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Badrul H. Chowdhury
Missouri University of Science and Technology, bchow@mst.edu

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EFFECT OF CENTRAL STATION PHOTOVOLTAIC PLANTS ON POWER SYSTEM SECURITY

Badrul H. Chowdhury
Assistant Professor
Electrical Engineering Department
University of Wyoming
Laramie, WY 82071-3295

ABSTRACT

The value of photovoltaic (PV) plants to electric utilities is investigated under constraints of power system security. The generally adopted methods of analysis for determining the "capacity credit," "energy displacement" and "production cost savings" due to the PV plants have neglected the adverse conditions that may arise out of a random pre-selection of a substation where PV power is injected into the system. This paper presents an extensive approach at determining the realistic value of a PV plant to the utility. The method consists of using a power flow algorithm to determine system conditions under specific load scenarios. Identification of bus voltage violations and branch overloads is an integral part of the method. The location of the substation where PV is included is very important. Determination of system behavior under contingency conditions with and without PV is also investigated. This indicates whether the power system can withstand disturbances in the presence of PV power. The value of the PV plant can then be determined by finding the maximum PV penetration that does not cause the system to become insecure. The analysis is carried out on a small test system but is generally applicable to any size power system.

INTRODUCTION

The value of photovoltaic (PV) plants to electric utilities has been a fiercely debated topic for several years. Researchers have adopted different methods of analysis to determine the correct "capacity credit," "energy displacement" and "production cost savings" due to the PV plants [1-8]. One of the most popular methods of comparative study is to first execute an annual production cost routine on a "base" case with no PV plant included and then execute the routine on the same system but with the load modified by the photovoltaic generations. The difference in operating costs is a direct indication of the production cost savings due to the PV plant. Determining the capacity credit is tentamount to determining the thermal capacity of the plant which can be permanently taken off line without adversely affecting the reliability of supplying the load. Some attempt has also been made at integrating the PV plant in the utility's capacity expansion plans as is evident from the references included. Results of this analysis indicate the capacity deferment that is made possible by the presence of the PV plant.

In the approach outlined above, PV generation is used to get a modified unit commitment output. The unit commitment programs generally provide the information on thermal, hydro and combustion turbine (CT) units scheduled for a period of 24 hours to a week. This approach has several disquieting characteristics. These are:

1. PV output over the day or week of the unit commitment period is simulated using typical weather data at the site. While load forecasts during this period follow a certain trend and are generally considered to be accurate to a certain degree, the same cannot be said for the PV output. The reason is that, PV plant performance depends on the highly variable weather phenomena and are liable to extreme changes during the week. Therefore the amount of uncertainty introduced into the unit commitment program output is considerably increased because of the presence of PV power.
2. With the present approach, PV power is considered to be "forced" on the system. No care is taken to see whether the PV plant might be operating during a period of time when base-load units are operating. the latter are required to operate at the same level of generation throughout the day in order to be most economic. Also, no care is taken to see whether there is enough cycling capacity available at any time during which the net load changes substantially because of the "forced" PV generations.
3. The approach assumes firm capacity availability from the PV plant. In other words, the underlying assumption is that PV power is "available upon request".There is an inherent danger in such an assumption. With increasing amount of PV power, there comes a situation when some conventional dispatch units will not be scheduled by the unit commitment program which otherwise would have been scheduled because the unit commitment program is led to believe that there is enough firm capacity. This change in the generation schedule is not acceptable because of uncertainties involved with PV plant operation and the potential severity in system security because of loss of valuable spinning reserve.

PV power generation is dependent on the radiation intensity and therefore varies randomly due to the random movement of the cloud cover. PV plants are therefore intermittent generation sources which cannot be dispatched in a manner similar to thermal plants under the present dispatch strategy applied by utility operations. Any value analysis methodology must incorporate the intermittency of the PV plant generation so that problems of operating the power system in its presence can be identified. The trouble-free operation of the power system may require controlling the PV plant output or modifying the system dispatch strategy. Such a modified dispatch strategy is presented in [9]. Control actions such as those reported therein overcome some of the problems as stated earlier but will definitely reduce the value of the PV plant to the utility. Under such restricted operating conditions, the capacity credit determined under off-line planning studies cannot yield realistic numbers.

