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A verification analysis of power quality and energy yield of a large scale PV rooftop

B. Plangklang *, N. Thanomsat, T. Phuksamak

Department of Electrical Engineering, Faculty of Engineering, Rajamangala University of Technology Thanyaburi, Rangsit-Nakhonnayok Rd., Klong 6, Thanyaburi, Pathumthani 12110, Thailand

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ABSTRACT

The power quality and energy yield of a large scale PV rooftop power plant in Samut Songkhram province are analyzed and presented in this paper. The power quality is examined and analyzed from the measured data to comply with the Provincial Electricity Authority (PEA) standard in Thailand. The measured parameters used in this study are as follows: the RMS Voltage, Frequency, Total Voltage Harmonic Distortion (THDv), and Voltage ripple. Certain parameters of measured data are used to calculate the distributed power yield and then compared with the Homer program simulation respectively. The investigated PV rooftop system has the installed capacity of 987.84 kWp. From the monitoring results, it found that the highest power yield was 778.125 kW while the simulation result was 783 kW. Moreover, based on the PEA standard EN 50160 with the cumulative percentile at 95% for PV rooftop power plant, the measured data showed that the power quality of this power plant passed the PEA regulations for its distribution network connecting system.

1. Introduction

The renewable energy production in Thailand especially for PV systems is increasing continuously as in other places, the growing up of PV rooftop installations has been resulted by renewable energy schemes at either domestic or commercial building premises (Eke and Senturk, 2013; Sun et al., 2012; Menoufi et al., 2013; Muhammad-Sukki et al., 2014; Hachem et al., 2014). There are many reasons for this impact such as technology developments, the lower costs of technology, the higher subsidization from the government in renewable energy sources, and environmental concerns. Thus this paper presents a large scale PV rooftop power plant which is the first large scale PV rooftop system in Samut Songkhram, Thailand under 1 MW installation capacity. Before generating into the grid, this power plant must pass the Provincial Electricity Authority (PEA) regulations for its distribution network and connecting system inspections.

Several researchers have studied the designs and the economy of PV rooftop system (Fernandez-Infantes et al., 2006; Ren et al., 2009a,b; Wittkopf et al., 2012; Ko et al., 2015; Miranda et al., 2015; Gong and Kulkarni, 2005; Ioannou et al., 2014; Acquaviva et al., 2000; Ayompe et al., 2011). They found the problems associated with protection systems and its safety. The grid interface and power quality in particular are created by a large number of grid-connected PV rooftop systems at present (Aiello et al., 2006a).

There are many different types of power qualities. The goal is to create a sinusoidal of received current as an output of the grid connected to the PV rooftop plants. Nevertheless, harmonics are found in the output PV current because the inverter and variable power are used in the PV system to flow into the grid. Furthermore, the flowing of currents through the impedances of the distribution system (variable with frequency) results in voltage distortion of system (Grady and Santoso, 2001).

The subjects of this research paper (Aiello et al., 2006b; Papaioannou et al., 2008) are also involved the practical interaction of installed PV system and distribution grid. Since only few literatures and researchers have discussed power quality disturbances and the contribution of PV system for grid harmonic level utilization in particular (Grady and Santoso, 2001; Papaioannou et al., 2008; Batrinu et al., 2006; Menti et al., 2011; Chicco et al., 2005; McNeil and Mirza, 1983; Schlabbach, 2008), the need to further such study becomes significant. The subjects of several international standards of power quality (IEEE Standard, 2003; EN 50160, 0000) describe that voltages and the level of harmonic distortion in grid currents result from grid-connected PV systems. The limit of Total Voltage Harmonic Distortion (THDv) is 8% based on the European standard EN50160 (EN 50160, 0000), and this can increase up to the 40th

* Corresponding author.
E-mail address: boonyang.p@en.rmutt.ac.th (B. Plangklang).

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Table 1
The minimum and the maximum voltage level standards of PEA.

