Distributed Generation System's Impact on Power Quality

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***Abstract* -- This paper presents the study of impacts on power quality because of a Distributed Generation (DG). A Rayong-based distribution feeder which is integrating with the 0.996MW of solar Photovoltaic (PV) rooftop system is utilized as the case study. Moreover, an additional DG is modeled and simulated to consider power quality based on size and location of the new DG. The DIgSILENT PowerFactory is used to model and simulate the behavior of the DG system integrating to the distribution system in different scenarios.**

***Index Terms*—DG system, Power Quality, Solar Photovoltaic (PV)**

I. INTRODUCTION

As the energy demand growth, the distributed generation sources have been realizing to the utility grid. The adding of DG on distribution feeder affects the power quality in many directions, for example voltage fluctuation, flicker, and harmonic injections [1]. The DG is increased especially on grid connected systems. As mentioned, the increasing of DG may bring some impacts on power quality of distribution system. These impacts need to be inspected and considered if power quality of system meet power quality standard. Ultimately, the main point is to make sure that the further impacts would not be worst, but be better if additional DG is added.

In this paper, the case study of impact of the existing solar PV rooftop (as DG unit) integrating on the utility distribution grid is investigated. This case study is based on a distribution feeder of the Provincial Electricity Authority (PEA), in Rayong, Thailand. The power quality is determined based on the measurement of existing DG. Moreover, additional DG is modeled and simulated to consider power quality based on size and location of the new DG.

In the DG test unit, power quality is measured at the PCC of the DG system. Moreover, the DIgSILENT PowerFactory program is used to simulate in order to evaluate the additional DG system that could affect power distribution system [2],[3],[4],[7]. The result of simulation is used to validate the system parameters which will be utilized to determine effect of the DG to the PEA utility grid as the DG could not produce output power because of either system failure or weather condition[9]-[11]. Moreover, power quality, reliability, and stability of the system are analyzed and predicted as the solar PV power system is increasing in the future. The limitations of the current of PEA distribution are also determined through the simulation.

This paper is divided into 4 parts. The solar PV generation system is in part II. Distribution system and standard is describes in part III. Power quality evaluation is in part IV. Ultimately, simulation and experimental results, and conclusion will be presented in part V to VII.

II. SOLAR PV GENERATED POWER SYSTEM

Fig. 1 shows a basic solar PV generation system which includes PV arrays, a DC-DC converter, inverter, LC filter and utility grid. PV arrays produce DC power with uncontrollable voltage level depending on the sunlight. A DC-DC converter is used to boost up the voltage from PV array to usable voltage level. After that, an inverter is used to convert direct current to alternating current. Fig. 2 shows a solar PV rooftop which has multi dc-dc converters sharing dc link. With this structure, the system can provide better maximum power point tracking.

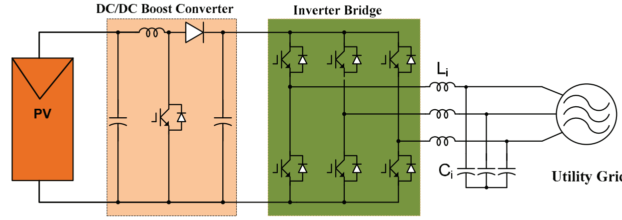

Fig.1 Solar PV generated power system

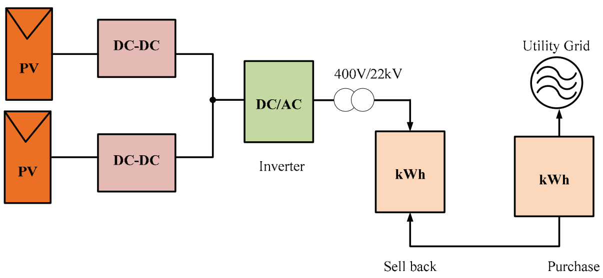

Fig.2 block diagram of solar PV-rooftop with grid connected system

III. Case Study PEA distribution system and standard of power quality

A. PEA distribution system (Pluak Deng 3 Area)

The system used in this study is the Pluak Deng 3 Substation, Rayong, Thailand as shown in Fig.3. This substation is to supply electrical power to the Hemaraj Eastern Seaboard Industrial Estates. The sub- diagram of the system is shown in Fig 4. In this substation, the electrical voltage steps 115kV down to 22 kV with a 50 MVA transformer. There are 5 feeders (F7 to F 10) from the transformer. A solar PV rooftop distributed generation system is connected to the utility grid through feeder 9 and it is located at 9 km in length from the substation as shown in Fig 5. The potentially maximum power is 996kWp.

