand. The location of the PV power plant lay between latitude 13.9 N and longitude 101.5 E with a tilt angle of 17 degrees, as shown in Fig. 3. A single line diagram of the PV power plant is illustrated in Fig. 4. Furthermore, the specifications of the thin films PV module are illustrated in Tables 1 and 2, and the specifications of the inverter are shown in Table 3.

Six of 1,250 kVA, nominal voltage 22000 - 315/315 V, oil type step-up power transformers were used in this PV power plant. The ventilating system of the power transformer is ONAN, and the vector group of the power transformer is Dy11y11, as shown in Table 4.

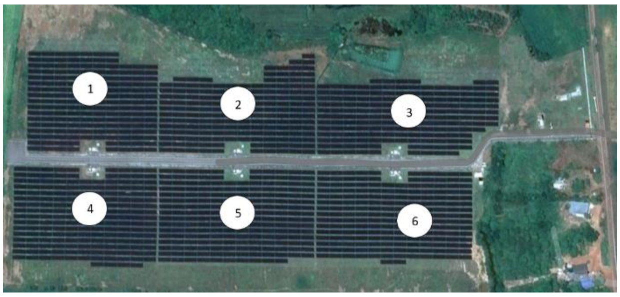


Fig. 3. Location of the PV power plant in Prachin Buri province, central Thailand [20].

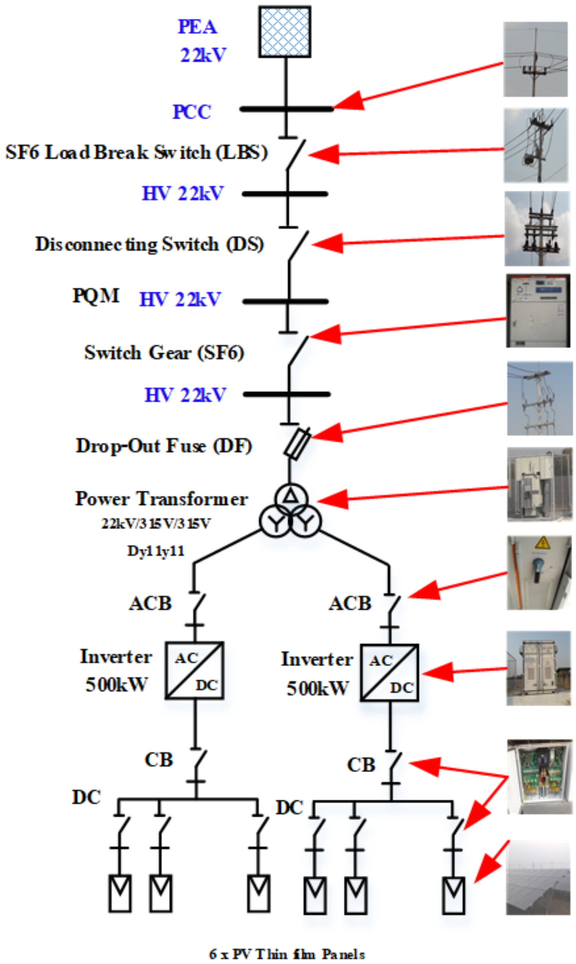


Fig.4. Single line diagram of the 6 MWP PV power plant.

Table 5. shows the rated current of XLPE cable with copper conductor, and the rated voltage at 0.6/1kV. The maximum temperature of the conductor is 90 oC, and the ambient temperature is 30 oC in the ground or direct burial.

The 6 MWp of the PV power plant was divided into six of sub-PV power plants with 1 MWp power rating. Each sub-PV power plant consisted of two inverters 500 kWp connecting to a 1250 kVA power transformer and connecting to the power distribution system of the Provincial of Electricity Authority (PEA).