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The value of a PV plant therefore must be evaluated under both disptach conditions as well as power system security conditions. The latter is extremely important because the removal of a firm capacity like a coal plant under the assumption of capacity credit to the PV plant may render the system insecure under certain load conditions. This situation can be avoided by studying the security conditions in the presence of PV plants under varying load conditions before making a decision on the exact amount of capacity credit due to the the PV plant.

This paper presents an extensive approach at determining the realistic value of a PV plant to the utility. The method of study consists of integrating PV power generations with the normal operations of the power system. The utility is interested in determining whether the system remains secure with the inclusion of PV power into the grid.

METHOD OF STUDY

Before an analysis can be executed, it is important to investigate the relationships between the utility load profile and the PV power generations during particular days. It is well known that utility load demands vary considerably from one season to another. Also, seasonal changes in the solar irradiance have an effect on the PV plant outputs. Since system security conditions change with load, it becomes necessary to investigate the relationship of system loading and PV plant output.

Daily Load Profile and PV output - A Chronological Relationship

Figure 1 shows the relationship between utility load demand and PV plant generations during five consecutive days in the month of January for a typical utility in the western U.S. The PV generations are simulated using actual irradiance data at the site.

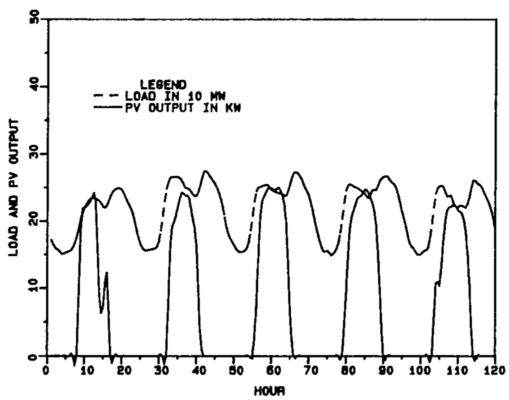

Figure 1. Typical load profile and PV output for five consecutive days in January.

From the figure, it is obvious that PV plant generation is a discontinuous output and the peak PV generation will vary on a daily basis. Thus, the peak could occur at at any time period from off-peak to peak demand hours. It is only fair to assume that depending on this chronological relationship between PV generation and load demand, the security condition in the system may vary considerably. Therefore, the effect of the spatial variation in the peak PV generation will be considered in the study. This is explained in the next figure.

Figure 2 shows a single-day typical summer load profile considered for the study.

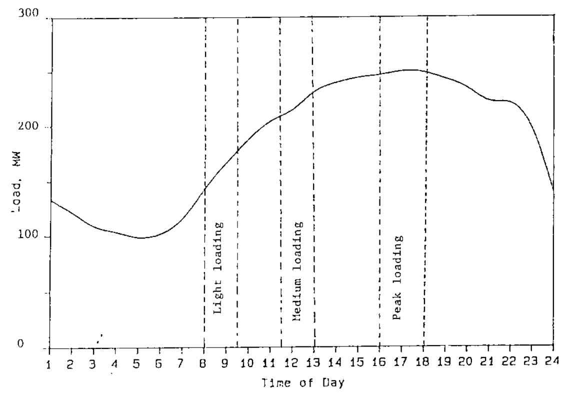

Figure 2. A typical load profile on a summer day.

Regions of peak, medium and light loadings are marked on the figure. Corresponding to these regions, PV plant generations can be recorded for use in the analysis. Peak load matching by the PV plant has always been considered to be most beneficial to the utility cost of operation because that would imply displacement of expensive thermal generating capacity. From the point of view of system security, peak load matching can prove to be fundamentally harmful to the system unless the PV plant location is selected with caution. An analysis to verify the above statement will be given in the results section.

