Impacts of PV Power Plants on Distribution Grid for Voltage Stability and Economic Values

Woraratana Pattaraprakorn
Chemical Engineering
Thammasat University
Pathumthani, Thailand
Email: pworarat@engr.tu.ac.th

Pornrapeepat Bhasaputra
Electrical and Computer Engineering
Thammasat University
Pathumthani, Thailand
Email: bporr@engr.tu.ac.th

Jedsada Pattanasirichotigul
Energy and Environmental Technology Management
Thammasat University
Pathumthani, Thailand
Email: jedsada.pattana@gmail.com

Abstract—**This paper presents the impact of photovoltaic power plants on distribution grid for voltage stability and economic values by using the central region of Thailand as the simulation system. This region has maximum load of demand with high potential of solar energy development, through varying load characteristic and solar characteristic which used actual existing data parameters from the current photovoltaic power plant in Thailand. Besides, the selected central region system without photovoltaic power plant is simulated as a base case then the contained photovoltaic power plants are also installed to investigate the impact of each case on distribution grid in term of the voltage stability and the total system energy losses by varying six connected buses and three installed distance locations. The simulation results show that the optimal location of photovoltaic power plant can enhance the economic operation of distribution utility over 12.3 million units a year at the same time the voltage stability does not has any effect to distribution grid. Finally, the impact of photovoltaic power plant should be studied before approve the installed location to optimize the social benefit.**

Keywords—photovoltaic power plant; voltage stability; economic values; impact ; distribution grid, simulation

I. INTRODUCTION

Among the demand of the consumed energy worldwide is increasing endlessly, the existing fossil fuel is constrained, the trying to find a new energy resource - the alternative/or renewable energy - is necessary things for human necessary to be an option for helping to slow using of fossil fuel with many kind of alternative energy including wind, solar, hydro, biomass, biogas, wave, tidal etc., in Thailand also has the Renewable Energy Development Plan 2008-2022-REDP [1] and the Alternative Energy Development Plan 2012-2021-AEDP [2] to support development of renewable and alternative energy in long term as 5,608 MW for REDP, and 9,201 MW for AEDP which is solar energy 2,000 MW for AEDP, 21.7 percent of all. Nowadays, many countries worldwide are forging ahead with renewable energy promotion at full steam. This is no exception for Thailand, the Announced Energy Policy and Planning, the Ministry of Energy of Thailand has increased the target of renewable energy share in the total energy consumption from formerly 20 percent within 15 years to 25 percent within 10 years by providing incentives for and help create confidence of investors to take part in strengthening Thailand's energy future through low-interest loan: revolving fund, venture capital: ESCO fund, tax incentives: BOI privilege, Adder, and Feed-in tariff (FiT) program, and having promoted power purchase agreement – PPA, as firm and non-firm kind of contract.

Furthermore, For Thailand Country - the solar energy map [3] - by considering the daily solar radiation for an annual average, most of country receive the maximum solar radiation during April and May with ranging 5.56 – 6.67 kWh/m^2-day which the areas with maximum solar radiation are at Northeastern part, and some areas of central region as an annual average and such this areas are accounted for 14.3 percent of an overall country. In Addition, it found the 50.2 percent of the total area receiving an annual average of solar radiation at 18 – 19 MJ/m^2-day. The total daily solar radiation of an annual average in an overall country area has a value of 18.2 MJ/m^2-day or/5.06 kWh/m^2-day and this result indicated of the rather high potentials of Thailand solar energy, leading to the technical potential of developing solar energy approach 50,000 MW, and the number of installed capacity of photovoltaic (PV) power plant is 787 MW totally, the fragmentation of PV power plant is quite high in central region as 383 MW from 787 MW where has strong solar radiation potential to develop solar energy such as solar farm, solar roof –top and solar thermal, especially PV power plant which can be connected to both of 115 kV transmission grid and 22 kV distribution grid, also having the highest of load demand because these area have a lot of industrial estate located in the central area of Thailand. Therefore, these are the reasons why the central region of Thailand is selected to be a case study of this paper. Last but not least, from the whole announced reinforcement of Thai government and limited fragmentation of solar potential area of Thailand are the importance things to make a confidence of investors to construct the PV solar power plant in central and northeast region of Thailand plentifully, and as comprehension that generated power of solar energy is not stable, count on daily weather, load characteristic , so these may contribute to have a lot of problems on power system network as well as weak point area necessarily if connected to power system network. Thus, this paper is done to investigate and prevent the problems so that it can be able to help to

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optimize the proper location for installation PV power plant, minimize energy loss through simulation method, and to help doing the energy policy along with enhancing the development of solar energy technology in Thailand sustainable next.