Voltage level	Steady state		Emergency	
	Max. (kV)	Min. (kV)	Max. (kV)	Min. (kV)
115 kV	120.7	109.2	126.5	103.5
33 kV	34.7	31.3	36.3	29.7
22 kV	23.1	20.9	24.2	19.8
380 V	418	342	418	342
220 V	240	200	240	200

harmonic. In Thailand, harmonic limits are considered the THD factor. In addition, when PV plants or PV rooftops are connecting to the public electrical grid, the regulatory requirements in the document (Provincial Electricity Authority, 0000) edited by Provincial Electricity Authority (PEA) must be considered. The maximum voltage or THD factor from the individual power generation must not exceed 3%.

Designing processes for a large scale PV rooftop system, monitoring power quality, and comparing energy yield between simulation and actual value are clearly presented in this paper. The PV rooftop system is designed and the anticipated PV operational problems, i.e. harmonic effect, voltage fluctuation are discussed. Finally, the energy yield of this system is simulated and analyzed with actual value from monitoring. This paper also discusses the technical performance of the installations by using parameters such as performance ratio.

2. Methods and design

2.1. Power quality

In an ideal power system, generating electricity from power producer should invariably and perfectly display a sinusoidal voltage waveform at every customer locations even though it is hard to save such desirable conditions. The standard deviation of the current waveforms and the voltage from sinusoidal are described in terms of waveform distortion, such as, voltage fluctuation, and harmonic distortion (De La Rosa, 2006).

2.1.1. Voltage

The voltage must be controlled by power producer in the range of maximum and minimum standards as defined in Table 1.

2.1.2. Frequency

It must be controlled to 50 ± 0.5 Hz. If the frequency is in the range of 48.00–51.00 Hz in 0.1 s, it is considered as a fault.

2.1.3. Voltage fluctuation

It must be controlled and ensured that there is no ripple voltage at the connection point venture beyond the standard. In typical measurement, P_{st} is used to assess the severity of voltage flicker in a short-time period (10 min) and P_{lt} is used to assess the severity of voltage flicker in a long-time period (2–3 h) according to Eqs. (1) and (2).

$$P_{st} = \sqrt[m]{(P_{st_1})^m + (P_{st_2})^m + \cdots + (P_{st_3})^m} \quad (1)$$

$$P_{lt} = \sqrt[3]{\frac{1}{n}\sum_{j=1}^{j=n}(P_{st_j})^3}. \quad (2)$$

P_{st} is used to assess the severity of voltage flicker in a short-time period.

P_{lt} is used to assess the severity of voltage flicker in a long-time period.

The value m shows the nature of voltage fluctuations.

The value n shows the number of P_{st} at the time of measurement.

Fig. 1. The location of PV rooftop plant.

2.1.4. Harmonics

Equipment with nonlinear characteristics such as transformers, fluorescent lamps, and especially the power electronic components causes harmonics befalling (Schlabbach et al., 1999). Several researchers have described that harmonic in PV system is generated by the converter. Despite the fact that the converter uses switching signals, such signals are not perfect sinusoidal (IEEE Recommended Practice, 2000).

The waveform distortion is evaluated at the harmonic orders ($h = 2, \ldots, H_{max}$) while $H_{max} = 40$ (EN 50160, 0000; Stojkov et al., 2009) all of which are typical values. For example, individual harmonics can characterize a voltage waveform:

$$X_h = \frac{V_h}{V_1} \quad \text{for } h = 1, \ldots, H_{max}. \quad (3)$$

Total Harmonic Distortion (THD) of voltage is defined as the ratio of the RMS value of all harmonic components of the Voltage (V_h), to the fundamental Voltage (V_1) based on the following Eq. (4)

$$THDv(\%) = \frac{\sqrt{\sum_{h=2}^{40} V_{h(rms)}^2}}{V_{1(rms)}} * 100\%. \quad (4)$$

$V_{h(rms)}$ is the value of the harmonic voltage number h.

$V_{1(rms)}$ is the voltage at the fundamental frequency of 50 Hz (see Table 2).