Applied Approach for Security Assessment

The following steps illustrate the sequential actions used for security assessment in the presence of PV power:

1. Use a modified dipatch strategy to determine the scheduled generations from all dispatchable thermal plants as well as the PV plant, for an optimal economic operation at a given load.
2. Use a power flow algorithm to determine system conditions under the specific load scenarios. This step identifies:
   a. bus voltages and angles
   b. branch flows, and
   c. total system losses.
3. Repeat steps 1 and 2 for different loadings, e.g. peak, medium and light loadings.
4. Steps 2 and 3 identify the security violations e.g., bus voltage violations and branch overloads. The location of the substation where PV is included is very important. If no security violations are observed, then continue; otherwise change PV penetration and go to step 1.
5. Determine system behavior under contingency conditions. This indicates whether the power system can withstand disturbances in the presence of PV power.
6. Compare results of the security assessment between the "base" case (where no PV power is considered) and a "modified" case (where PV power is included) in the system.
7. The value of the PV plant can then be determined by finding the maximum PV penetration that does not cause the system to become insecure.

RESULTS

A 14-bus test power system used for illustrating the methodology is shown in Fig. 3.

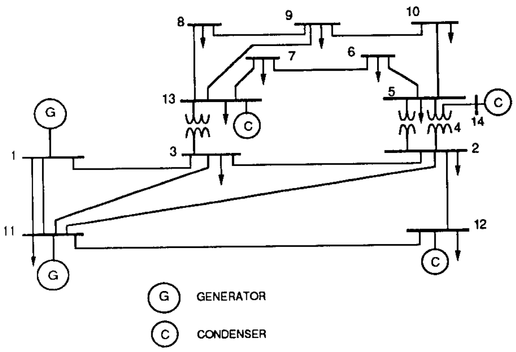

Figure 3. A 14-bus test power system.

PV penetrations of 5-15% of the total installed capacity were tested. It is assumed that the PV plant can be located in any bus on the figure.

Table 1 gives the transmission line loadings and voltage problems in the test system in the presence of PV generations at each bus considered separately. These are compared to a "base" case where no PV power is present in the system. The comparisons shown in Table 1 are for a peak demand level when the corresponding PV generation is 30 MW. This translates into a 11% penetration.

Column 2 of the table shows the effected line elements; column 3 shows the amount of line loadings; columns 4 and 5 show the buses and the increase/decrease of voltages at these buses respectively. The "base" case shows several lines which have more than 90% loadings, but no overloading is noticed. A line loading of 90% or above signifies that these may present potential overloadings under contingencies. The line connecting buses 11 and 1 has the most serious problem in the "base" case whereas, each of the twelve "modified" cases with PV present in the system will relieve this critical loading problem. However, other lines may become overloaded in the process. This is quite evident from the table. Also, bus voltages will be affected because of the presence of PV generations. For the test system, buses 2,3 or 4 were experiencing voltage increases while buses 5 through 10 consistently showed voltage decreases in all cases studied.

With the information provided in Table 1, it becomes easy to identify the PV plant location which will cause the most serious security problem in the system under peak loading condition. For the test system, this corresponds to buses 8,9 and 13. On the other hand, the optimum location is bus 12.

Table 2 shows comparisons of security parameters under medium loading conditions when the PV plant output is at 18 MW. The "base" case indicates no system security concerns. As would be expected, line overloadings are fewer than under peak loading conditions.

Contingency analysis with and without PV under both peak loading and medium loading conditions are shown in Tables 3 and 4 respectively. Only single line outage contingencies are considered in both loading cases. Results for four sample line outages are shown in the figures. Interestingly, PV power in most contingencies will relieve overloads. As an example, consider outage of the line between buses 1 and 3 in the peak loading case shown in Table 3. The "base" case shows overloadings on lines between buses 11 and 1, 11 and 2, 11 and 3 and 11 and 12. A PV plant at all bus locations except bus 11 show that the overload on the line between 11 and 12 is relieved. Similar conclusions can be reached from other contingencies under medium and light loadings.