II. METHODOLOGY

The investigation of impact of PV power plant on distribution grid is needed by; (a) voltage stability [4,5] , (b) economics loss, and (c) effect of disturbance grid situation on actual central region network of Thailand through system simulation. The selected distribution grid area for case study Plaukdeang district, Rayong province, Thailand - industries area - is selected to be case study where have many manufacturer located here. The connected capacity of PV power plant also is the important one, for constraint of rating of installed equipment, and to be accordance with Thailand's VSPP- Very Small Power Producers - grid regulation, for generators sized less than or equal to 10 MW, so the 8 MW PV power plant is applied for this study with every one minute running, throughout twenty-four hours investigation for each case. The flowchart of studying impact of PV power plant on distribution grid for voltage stability and economic values are summarized in Figure 1. The power system network consists of many characteristics as table 1.

Table 1: Characteristics of Plaukdeang Test System

Item	**System Characteristics**		
	Description	***Value***	***Unit***
1	Total External Generator (115 kV Slag Bus)	Infinity	MW
2	115 kV Substation	2	Bus
3	22 kV Bus	6	Bus
4	Total PV Generator	8	MW
5	Total Load	258	MW

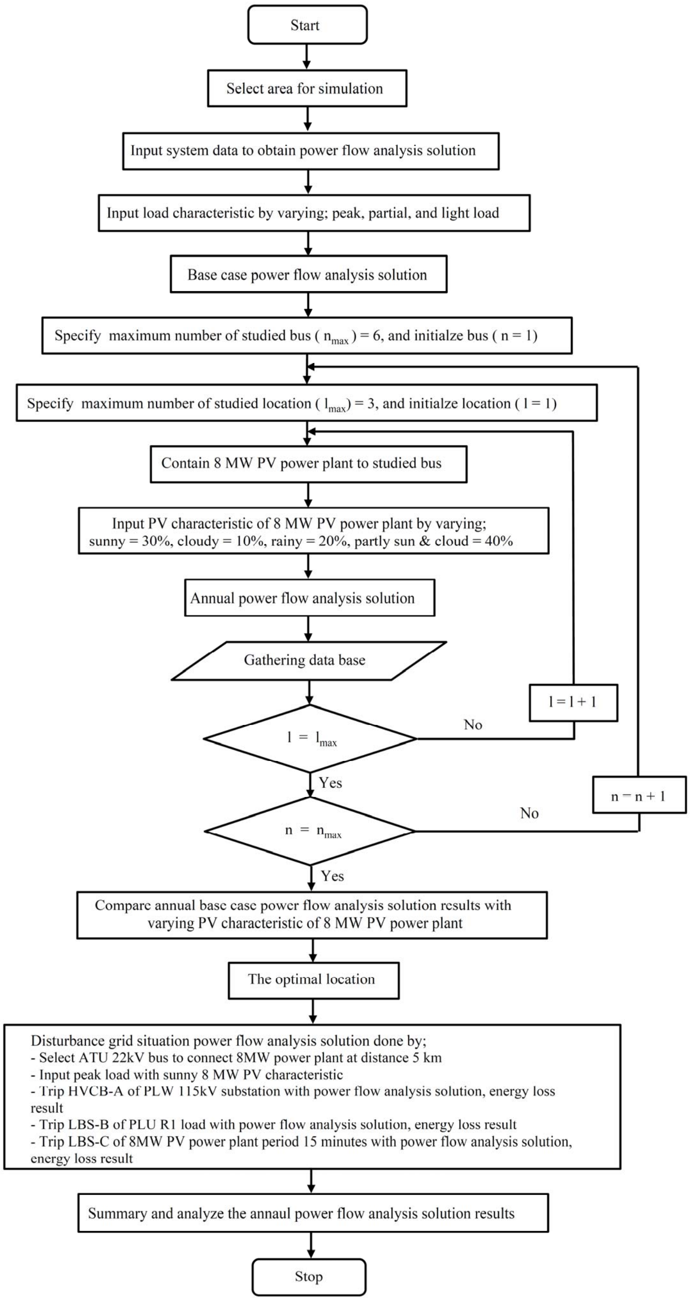

Figure1. Flowchart of studying impact of PV power plant on distribution grid for voltage stability and economic values