The standard deviation of harmonic that influences the distribution networks is not only initially visible, it also affects serious long-term outcomes; for example, resonant and stress conditions on power system, saturation effects in the core and increased heating of transformer affect another system and so on (Stojkov et al., 2009; Fekete et al., 2012).

2.2. Description of the PV rooftop site

The PV rooftop plant is located at latitude 13° 22 min North and 99° 58 min East in Samut Songkhram province, Thailand as show in Fig. 1.

The system has the installed capacity of 987.84 kWp which is composed of solar panels Poly Crystalline Module Size 245 Wp (Photovoltaic module Jinko Solar, 2015).
Array type 1 group: 4 array × 20 strings × 24 panels = 1920 modules.
Array type 2 group: 4 array × 22 strings × 24 panels = 2112 modules.

The PV arrays were installed on rooftop which the group 1–2–3–4 faced toward the North, the group 5–6–7–8 faced toward

Table 2
The standard defines the harmonics of the electric type of business and industry.

The Voltage at the connection point (kV)	Total harmonic distortion of voltage (%)	The harmonic distortion of the voltage of each rank (%)	
		Odd	Even
0.4	5	4	2
11,12,22,24	4	3	1.75
33	3	2	1
115 or more	1.5	1	0.5

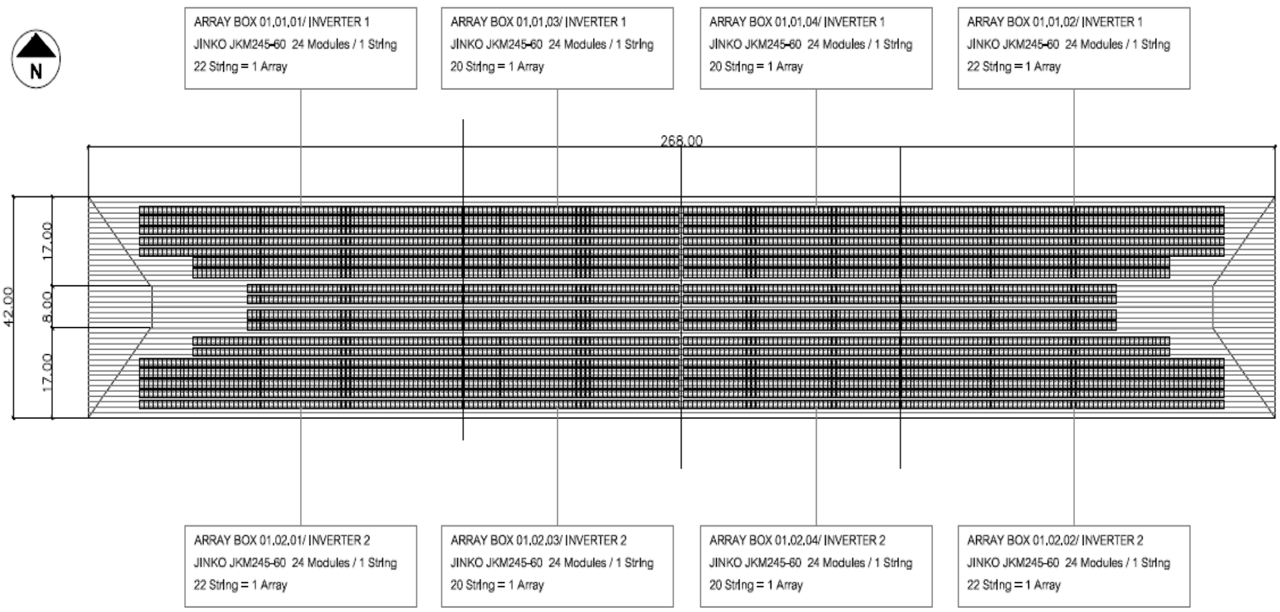

Fig. 2. The design of installation PV rooftop.

the South and the tile angle of both side are 13° as shown in Fig. 2. The PV rooftops were connected to inverter as shown in Fig. 3. There are two central inverters of 500 kW. The inverters are connected via Main Distribution Board (MDB) to the three-phase transformer and distribution grid of 22 kV, 50 Hz PEA on distribution system.