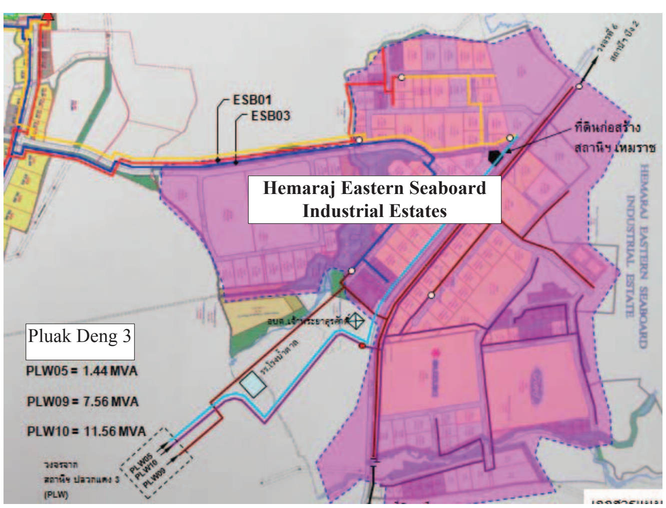

Fig.3. Map of the Plauk Deng 3 substation, in Hemaraj Eastern Seaboard Industrial Estates, Rayong, Thailand

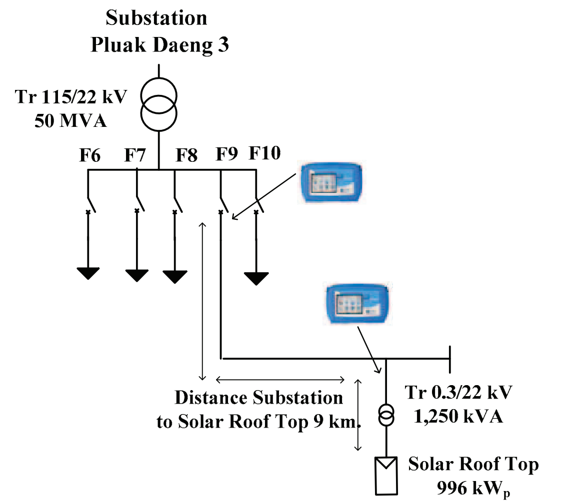

Fig.4. Single line diagram of a grid connected solar roof top

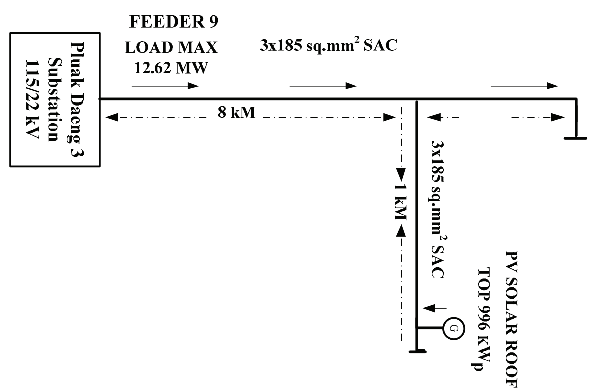

Fig.5 Single line diagram power flow of the Pluak Daeng 3 substation

B. Power quality standard

To be allowed to connect to PEA's distribution system, the solar PV rooftop system is required to meet power quality standard as shown in Table I and Table II. These power quality standards are from IEEE Std. 1159-1995 for (Recommended Practice for Monitoring Electric Power Quality), EN 50160-1994 for voltage characteristics of electricity supplied by public distribution systems, PRC – PQG – 01 / 1998 for harmonic, and PRC – PQG – 02 / 1998 for flicker [2] -[8].

TABLE I
STANDARD OF POWER QUALITY

Voltage level	20.9 - 23.1 kV
Frequency (Hz)	49.5-50.5 Hz
Voltage unbalance	< 2 %
Power factor (Pf)	> 0.85
Total harmonics distortion(THD_v, %)	< 4 %
Flicker (Plt)	< 0.8

TABLE II
STANDARD OF CURRENT HARMONIC ORDER FOR 22 KV SYSTEM

Order	2	3	4	5	6	7	8	9	10
Standard 22 kV (Amp)	11	7	5	9	4	6	3	2	2
Order	11	12	13	14	15	16	17	18	19
Standard 22 kV(Amp)	6	2	5	2	1	1	2	1	1

IV. POWER QUALITY EVALUATION

The case study is the solar PV power generation system with 996 kWp which is connected to the PEA distribution system at PCC as shown in Fig 4. The single line diagram power flow of the Pluak Daeng 3 substation is detailed in Fig 4. The power quality information is measured at the PCC and line outgoing of the feeder 9.