Table 1. Specifications of thin-film PV panel size 125 Wp [16]

PV characteristics (STC)	Value
The maximum power (P_{max}) of PV module at STC	125 Wp
Open circuit voltage (V_{oc})	59.7 V
Short – circuit current (I_{sc})	3.37 A
The voltage at the point of maximum power (V_{mpp})	45.5 V
Current at point of maximum power (I_{mpp})	2.75 A
Module efficiency	8.9 %

Table 2. Specifications of thin-film PV panel size 130 Wp [16]

PV characteristics (STC)	Value
The maximum power (P_{max}) of PV module at STC	130 Wp
Open circuit voltage (V_{oc})	60.4 V
Short – circuit current (I_{sc})	3.41 A
The voltage at the point of maximum power (V_{mpp})	46.1 V
Current at point of maximum power (I_{mpp})	2.82 A
Module efficiency	93 %

Table 3. Specifications of inverter 500MX [17]

Inverter characteristics	Value
DC input of inverter	
Maximum voltage PV input (V_{max})	1000
Minimum voltage PV input/Startup input voltage (V_{min})	460 - 500
MPP voltage range for nominal power (V)	460 - 850
No. of independent for nominal power (PCS)	1
No. of DC input (PCS)	6 - 8

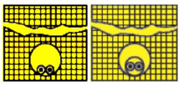
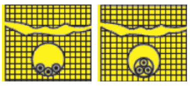
Table 3. Specifications of inverter 500MX [17] (cont'd)

Inverter characteristics	Value
Maximum PV input current (A)	1220
Maximum DC short circuit current (A)	1460
AC output of inverter	
AC output power	550 kVA @ 50 ºC, 500 kVA @ 55 ºC
Maximum AC output current (A)	1008
Nominal voltage (V)	315
Nominal grid frequency/Grid frequency range (H_z)	50/45-55, 60/55-65
THD (%)	<3(at nominal power)
DC current injection (%)	< 0.5
Power factor at nominal power/AdjusTable power factor	>0.99/0.8leading – 0.8 lagging
Feed-in phases/Connection phases	3/3
Maximum efficiency/Euro efficiency (%)	99.0 / 98.7

Table 4. Specifications of 1,250 kVA, Step-up Transformer [18]

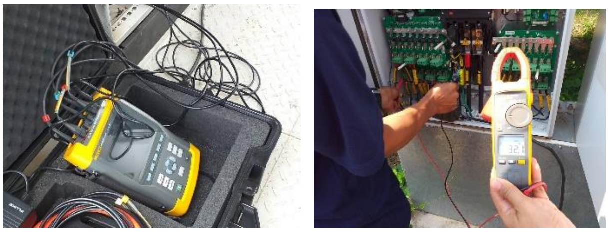
Transformer characteristics	Value
Rated power (kVA)	1250(625/625)
Frequency of transformer (H_Z)	50
Primary Voltage (V)	22000 V
Secondary Voltage (V)	315/315 V
Maximum short circuit rate (kA)	38.18 kA
Phase (ϕ)	3ϕ
Tapping	± 2 x 2.5%
Vector group	Dy11y11
Noise level	≤ 59 dB
No load loss	0.95 kW (base on 1250kVA at 75ºC)
Load loss	4.75 kW (base on 625kVA at 75ºC)
Transformer step	5

Table 5. Specifications of XLPE high voltage cable [19]

Size (mm^2)	2 conductors Single or multi-core 	3 conductors Single or multi-core 
6	54 (A)	47(A)
10	71(A)	63(A)
35	150(A)	132(A)
95	271(A)	238(A)
150	355(A)	312(A)
300	543(A)	475(A)

5. ACTUAL DATA MEASURED EVERY 15 MINUTES ALL 4 TIME PER HOURS AT THE PV POWER PLANT

In this study, the actual data at the PV power plant were collected by using a digital power meter and real-time monitoring of the PV power plant. The actual data were collected from the combiner boxes, the inverters, and the power quality measurement (PQM), respectively.



(a) Power meter (b) Clamp meter

Fig. 5. The Measuring devices used at the PV power plant

(a) Combiner box (b) Communication data set

(c) PV string combiner box (d) Common positive and negative

Fig. 6. The measurement position at the PV power plant

The measuring devices used to measure the actual data are shown in Fig. 5, and the measurement position to measure the actual data is shown in Fig. 6. The actual data were measured at the combiner box under the PV panels - all combiner boxes were connected to the input of inverter by using XLPE underground cables in nonmetal conduits. The average distance between the main combiner box to the step-up power transformer in the powerhouse container was about 200 m. The wiring cable distance from the PV panels to the sub-combiner boxes was about 50 m. The length of high voltage cables to the medium voltage switchgear was about 800 m, and the distance from the medium voltage switchgear to the point of the common coupling (PCC) was about 600 m.