2.3. Energy in grid connected analysis

The grid connected PV system can be indicated by performance Eqs. (5) (How to calculate, 2015). The global formula used to estimate the performance ratio of the PV system is in this equation.

$$PR = \frac{E_{AC}}{A \cdot \eta_{mpv} \cdot H_t}. \tag{5}$$

PR is Performance ratio of installation PV system.
E_{AC} is average energy output from AC (kWh).
η_{mpv} is module efficiency at STC (%).
H_t is average solar radiation on tilted panels per year (kWh) in Thailand about 2010 kWh/m^2 (Photovoltaic Geographical Information, 2015).

Several researchers have described that performance ratio is very important value used to evaluate the quality of PV installation. It provides the performance of the installation, independent of the orientation and inclination of the panel. It also includes all losses (How to calculate, 2015).

3. Results of the measurement data

3.1. Power quality evaluation measurement

The power quality measurement of power producer is based on the standard specification of PEA. All data were collected and analyzed by Power Quality Analyzer in 10 min of 7 days and then evaluated based on the standard EN 50160. All data are arranged in ascending order, and the 95% is used to represent the assessment which the frequency used 99%. The Evaluation of the power quality is shown in Figs. 4–10 and in Tables 3–4.

Table 3
The assessment of power quality from PV power plant.

Parameter	Phase	Benchmark	CP 95 (%)	Assessment
Voltage	A	22 ± 5% (21.9–23.1 kV)	22.485	Pass
	B		–	–
	C		22.672	pass
Frequency		50 ± 1% (49.5–50.5 Hz)	50.05[a]	Pass
THD_V	A	$THD_V < 4\%$	1.578	Pass
	B		–	–
	C		1.323	Pass
P_{st}	A	$P_{st} < 1$	0.354	Pass
	B		–	–
	C		0.351	Pass

[a] Note: As a measurement of the two elements (3 Phase: 2PT 2CT), which measured only phase A and phase C.

From Fig. 4, it was found that the obtained value was 22.485 kV. From Fig. 5, the frequency of CP 99 was 50.04 Hz. From Fig. 6, the Total Harmonic Distortion Voltage (THD_V) at phase A of CP 95 was 1.578. From Fig. 7, the voltage ripple P_{st} at phase A of CP 95 was 0.354. The data of power quality was shown in Table 3.

According to the above data on the results of the power quality measurement each day, there was a significant report on the 6th day. It was a rapid fault on the power grid which caused by the voltage sags in the distribution system of the PEA as shown in Fig. 8. However the voltage sags was not more than the standard based on