The collected data is used as inputs of the DIgSILENT PowerFactory program and Geographic Information Systems (GIS) for simulation.

The result of simulation is used to validate the system parameters which will be utilized to determine effect of the PV generation system to the PEA utility grid as the PV system could not produce output power because of either system failure or weather condition.

Moreover, power quality, reliability, and stability of the system are analyzed and predicted as the solar PV power system is increasing in the future. The limitations of the current of PEA distribution are also determined through the simulation.

V. EXPERIMENTAL AND SIMULATION RESULTS

A. Measurement Set Up

The power quality measurement set up is shown in Fig. 6 to Fig.9. Fig. 6 and 7 shows the measurement set up at the Plauk Deng 3 substation. Fig. 8 and 9 shows the set up at the PCC where the PV rooftop is tied to the distribution feeder.

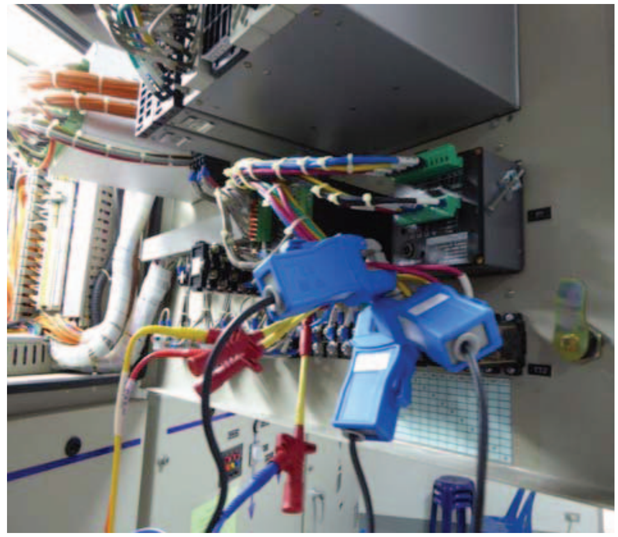

Fig.6 Power quality measurement set up at the Plauk Deng 3 substation

Fig.7 Power quality measurement set up at the Plauk Deng 3 substation

Fig.8 Power quality measurement set up at the PCC (Solar PV rooftop station)

Fig.9 Power quality measurement set up at the PCC (Solar PV rooftop station)

B. Experimental Results

Fig. 10 to 14 show experimental results which were measured at the PCC of the solar PV rooftop system. Line voltage is measured and shown in Fig. 10. The detail of measurement is shown in table III. From this table, it can be seen that the average line voltage is about 22.1kV. The minimum line voltage is on phase A-B which is about 19.5kV and maximum line voltage is 22.9kV for all line voltage. Fig. 11 shows power produced from the PV system which was measured at the PCC on August 14, 2014. Electrical power was generated from 6.00AM to 6.00 PM. The maximum produced power is 1.5MW and the average power is 0.517 MW. Even though, the PV system generated 1.5MW, it can only sell 1MW of generated power to the grid and the rest 0.5MW of generated power is injected to the grid for free.

Moreover, it can be seen that in the afternoon the generated power was drop very fast especially at 4:00PM as shown in Fig.11. This scenario occurs because of shading on PV arrays. The voltage on each phase respective to the generated power is shown in Fig.12. and 13. Fig. 12 shows Short-Term Severity Values (Pst) which is in standard range (less than 1). Fig. 13 shows Long-Term Severity Values (Plt) which is also in standard range(less than 0.8). The harmonic distortion is shown in Fig.14 and the measured details are shown in table V.

TABLE III
LINE VOLTAGE COMPARISON MEASURED AT PCC OF THE SOLAR PV ROOFTOP SYSTEM

	Min	Max	Avg	95%
A-B Vrms	19519	22909	22120	22625
B-C Vrms	20696	22946	22141	22653
C-A Vrms	20345	22907	22139	22620