6. RESULTS AND DISCUSSION

The data collected from the power meter and real-time monitoring were analyzed in each part by computing from the sub-combiner boxes backward to the PCC. The characteristics of the generated power from the PV power plant vary with the solar radiation time. The complexity of the system and the limitation of the data collection point from the measurement process affected the accuracy rate of the proposed methodology. The single line diagram of the PV power plant, as illustrated in Fig. 2., can be used to find the indirect power loss as shown Equation (6). Six parameters related to the total power loss. Furthermore, the linear fitting curve of the total generated power at the PCC is shown in Fig.8. Thus, the total power loss equation is revealed in Equation (7). The variation value of the power loss equation is 0.94363.

$$Loss_{Total} = Loss_{PV} + Loss_{Combiner} + Loss_{Inv} + Loss_{Trans} + Loss_{SwitchGear} + Loss_{VSPP} \tag{6}$$

$$Loss_{Total} = 0.0597x + 3.4908 \tag{7}$$

$$R^2 = 0.9463 \tag{8}$$

Equation (6) represents the total power loss in a PV power plant ($Loss_{Total}$) consist of PV panel loss ($Loss_{PV}$), combiner box connection loss ($Loss_{Combiner}$), inverter loss ($Loss_{Inv}$), transformer loss ($Loss_{Trans}$), switchgear loss ($Loss_{SwitchGear}$) and VSPP system loss ($Loss_{VSPP}$), respectively. R is the variance value.

The generated power from the PV panels was collected at the combiner box and transferred through the inverters, a step-up transformer, and a high voltage power transmission line. The actual power loss in each portion directly affected the reduction of the generated power of the PV power plant.

The generated power from the PV panels through the combiner boxes on the measurement period is shown in Fig.7. As illustrated in Fig.7, the maximum generated power of 5,432.25 kW was observed on 72^{th} period. Meanwhile, the total system power loss of the PV power plant measure at the combiner box obtained the maximum power loss of 314.57 kW at the same measurement period of the maximum generated power. However, as shown in Fig.7, the generated power and the total system power loss show different values along at different periods. The actual system power loss increased with an increase in generated power.