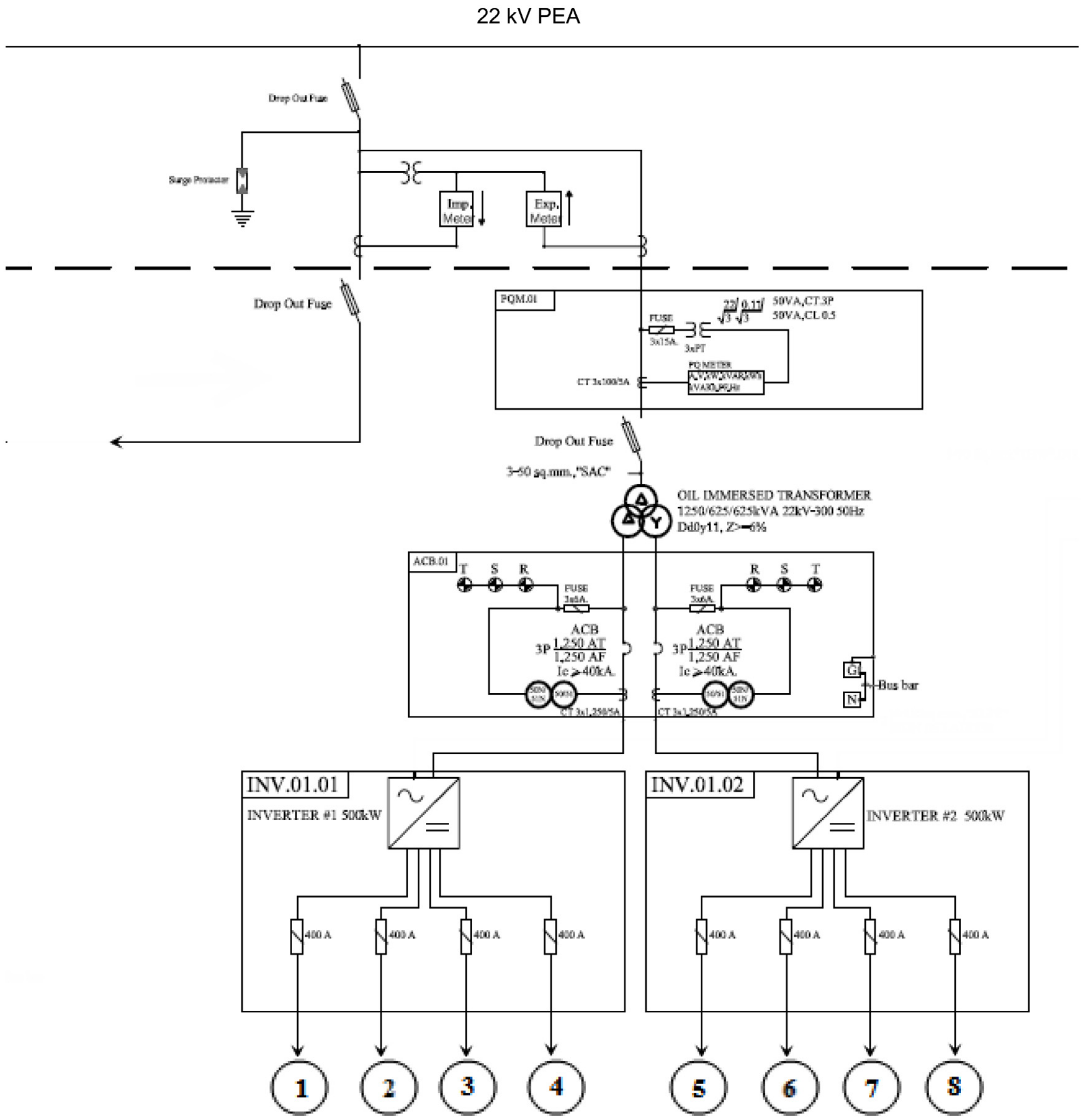

Fig. 3. Single line diagram of PV rooftop installation.

the PEA for the grid connected system therefore the system was able to connect to the grid. The results are shown in Table 4.

From Fig. 8, there was the voltage sags for 0.08 s at Phase C and then return to normalcy. This caused a short circuit on a transmission line, and then caused voltage sags in distribution of PEA. The condition causing the voltage flicker is shown in Fig. 9. It directly affects the power quality evaluation of the grid connecting system.

3.2. Evaluation of electric power measurement

The measurement of maximum power output of one week measurement on 19–26 May 2014 from the PV rooftop power plant can supply to the distribution system up to 778 kW at the time of 12.20 PM as shown in Fig. 10.

4. Analysis of Homer simulation results

To investigate the energy yield, the Homer simulation was selected. This will help to determine of the energy production and the comparison study. This simulation designed for PV system to

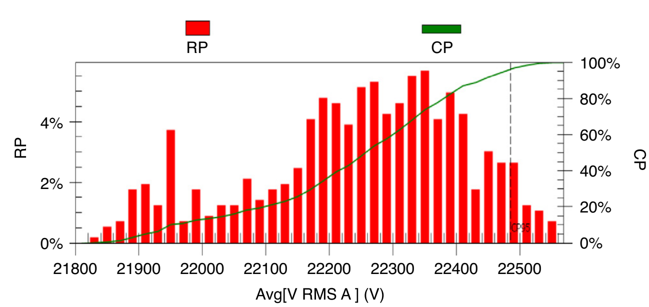

Fig. 4. Evaluation of voltage RMS at phase A.

the Grid and then configured the designed system by entering the coordinate values used in this study. They are at latitude 13° 22′ North and longitude 99°58′ East and all PV arrays are at slop of 13° with one central inverter as shown in Fig. 11. The detail of solar resource is shown in Fig. 12.