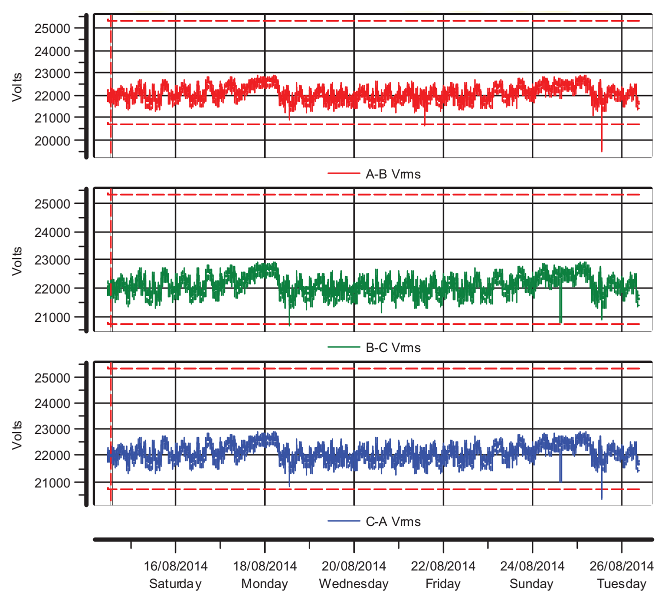

Fig.10 Voltage at PCC of Solar PV rooftop station

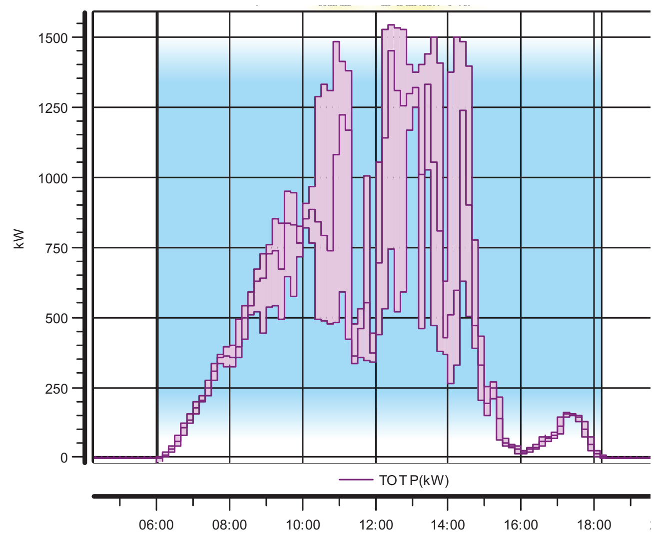

Fig.11 Power produced on August 14, 2014

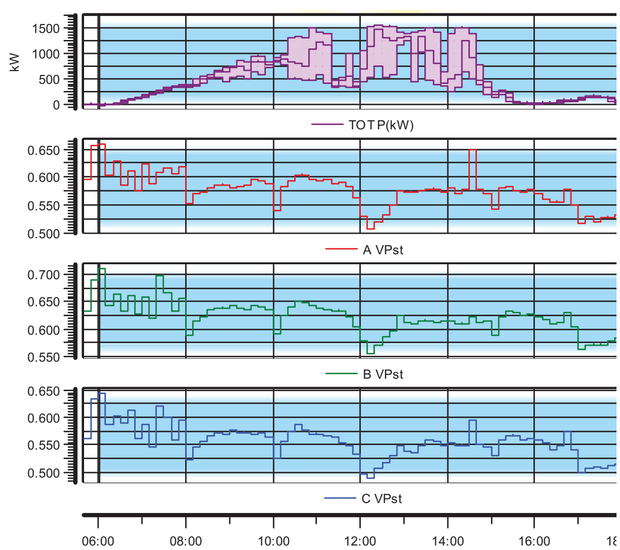

Fig.12 Voltage variation, Short-Term Severity Values (Pls)

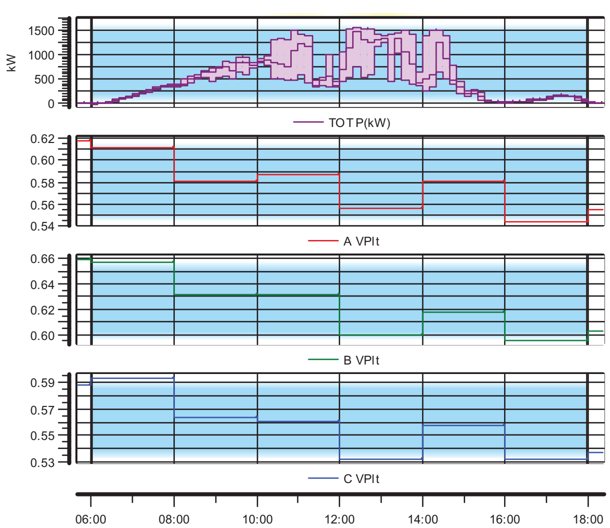

Fig.13 Voltage variation, Long-Term Severity Values (Plt)