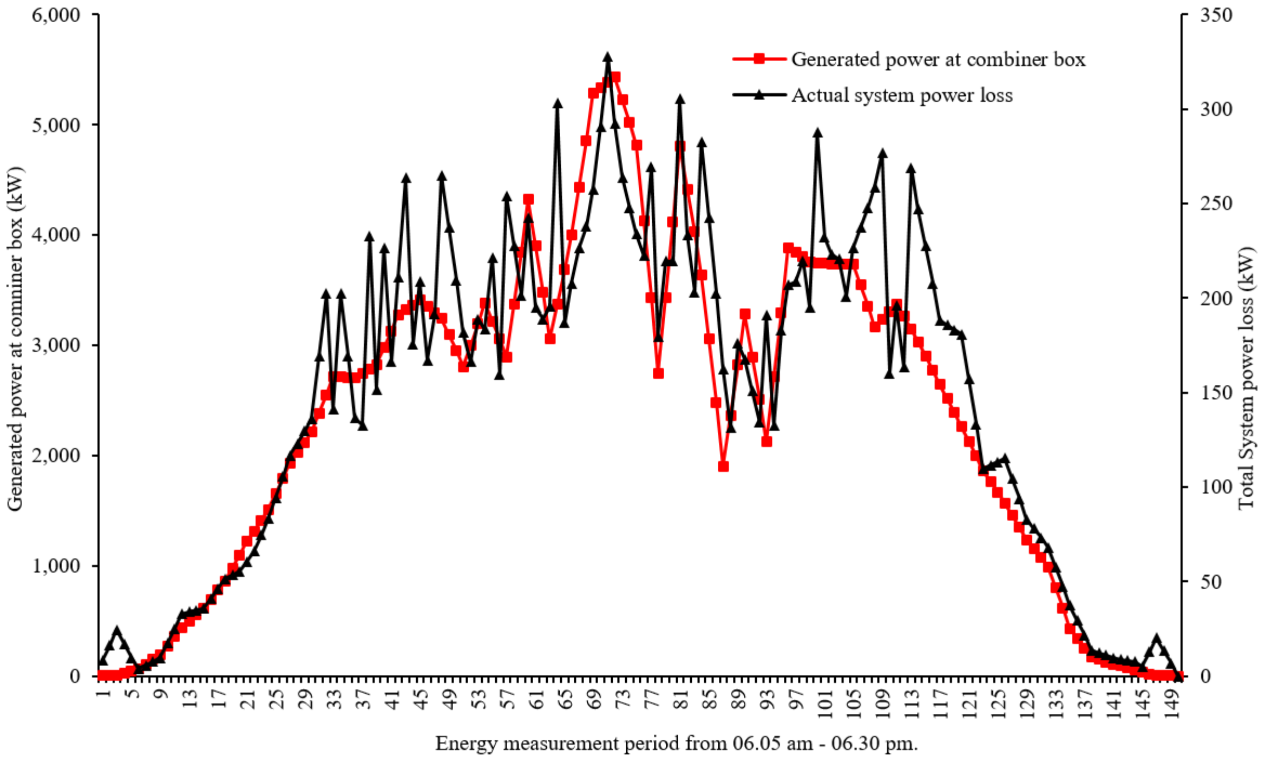


Fig.7. The Total generated power at the combiner box and the actual system loss of the plant studies.

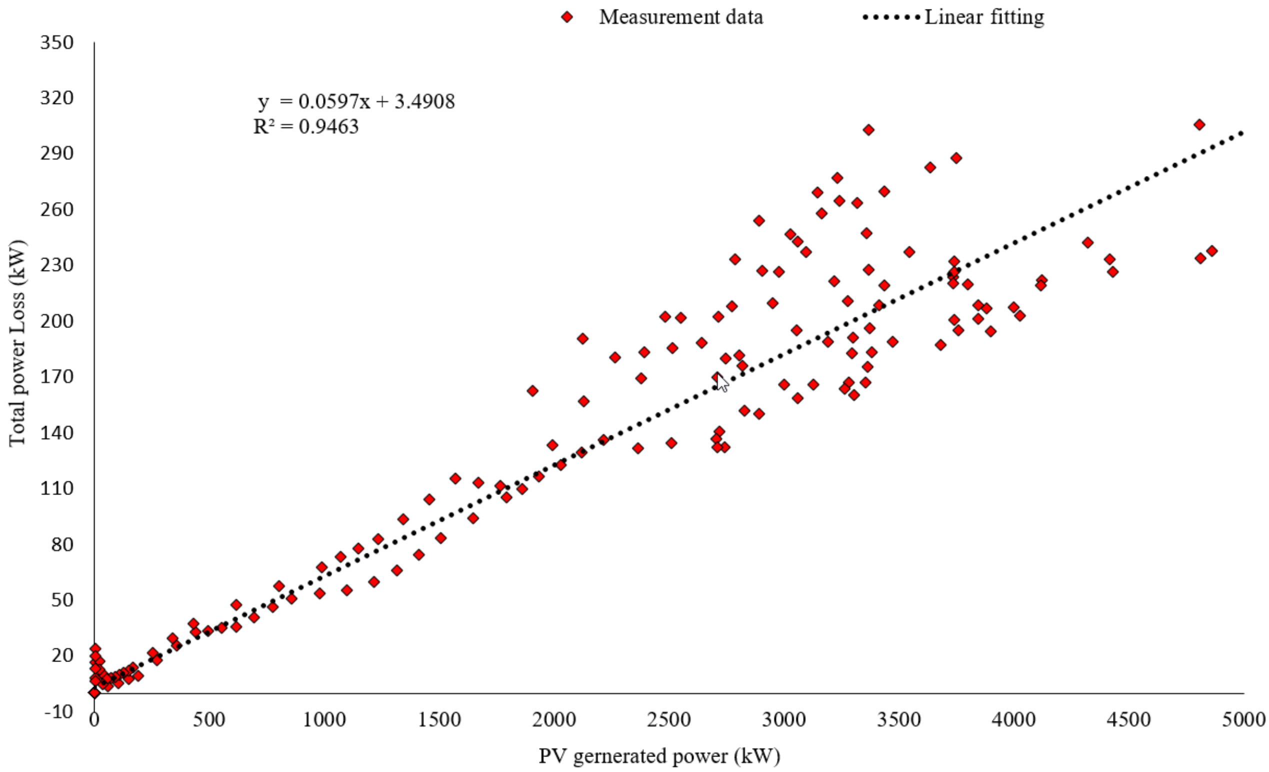


Fig.8. The linear fitting of the total generated power and the actual power loss of the PV power plant.