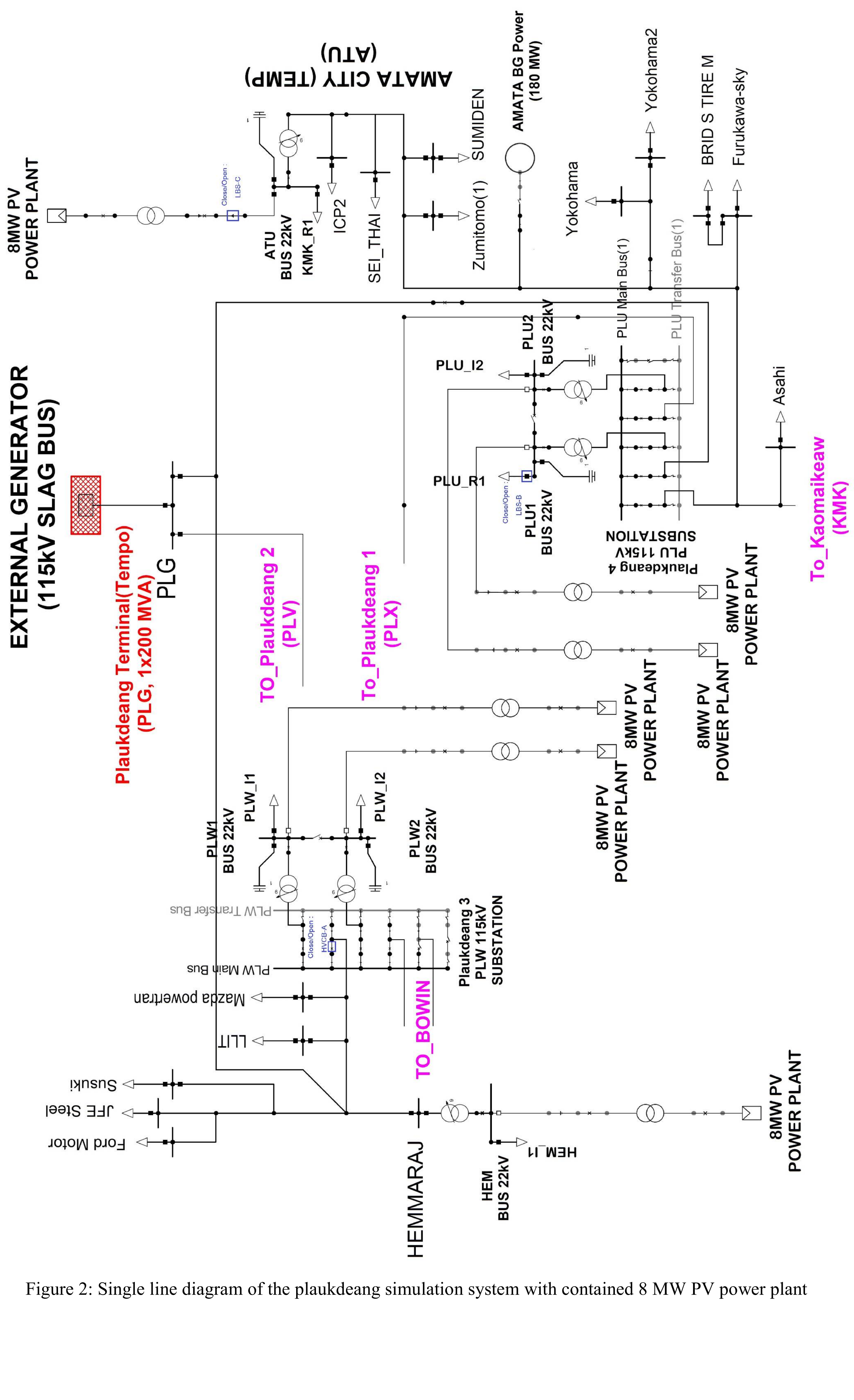

Figure 2: Single line diagram of the plaukdeang simulation system with contained 8 MW PV power plant