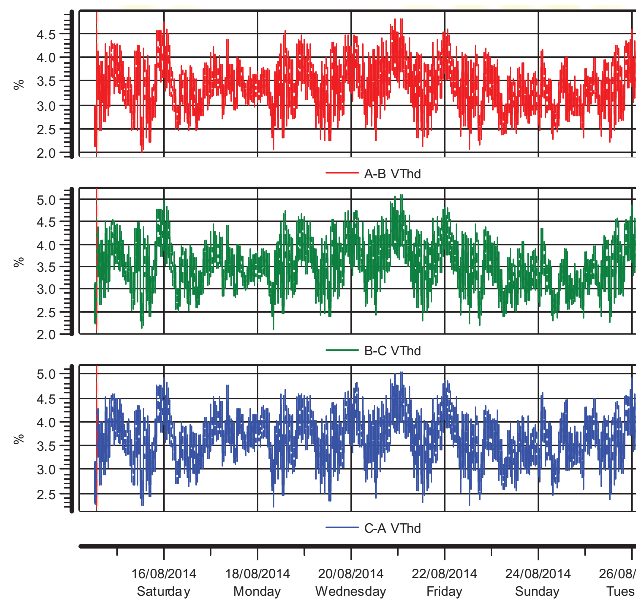

Fig.14 Harmonic Distortion measured at the PCC

C. *Assessment of power quality*

Because the sunrise and sunset period [7-8], the PV power generation of the case study is considered during 6:00 AM to 6:00 PM. Table IV presents experimental results which are measured at PCC and table V is comparison of standard and measured harmonic current.

TABLE IV
RESULTS OF MEASURING AT PCC OF THE GRID TIED WITH PV ROOFTOP RESOURCE

Parameter	Phase	CP 95	PEA	Result
Voltage level (kV)	AB	*22.604*	± 5 % (20.9 -23.1 kV)	pass
	BC	*22.602*		
	CA	*22.612*		
Voltage unbalance		0.128	< 2 %	pass
Frequency (Hz)		*50.03*	49.5-50.5 Hz	pass
Power factor (Pf)		*0.945*	> 0.85	pass
Total harmonics distortion (THDv, %)	AB	*3.844*	< 4 %	pass
	BC	*3.910*		
	CA	*3.990*		
Flicker (Plt)	A	*0.670*	< 0.8	pass
	B	*0.727*		
	C	*0.648*		

TABLE V
MEASURING RESULTS COMPARED WITH STANDARD OF HARMONIC ORDER CURRENT

Order	2	3	4	5	6
Standard (Amp)	11	7	5	9	4
Result (Amp)	0.13	0.19	0.11	1.7	0.08
Order	7	8	9	10	11
Standard (Amp)	6	3	2	2	6
Result (Amp)	1.1	0.05	0.1	0.03	0.3
Order	12	13	14	15	16
Standard (Amp)	2	5	2	1	1
Result (Amp)	0.03	0.3	0.03	0.88	0.02
Order	17	18	19		
Standard (Amp)	2	1	1		
Result (Amp)	0.1	0.03	0.19		

VI. SIMULATION

A. *Simulation Set Up*

The simulation set up of the solar PV rooftop system is modeled as shown in Fig.15 [2]. Simulation is conducted through the DIgSILENT PowerFactory program. The total distribution feeder length from the feeder 9 of the Plauk Deang 3 to the end of the distribution feeder is 10 km. The PCC is located at 9 km from the substation.

B. *Simulation Results*

There are 6 scenarios to be studied in this paper which are as follows:

1) PEA distribution feeder without solar PV system
2) PEA distribution feeder with 996 kWp solar PV system at PCC
3) PEA distribution feeder with 4 MWp solar PV system at PCC
4) PEA distribution feeder with 996 kWp solar PV system at PCC and additional 1MW at 1km from the substation.
5) PEA distribution feeder with 996 kWp solar PV system at PCC and additional 1MW at 4km from the substation.
6) PEA distribution feeder with 996 kWp solar PV system at PCC and additional 4MW at 4km from the substation.

The scenario1 to 3 have been simulated and already discussed in [4]. The objective of this paper is to see the impact of the DG on PEA distribution feeder in different location and PV's size.

C. *Scenario 1-3, existing 996kWp solar PV generated power system*

Fig. 16 is simulation results of the PEA original system (before connecting to a 996kWp of PV system). It can be seen that the voltage at the end of the feeder (10 km from substation) is 0.956 pu and the loss of transmission line is 0.73MW. In this case, the feeder is about 7.5 km distance caring over 80 percent of the maximum current capacity.