The simulation energy result was 1,575,584 kWh/yr or 1.58 GWh/yr with the operation hour of 4400 h/yr. The energy supplied into the grid was 1,496,808 kWh/yr or 1.49 GWh/yr. The average

Table 4
The power quality results of the monitoring day.

Parameters	Phase	Day 1	Day 2	Day 3	Day 4	Day 5	Day 6	Day 7
	A	22.47	22.32	22.35	22.45	22.51	22.52	22.43
Voltage	B	–	–	–	–	–	–	–
	C	22.68	22.57	22.56	22.64	22.70	22.71	22.64
Frequency		50.05	50.05	50.05	50.06	50.04	50.04	50.05
	A	1.19	1.45	1.45	1.54	1.32	1.79	1.61
THDv	B	–	–	–	–	–	–	–
	C	0.95	1.15	1.13	1.21	1.05	1.58	1.31
	A	0.23	0.34	0.37	0.32	0.26	0.48	0.30
P_{st}	B	–	–	–	–	–	–	–
	C	0.34	0.30	0.28	0.37	0.34	0.35	0.38

[a] Note: As a measurement of the two elements (3 Phase: 2PT 2CT), which measured only phase A and phase C.

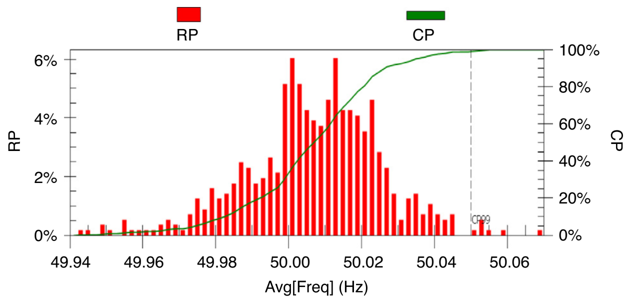

Fig. 5. Evaluation of frequency.

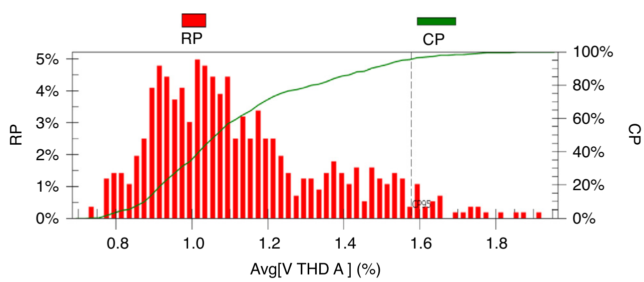

Fig. 6. Evaluation of THDv at phase A.

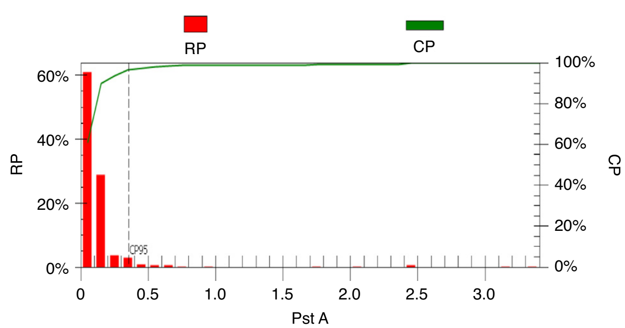

Fig. 7. Evaluation of the voltage flicker P_{st} at phase A.

energy output from PV system was 4317 kWh/d or 4.3 MWh/d and capacity factor was 16.2%, monthly average electric production is shown in Fig. 13.

The comparison of energy output between simulation and monitoring data is shown in Table 5. The comparison of the performance ratio of the PV system between simulation and monitoring data is also shown in Table 6.