The Plaukdeang Simulation System - the power flow analysis method [6,7] - that without connection of PV power plant is run to be base case simulation system by varying characteristic of load as peak load, part load and light load. The system is shown in figure 2. Each of installed 8 MW PV power plant position – total six 22 kV bus - and base case are compared to investigate that installed distance have any effect to system or not, by analysis effect in terms of voltage stability and losses. For this research, the 8 MW PV power plant will be installed in each 22 kV Bus, actual local distribution grid, in Plaukdeang district area, one by one bus, six bus totally, and without installation of the 8 MW PV power plant is the base case. Throughout twenty four hours of study period, the power system is simulated by considering behavior of voltage stability and system economic values are; In terms of voltage stability by using power flow analysis method [8,9], the magnitude of voltage in per unit (p.u.) is demonstrated in a day, when compared between installed the 8 MW PV power plant and base case. In case of system economic value, the system losses in mega-watt-hour (MWh) is investigated in a day, when compared between installed the 8 MW PV power plant and base case, and distance of installation from 22 kV bus to the 8 MW PV power plant is concerned by varying distance are; five kilo-meters (km), ten km and twenty km to optimize the suitable location for installation the 8 MW PV power plant. The deviation energy loss is also investigated to be the data for calculation economic loss. The Suitable Installed Position of PV Power Plant Simulation, from the installed distance of PV power plant simulation, the best position will be selected from six 22 kV bus by considering voltage magnitude, not out of range 0.95-1.05 p.u./or ± 5 percentage (%) of 22 kV grid voltage refer to voltage grid regulation and minimum losses. In case of economic values, system losses are investigated in a day, by running twenty four hours of study period, and it is shown in term of energy losses, MWh. Besides, it will be changed to kilo-watt-hour (kWh), called "Unit", and converted to baht/p.u. When energy losses; 1 unit = 3.50 Baht/Thai. Finally, total cost per year must be compared in each study case to minimize the lowest cost to optimize installed distance and proper location. The effect of disturbance grid situation simulation is also investigated on this research, as well-know that power system is operated both of normal and disturbance grid situation, so the disturbance grid situation is assumed as follows as;

(a) Tripped Plaukdeang 3 Substation, called "PLW", by tripping SF_6 high voltage circuit breaker, HVCB-A, and the 8 MW PV power plant installed at AMATA CITY (TEMP).
(b) Tripped PLU-R1 load, by tripping SF_6 load break switch, LBS-B, and the 8 MW PV power plant installed at AMATA CITY (TEMP).
(c) Tripped the 8 MW PV power plant that installed at AMATA CITY (TEMP), by tripping SF_6 load break switch, LBS-C.

III. RESULTS

The results of maximum and minimum voltage magnitude and energy losses per day with energy saving per day are demonstrated in table and graph. The simulation results are summarized in four portions are ; (a) base case simulation, (b) installed distance of PV power plant simulation, (c) the impact of system disturbance situation, and (d) conclusion as shown in table 2, 3, 4, 5, 6, 7 and 8, respectively, to investigate the suitable installed location and distance of PV power plant -minimum energy losses and voltage magnitude in range 0.95-1.05 p.u./or ± 5% of 22 kV distribution grid - the comparison of the result of voltage magnitude and energy losses and energy saving between base case study and others - total amount thirty-six study cases - are necessary as follows;

A. Base Case Simulation

From table 2, the maximum and minimum results of voltage magnitude in p.u. after done simulation system without installed 8 MW power plant is done, by varying three load characteristic; the peak, partial and light load are demonstrated to be base case. It is found that the maximum voltage magnitude is 1.0420 p.u. at HEM 22kV bus, on partial load characteristic, and the minimum voltage magnitude is 1.0180 p.u. at ATU 22 kV bus, on peak load characteristic. From table 3, the maximum and minimum results of energy losses in MWh after done simulation system without installed 8 MW power plant is done, by varying three load characteristic; peak, partial and light load are also demonstrated to be base case. It is found that the maximum energy losses is 48,601.714 kWh on peak load characteristic, and the minimum energy losses is 16,827.738 kWh on light load characteristic. Therefore, from table 2 and 3, the behavior of voltage magnitude is not out of range 0.95-1.05 p.u./or ± 5% of 22 kV distribution grid, and the energy losses will be increased follow the demand load, moreover, energy losses is depend on load characteristic except the location of 22 kV bus.