Fig. 14 shows a simulation results as a 996 kWp of solar PV system is connected to the PEA distribution feeder. The voltage at the end feeder increases from 0.956 pu to 0.959 pu. Moreover, capability of distribution feeder which is more than 80 percent decreased from 7.5 km to 3 km of distance from substation.

Fig. 18 shows simulation results as a 4 MWp of solar PV system is connected to PEA distribution line. The voltage increases from 0.956 pu to 0.968 pu. Moreover, capability of distribution line will be less than 80 percent for entire distribution line. Nevertheless, the customer who is located close to the solar PV system may receive the impact of temporary under voltage when power of PV system decrease because either solar arrays are covered by cloud or the PV system fails in operation. In this case, the voltage of loads connected near the PV system will change from 0.968 pu to 0.956 pu. As a result, the customers nearby the PCC will get affected of voltage drip.

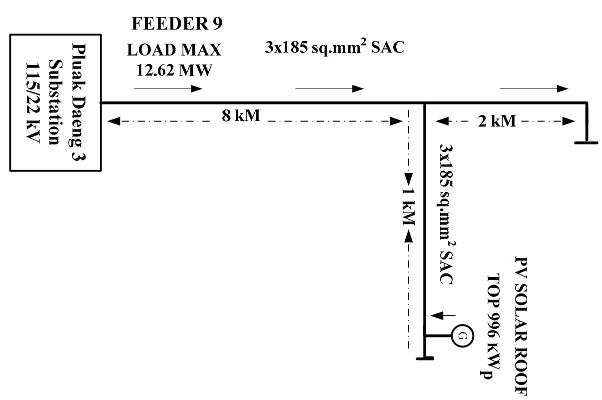

Fig.15. Simulation set up of Solar PV rooftop system

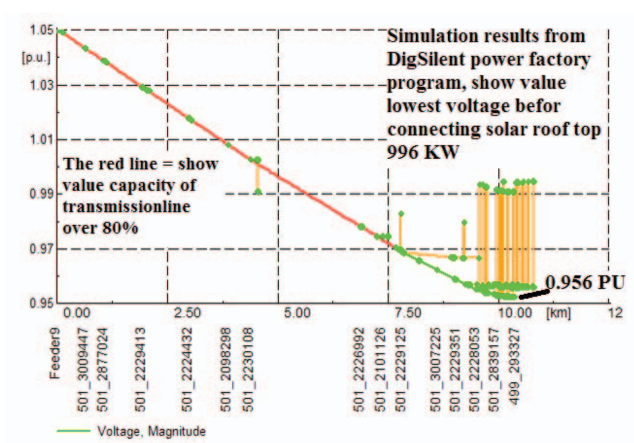

Fig. 16. Simulation result when without PV solar

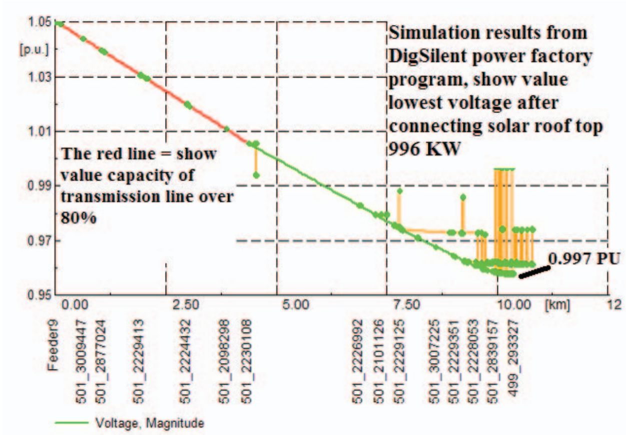

Fig. 17. Simulation result when connected with 0.996MW solar PV system at 9km

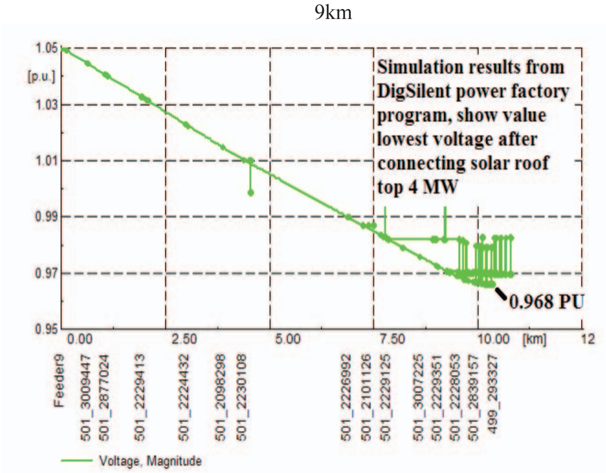

Fig. 18. Simulation result when connected with 4MW solar PV system at 9km

D. Scenario 4, the existing 996 kWp solar PV system connected with additional 1 MW of DG at 1km of distribution Feeder

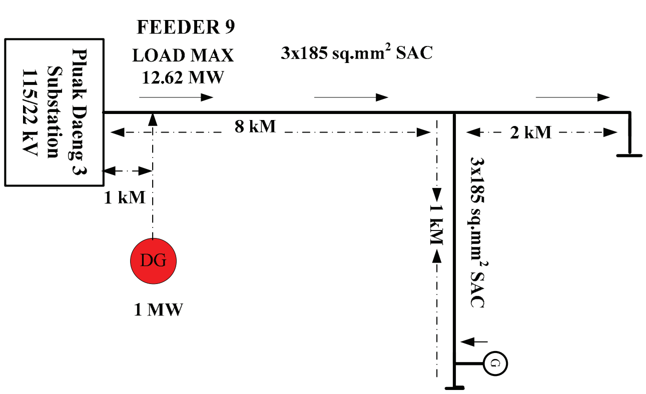

Fig.19 Simulation model of the existing 996 kWp solar PV system connected with additional 1 MW of DG at 1km of distribution Feeder