The both mentioned values are very similar but there are some different values because the homer simulation can simulate only one side of array surface tilted angle. For this PV rooftop plant, there are 2 side array tilted angles which affecting PV system output. Other reason on this comparison study should be climate, usually from May to October is the rainy season, but this year such

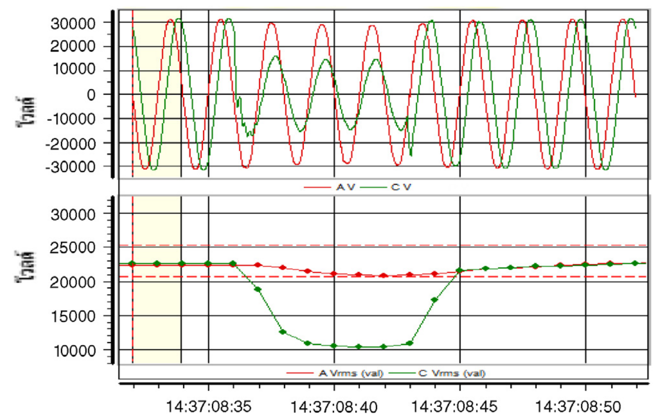

Fig. 8. Wave form of voltage sag on the 6th day.

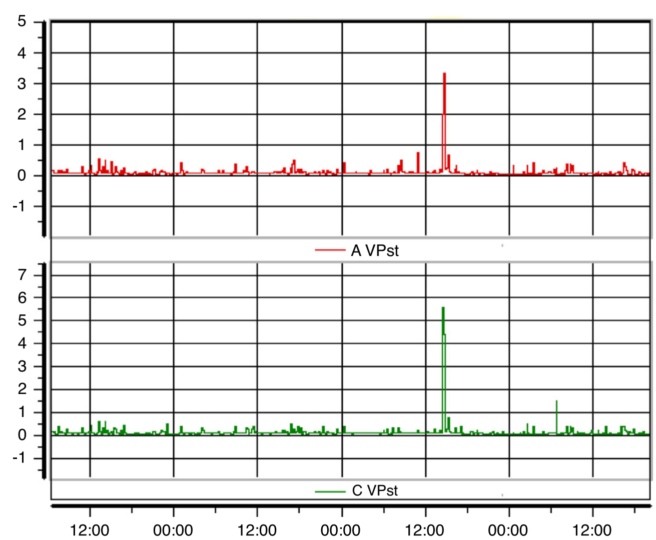

Fig. 9. Voltage flicker during voltage sags.

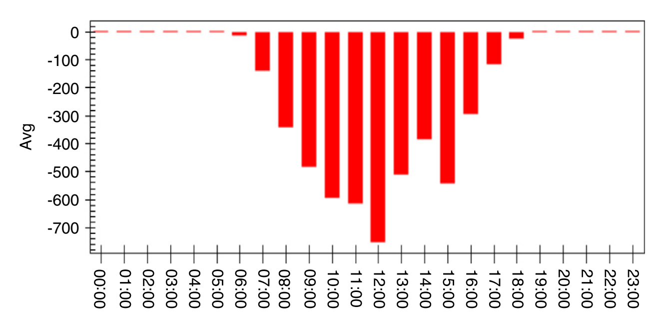

Fig. 10. The average power output 1 week from PV rooftop power plant.

Table 5
The output between the simulation and monitoring data.

Month	Energy sold by producer (2014–2015) (kWh)	Energy sold by Homer (kWh)
Jan	118,640	136,539
Feb	128,000	123,897
Mar	138,527	144,672
Apr	128,390	139,237
May	120,080	120,741
Jun	124,980	106,951
Jul	122,740	111,244
Aug	128,740	113,674
Sep	124,580	116,037
Oct	107,360	120,511
Nov	117,020	123,296
Dec	104,060	140,009
Annual	1,463,117	1,496,808

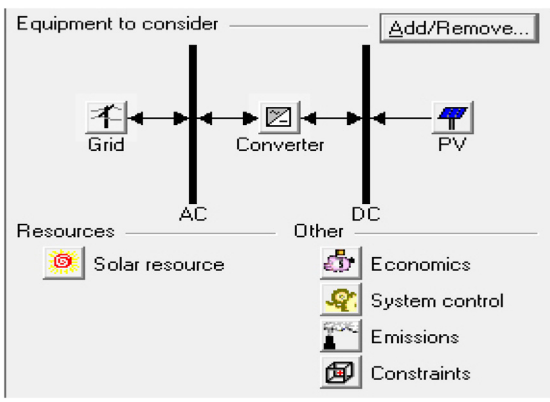

Fig. 11. The system simulation in Homer.