Table 2: Results of Voltage Magnitude for Base Case Simulation System

22 kV BUS	Result of Voltage Magnitude in p.u.					
	Load Characteristic					
	Peak		***Partial***		***Light***	
	Max.	**Min.**	**Max.**	**Min.**	**Max.**	**Min.**
ATU	1.0326	1.0180	1.0354	1.0185	1.0382	1.0248
PLU1	1.0353	1.0217	1.0380	1.0217	1.0368	1.0272
PLU2	1.0353	1.0217	1.0381	1.0218	1.0369	1.0273
PLW1	1.0357	1.0214	1.0383	1.0246	1.0386	1.0300
PLW2	1.0357	1.0214	1.0383	1.0247	1.0384	1.0297
HEM	1.0414	1.0406	1.0420	1.0293	1.0301	1.0295

Table 3: Results of Energy Loss for Base Case Simulation System

22 kV BUS	Result of Energy Loss in kWh		
	Load Characteristic		
	Peak	***Partial***	***Light***
ATU	48,601.714	34,976.330	16,827.738
PLU1	48,601.714	34,976.330	16,827.738
PLU2	48,601.714	34,976.330	16,827.738
PLW1	48,601.714	34,976.330	16,827.738
PLW2	48,601.714	34,976.330	16,827.738
HEM	48,601.714	34,976.330	16,827.738

B. Installed Distance of PV Power Plant Simulation

From table 4, the results of maximum and minimum voltage magnitude in p.u. after done simulation system with installed 8 MW power plant by varying three load characteristic; peak, partial and light load, and four PV power plant characteristic; sunny, rainy, cloudy, and party sun & cloud, moreover, the distance of installation are also demonstrated by varying distance at five km, ten km and twenty km. From table 5, the results of maximum and minimum economic loss in kWh after done simulation system with installed 8 MW power plant by varying three load characteristic; peak, partial and light load, and four PV power plant characteristic; sunny, rainy, cloudy, and party sun & cloud, moreover the distance of installation are also demonstrated by varying distance at five km, ten km and twenty km. From table 6, the results of maximum and minimum deviation of energy loss in % after done simulation system with installed 8 MW power plant by varying three load characteristic; peak, partial and light load, and four PV power plant characteristic; sunny, rainy, cloudy, and party sun & cloud, moreover the distance of installation are also demonstrated by varying distance at five km, ten km and twenty km. From table 7, the result of maximum energy loss per year and maximum saving energy per year are calculated to be economic loss and saving in baht unit per year when the 8 MW PV Power Plant is installed by varying three load characteristic; peak, partial and light load, and four PV power plant characteristic; sunny, rainy, cloudy, and party sun & cloud, and the distance of installation are also demonstrated by varying distance at five km, ten km and twenty km.

In case of voltage magnitude, from the table 4, after done simulation of thirty-six study cases found that the maximum value is 1.042000 p.u. while installed 8 MW PV power plant at HEM 22 kV bus, distance 10 km and 20 km, partial load pattern, and rainy weather, and the minimum value is 1.018001 p.u. while installed 8 MW PV power plant at ATU 22 kV bus, distance 20 km, peak load pattern, sunny weather. When compare results with base case, the voltage magnitude rather not change. Therefore, it can be concluded that location and distance of installation PV power plant are not impact to distribution grid system on voltage stability. Besides, the results of voltage magnitude of all 22 kV bus in p.u. when installed 8 MW PV power plant at ATU 22 kV bus with distance 5 km, peak load and sunny weather in terms of graph characteristic is also demonstrated in figure 4, it found that the voltage magnitude values are oscillated in range 1.041400 to 1.018050 p.u. - maximum value is 1.041400 p.u. at HEM 22 kV Bus and minimum value is 1.018050 p.u. at ATU 22 kV Bus - not out of range 0.95-1.05 p.u./or ± 5% of 22 kV distribution grid.