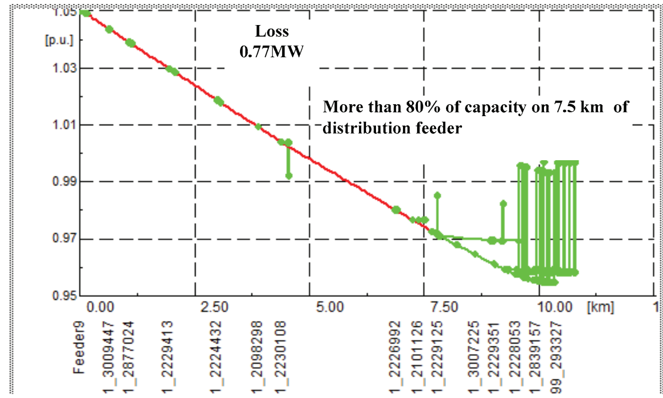

Fig.20 Simulation results of the existing 996 kWp solar PV system connected with additional 1 MW of DG at 5 km of distribution feeder

E. Scenario 5, the existing 996 kWp solar PV system connected with additional 1 MW of DG at 5km of distribution Feeder

Fig. 21 through Fig. 24 show simulation models and simulation results in different scenarios. The comparison on location of DG, size and losses is detailed in table VI. The scenario 2 to 3 is the model with increasing the size of DG over the existing 0.996MW DG system. Moreover, the scenario 4 to 6 is the model with integrating the extra DG (in the future) at different size and location. As shown on scenario 4 and 5, the existing system integrating with additional 1MW of DG at 1km and 5km from the substation will introduce 0.77MW and 0.69MW losses, respectively. The lowest losses occur when the existing 0.966MW is integrating with 4MW of additional DG as shown in scenario 6.

In different scenarios, it can be seen that without the DG, the transmission loss is highest at 0.84MW. With the existing DG (996 kW), the transmission loss is 0.75MW. In the scenario 3, the DG is assumed to be 4MW and the loss is only 0.53MW. In scenario 4-6, the additional DG is added to the system in different locations and sizes. In scenario 4, by adding 1MW of additional DG at 1km from the substation, 0.77MW of loss is created. Ultimately, the simulation was done by adding 4MW of additional DG at 1km and 5 km, providing 0.69 and 0.51 MW losses, respectively.

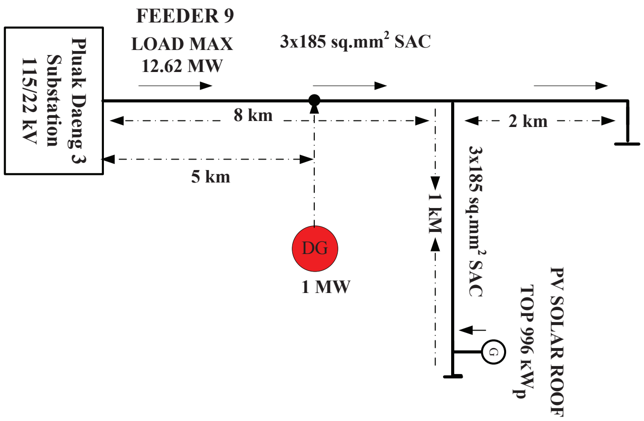

Fig.21 Simulation model of the existing 996 kWp solar PV system connected with additional 1 MW of DG at 4 km of distribution feeder