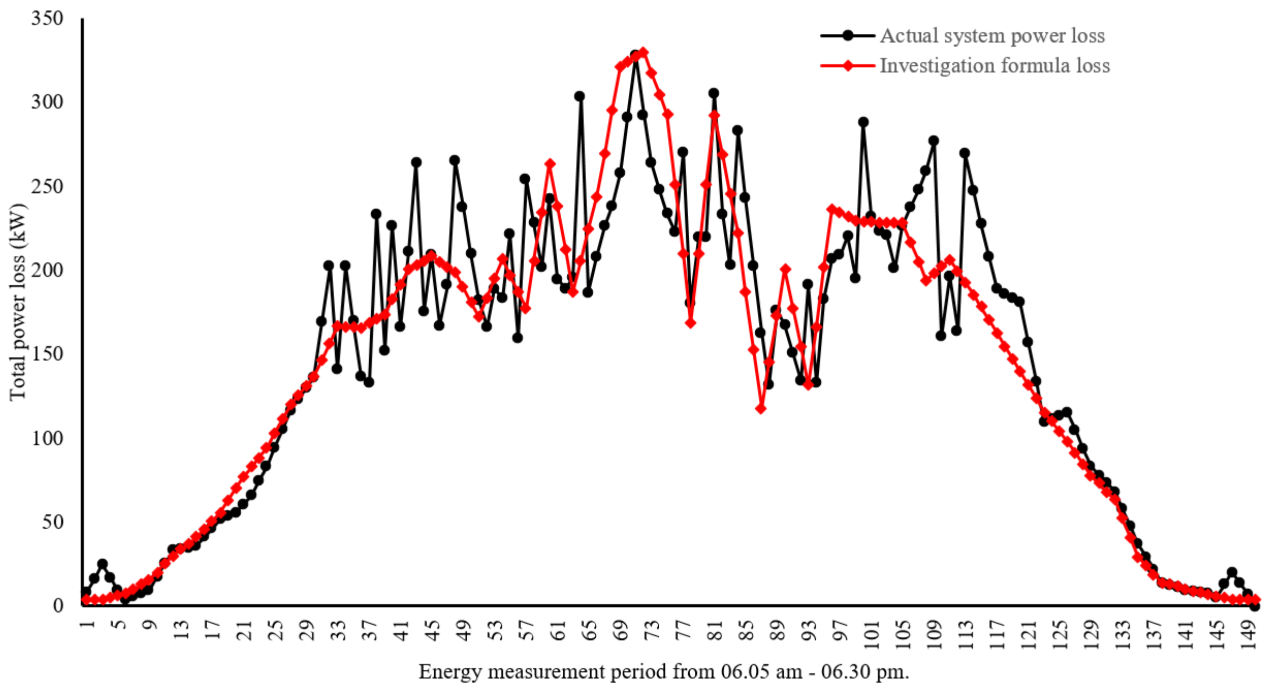


Fig. 9. A Comparison of the actual total power loss and the calculated total power loss.