In terms of energy losses a day, from table 5, after done simulation of thirty-six study cases found that the maximum energy losses value is 50,467.205 kWh/day while installed 8 MW PV power plant at HEM 22 kV bus, distance 20 km, peak load pattern, sunny weather, and the minimum energy losses value is 16,662.313 kWh/day while installed 8 MW PV power plant at ATU 22 kV bus, distance 5 km, light load pattern, rainy weather. Make a compare results with base case found that when installed 8 MW PV power plant at ATU 22 kV bus, distance 5 km, energy can be saved as 165.425 kWh/day. And when installed 8 MW PV power plant at HEM 22 kV bus, distance 20 km, the energy is lost as 1,865.491 kWh/day. From table 6, after done simulation of thirty-six study cases found that the maximum % deviation of energy losses value is 11.328% a day while installed 8 MW PV power plant at HEM 22 kV bus, distance 20 km, light load pattern, sunny weather, and the maximum % deviation of energy saving value is 1.444% a day while installed 8 MW PV power plant at ATU 22 kV bus, distance 5 km, partial load pattern, sunny weather. From table 7, make a compare results of the economic loss of energy, refer to table 6, with base case found that when installed 8 MW PV power plant at ATU 22 kV bus, distance 5 km, it can be saved cost as 0.645 Million Baht /year. And when installed 8 MW PV power plant at HEM 22 kV bus, distance 20 km, the cost is increased as 2.435 Million Baht /year. Therefore, it can be concluded that location and distance of installation PV power plant are impact to distribution grid system on energy losses and economic loss.

Table 4: Results of Voltage Magnitude Simulation for Installed Distance of 8 MW PV Power Plant

Voltage Magnitude Value	Distance in km	Voltage Magnitude in p.u.	At Load Characteristic	At PV Characteristic	At BUS 22kV
Maximum	5	1.041999	Light	Sunny	HEM
	10	1.042000	Partial	Rainy	HEM
	20	1.042000	Partial	Rainy	HEM
Minimum	5	1.018042	Peak	Cloudy	ATU
	10	1.018022	Peak	Cloudy	ATU
	20	1.018001	Peak	Sunny	ATU

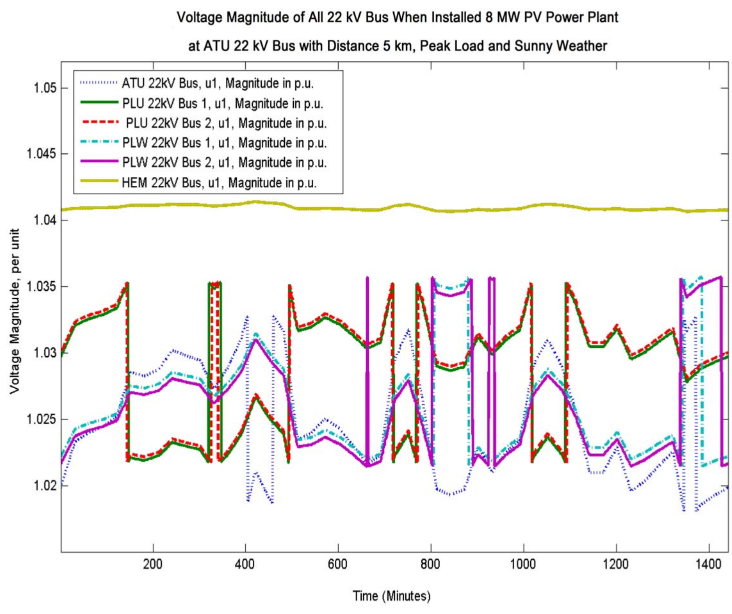

Figure 4: Voltage magnitude of all 22 kV bus when installed 8 MW PV power plant at ATU 22 kV bus with distance 5 km, peak load and sunny weather

Table 5: Results of Energy Loss Simulation for Installed Distance of 8 MW PV Power Plant

Energy Loss Value	Distance in km	Energy Loss in kWh	At Load Characteristic	At PV Characteristic	At BUS 22kV
Maximum	5	49,040.893	Peak	Sunny	HEM
	10	49,529.871	Peak	Sunny	HEM
	20	50,467.205	Peak	Sunny	HEM
Minimum	5	16,662.313	Light	Rainy	ATU
	10	16,758.525	Light	Cloudy	ATU
	20	16,770.320	Light	Rainy	ATU