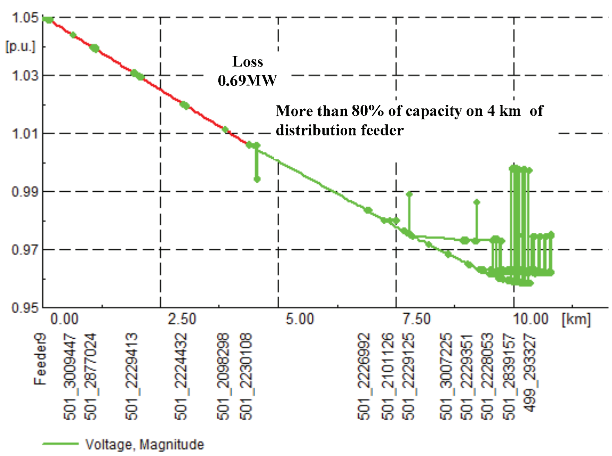

Fig. 22 Simulation results of the existing 996 kWp solar PV system connected with additional 1 MW of DG at 5 km of distribution feeder

F. Scenario 6, the existing 996 kWp solar PV system connected with additional 4 MW of DG at 5 km of distribution feeder

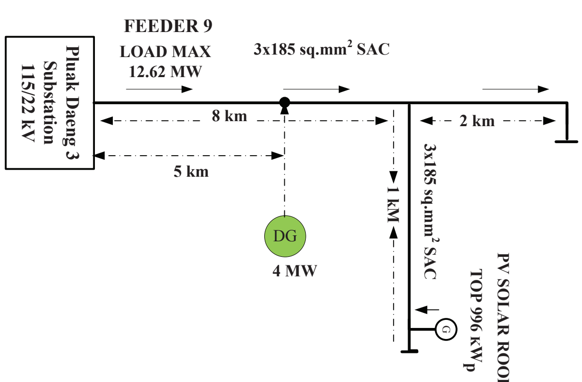

Fig.23 Simulation model of the existing 996 kWp solar PV system connected with additional 4 MW of DG at 5 km of distribution feeder

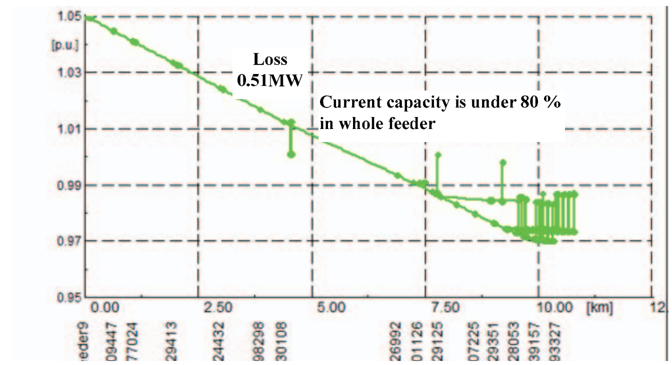

Fig.24 Simulation results of the existing 996 kWp solar PV system connected with additional 4 MW of DG at 5 km of distribution feeder

TABLE VI
LOCATION, SIZE AND LOSSES COMPARISON ON DIFFERENT SCENARIOS

Scenario	Existing DG MW	Additional DG		Sum DG MW	Feeder length on over designed capacity km	Losses MW
		Size MW	Location (km)			
1	-	-	9	0	7.5	0.84
2	0.996	-	9	1	3	0.73
3	4	-	9	4	0	0.59
4	0.996	1	1	2	7.5	0.77
5	0.996	1	5	2	3	0.69
6	0.996	4	5	5	0	0.51

VII. CONCLUSION

In the PV grid - connected system, the measuring results are shown that all parameter values are within the limit of the PEA's standard. The simulation results have been shown that the capability of distribution feeder is increased to carry load demand. As the PV installation capacity is increased, the voltage at PCC increases. However, the voltage variation due to no PV and PV grid – connected system will effect to sensitive load in industry area. In the simulation, the maximum DG on the feeder 9 of Plauk Deng substation is 5MW at 5km distance from the substation.

ACKNOWLEDGMENT

The authors gratefully acknowledge the support of the Provincial Electricity Authority (PEA), Thailand and Faculty of Engineering, Kasetsart University, Si Racha campus on this project.

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978-1-4799-8374-0/15/$31.00