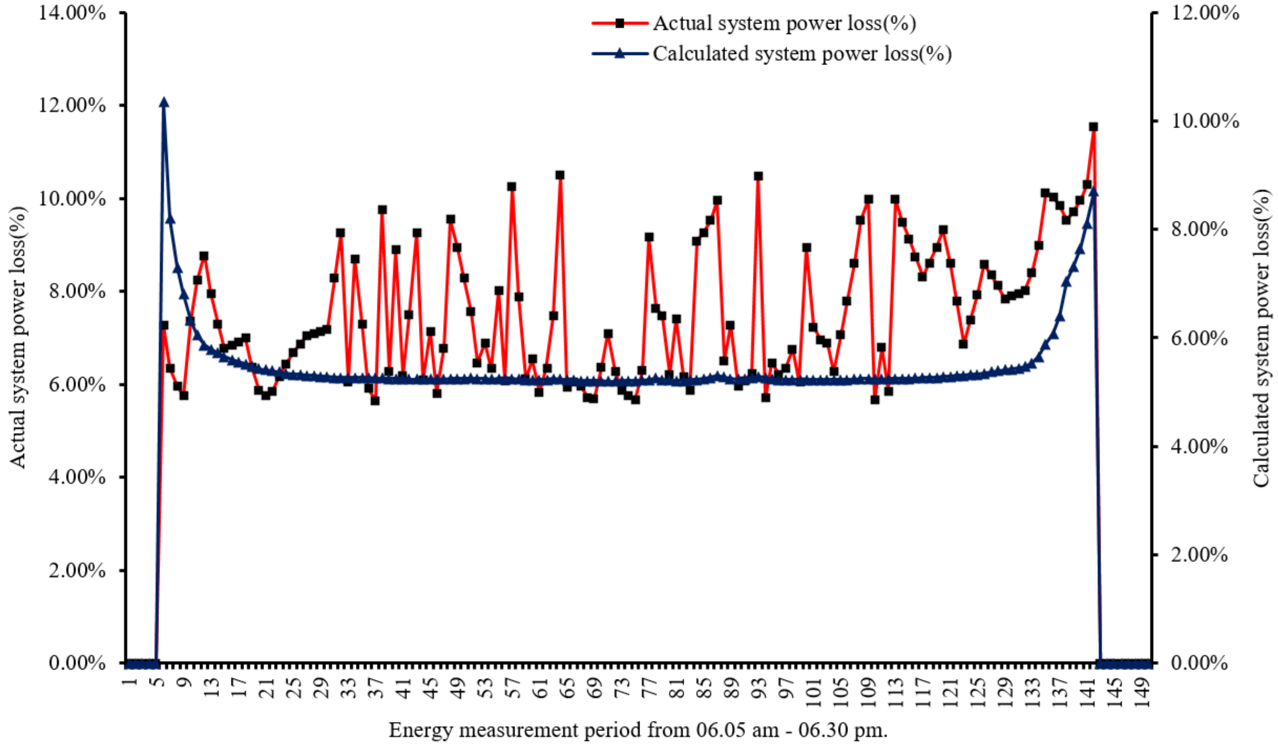


Fig. 10. A Comparison of the actual power loss and the calculated power loss in percentage based on the generated power at the combiner box

Fig.8 illustrates a linear trend of the relationship between the actual system power loss and the generated power can be observed. Direct fitting technique was applied to determine the linear equation of the total power loss and the generated power. The equation (7) with the R-square of 0.9463 is the fitting result meaning that this equation can be accepted. Thus, this equation can be used to estimate the power loss of a PV power plant and also make it easier to find the generated power loss too.

The comparison of the total actual system power loss and the calculated power loss via the investigated equation is shown in Fig.9. As illustrated in Fig. 9, both data seem reasonably close. Furthermore, by using MAPE, the comparison of the analysis results from the actual measurement data and the results using the mathematical models in equations (7) was made. It was found that the error was approximately 29.5559%. However, the system power loss increased with an increase in the generated power of the PV power plant, but the total system power loss per generated power remained at about 6.44%. It should be noted that the total power loss of the PV power plant calculated from the proposed methodology can apply to another case.

The comparison data between the actual power loss and the estimated power loss in percentage based on the generated power at the combiner boxes is shown in Fig.10. During the start-up and the shutdown periods of the PV power plant, the total power loss is higher than the generated power because the generated power from the PV panel is less than the total power loss of the step-up transformer. The average actual power loss is 6.44 %, while the calculated power loss is 6.38%. Therefore, the average calculated system power loss is less than the actual system power loss by 0.06%.

7. CONCLUSION

The results of this paper indicated a possible successful investigation of the total power loss equation in the large-scale PV power plant based on the actual measurement data. The power loss equation is a linear relationship between the generated power and the system power loss of the PV power plant. The validation of the investigated equation was done by comparing the actual power loss and the estimated power loss from the investigated equation. The investigated equation can be used to calculate the total power loss in the large-scale PV power plant. A comparison of the actual total power loss and the estimated power loss showed a similar trend with the generated power even though a difference in the data could be observed. Finally, the comparison between the actual system power loss and the calculated power loss in percentage based on generated power at the combiner boxes was made, and it was found that the average estimated power loss was less than the actual power loss by about 0.06 %.

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