Table 6: Results of % Deviation of Energy Loss & Saving Simulation for Installed Distance of 8 MW PV Power Plant

Deviation Energy Loss & Saving Value	Distance in km	Deviation Energy Loss & Saving in Percentage	At Load Characteristic	At PV Characteristic	At BUS 22kV
Maximum Loss	5	+ 2.864	Light	Sunny	HEM
	10	+ 5.774	Light	Sunny	HEM
	20	+ 11.328	Light	Sunny	HEM
Maximum Saving	5	- 1.444	Partial	Sunny	ATU
	10	- 0.723	Partial	Rainy	ATU
	20	- 0.341	Light	Cloudy	ATU

Table 7: Results of Economic Loss & Saving for Installed Distance of 8 MW PV Power Plant

22kV Bus	Distance in km	Energy Loss & Saving/Year		Economic Loss & Saving/Year	
		Deviation Energy Loss & Saving in Percentage	Base Case in MWh	Unit Cost in Baht/kWh	Total Cost in Million Baht/Year
Maximum Energy Loss at HEM Bus	5	+ 2.864	6,142.12	3.5	+ 0.615
	10	+ 5.774	6,142.12	3.5	+ 1.241
	20	+ 11.328	6,142.12	3.5	+ 2.435
Maximum Saving Energy at ATU Bus	5	- 1.444	12,766.36	3.5	- 0.645
	10	- 0.723	12,766.36	3.5	- 0.323
	20	- 0.341	6,142.12	3.5	- 0.073

C. Impact of System Disturbance Grid Situation

The previous voltage magnitude stability result shown that either of distance and position for installed the 8 MW PV power plant in terms of voltage does not have any effect to distribution grid, so the studying impact of system disturbance situation, only energy saving is shown in table 8 by concentration on ATU 22 kV bus. From table 8, the results of deviation of energy loss in % after done simulation system with installed 8 MW power plant by considering peak load characteristic and sunny weather for PV power plant characteristic, at distance 5 km. In terms of energy losses a day, after done simulation three kind of disturbance grid situation are; tripped substation, tripped load and tripped PV power plant, make a compare results of the economic loss of energy, refer to table 8, with base case found the maximum % deviation of energy saving value is 18.711%, 19.691% and 1.335% a day, while tripped PLW substation, tipped PLU R1 load and 8 MW PV power plant period 15 minutes, respectively, and the maximum economic saving value is 11.617 Million Baht/year, 12.225 Million Baht/year and 0.828 Million Baht/year, respectively. Thus, it can be concluded that installation of PV power plant on distribution grid helps to save energy and economic losses whenever disturbance grid situation take place.

Table 8: Results of Economic Saving for System Disturbance Situation

22kV Bus	Disturbance Situation	Energy Saving/Year		Economic Saving/Year	
		Deviation Energy Saving in Percentage	Base Case in MWh	Unit Cost in Baht/kWh	Total Cost in Million Baht/Year
ATU Bus, installed distance at 5 km, peak load	Tripped PLW Substation	- 18.711	17,739.63	3.5	- 11.617
	Tipped PLU R1 Load	- 19.691	17,739.63	3.5	- 12.225
	Tripped 8 MW PV power plant, 15 minutes	- 1.335	17,739.63	3.5	- 0.828

IV. Conclusions

In this paper, the results of simulation based on actual raw data condition – PV generated power pattern and load pattern - through changing installed location and installed distance found that the installation of PV power plant impact on distribution grid system in terms of energy losses and voltage magnitude. Besides, from an investigation, if the PV power plant is installed at the best location and the worst location found that the energy losses deviation is 33,805 kWh a day or/ 12,338,786 kWh a year, it can be converted to in term of economic loss as 43.19 million baht a year, and if the PV power plant is installed at the best location and the worst location found that the voltage magnitude deviation is 0.023999 p.u. Consequently, the locations along with the distances of installation PV power plant are impact on distribution grid system that are the reason why its managing properly in the future is the important thing so that it can help to prevent, optimize and minimize the effect of voltage stability and economic loss in utility distribution grid system appropriately, and help doing the energy policy along with enhancing the development of solar energy in Thailand sustainable next.

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