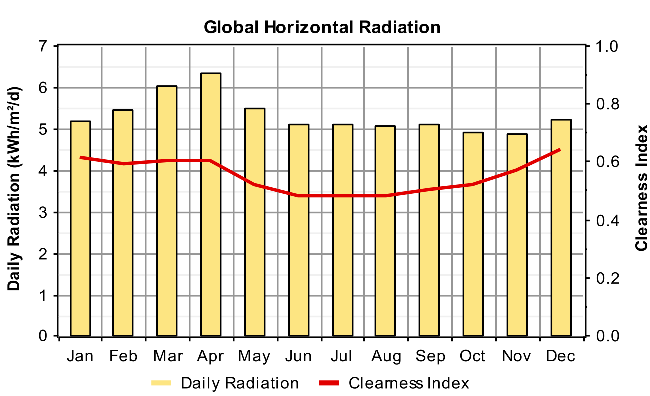

Fig. 12. Solar resource in Homer at latitude 13°22′ North and longitude 99°58′ East.

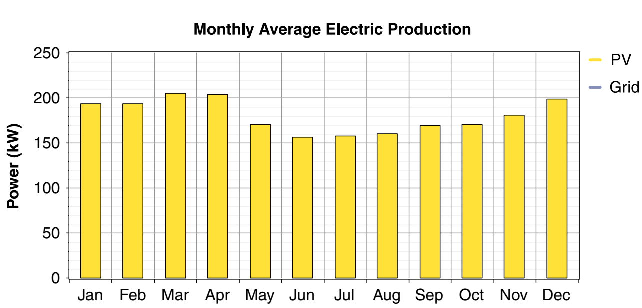

Fig. 13. The monthly average electric production.

the period had low rainfall. Thus PV rooftop system can produce higher than the simulation.

Table 6
The performance ratio of the PV system between the simulation and monitoring data.

The performance ratio of the PV system (PR)	
Measurement	Homer
74.38%	76.29%

5. Economics perspective

The annuity method is used for this study. The annuity is calculated as described in Eq. (6).

$$a = NPV \cdot \frac{i \cdot (1+i)^n}{(1+i)^n - 1}. \quad (6)$$

a is annuity [currency]
NPV is net present value [currency]
i is fictitious interest
n is planning horizon [year].

The PV rooftop plant has the total cost of 55,637,447 THB (exchange rate of 35.76 baht per USD at December 2015). The sale energy cost from PEA is 6.16 THB/Unit. If the interest rate is 7.785% in Thailand, by the annuity method, the payback period is about 9 years.

6. Conclusions

The performance of a large scale PV rooftop plants in Samut Songkhram, Thailand was analyzed. The power quality measurement was installed at the Point Common Coupling (PCC) with 22 kV, 50 Hz distribution systems of PEA in order to measure the voltage, frequency, Total Harmonic Distortion Voltage (THD_V), and voltage fluctuation for one week. The electric power generation from PV rooftop plant can supply electricity to distribution system. The average power output in one week duration from 6:30 a.m. to 18:40 p.m. was up to 778.125 kW, and power quality evaluation was also considered to pass the benchmark based on the Province Electricity Authority in terms of the grid connection. The key equipment in the grid connection is an inverter. In order to utilize technical procedures to decrease the harmonic effects while satisfying the requirements of the grid and also occupying the functional capability of anti-islanding, the qualified inverters could be used. The comparison energy output and performance ratio between measurement and simulation are similar. According to the annuity method, the payback period is about 9 years.

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