Table 1: Security assessment at peak demand period

CASE	LINE LOADINGS		VOLTAGE DEVIATIONS	
	LINE	LOADING	BUS #	CHANGE
Base Case: No PV	1 - 11 1 - 3 1 - 12 1 - 2 3 - 2 2 - 4	97% 92.40% 90% 92% 90.30% 90%	-	-
PV Plant generating 30 MW at bus 2	2 - 12 2 - 4	95.70% 92%	All load buses	Slight increase
PV Plant generating 30 MW at bus 3	2 - 12 3 - 2 3 - 13	90.50% Overload 90%	All buses	No change
PV Plant generating 30 MW at bus 5	2 - 12	94%	2, 3, 4 8	Increase Decrease
PV Plant generating 30 MW at bus 6	2 - 12 5 - 6	93.40% Overload	2, 3, 4 5, 8, 10	Increase Decrease
PV Plant generating 30 MW at bus 7	2 - 12 7 - 13 7 - 6	92.50% Overload	3 5, 6, 10	Increase Decrease
PV Plant generating 30 MW at bus 8	2 - 12 3 - 2 7 - 13 8 - 13 7 - 6 8 - 9	91% 91% Overload Overload 97% Overload	2, 3 5, 6, 7, 9, 10	Increase Decrease
PV Plant generating 30 MW at bus 9	2 - 12 3 - 2 7 - 13 9 - 10	92% 90% Overload Overload	2, 3 5, 6, 7, 8, 10	Increase Decrease
PV Plant generating 30 MW at bus 10	2 - 12 10 - 5	93% 91%	2, 3 5, 6, 7	Increase Decrease
PV Plant generating 30 MW at bus 11	11 - 12 11 - 2 2 - 4 11 - 3	91% 95% 90% 90%	All buses	No change
PV Plant generating 30 MW at bus 12	2 - 4	91%	All buses	No change
PV Plant generating 30 MW at bus 13	2 - 12 3 - 2 13 - 7 13 - 14 7 - 6	92% 92% Overload 97% Overload	2, 3 5, 6, 7, 10	Increase Decrease
PV Plant generating 30 MW at bus 14	2 - 12 4 - 14 4 - 5	94% Overload	2, 3, 4, 5 6, 7, 9, 10	Increase

Table 2: Security assessment at medium demand period

CASE	LINE LOADINGS		VOLTAGE DEVIATIONS	
	LINE	LOADING	BUS #	CHANGE
Base Case: No PV	All lines	Light to medium	-	-
PV Plant generating 18 MW at bus 2	All lines	Light to medium	All buses	No change
PV Plant generating 18 MW at bus 3	All lines	Light to medium	All buses	No change
PV Plant generating 18 MW at bus 5	All lines	Light to medium	2, 3, 4	Increase
PV Plant generating 18 MW at bus 6	All lines	Light to medium	2, 3, 6 5, 10	Increase Decrease
PV Plant generating 18 MW at bus 7	6 - 7	Overload	2, 3 5, 6	Increase Decrease
PV Plant generating 18 MW at bus 8	8 - 9	Overload	2, 3 5, 6, 7, 9, 10	Increase Decrease
PV Plant generating 18 MW at bus 9	All lines	Light to medium	2, 3 5, 6, 7, 8, 10	Increase Decrease
PV Plant generating 18 MW at bus 10	All lines	Light to medium	2, 3 5, 6, 7, 9	Increase Decrease
PV Plant generating 18 MW at bus 11	All lines	Light to medium	All buses	No change
PV Plant generating 18 MW at bus 12	All lines	Light to medium	All buses	No change
PV Plant generating 18 MW at bus 13	All lines	Light to medium	2, 3 5, 6, 7	Increase Decrease
PV Plant generating 18 MW at bus 14	4 - 14	93.50%	2, 3, 5 6, 7, 10	Increase

Table 3: Contingency analysis at peak demand period

CASE	LINE OUTAGES			
	1 - 3	11 - 2	2 - 12	9 - 13
	Overloads	Overloads	Overloads	Overloads
Base Case (No PV)	11 - 1, 11 - 2 11 - 3, 11 - 12	1 - 3, 11 - 12 3 - 2, 11 - 3	11 - 1, 11 - 12	8 - 9, 7 - 13 8 - 13, 5 - 10
PV Plant at bus 2	11 - 1, 11 - 2 11 - 3	11 - 12, 3 - 2 11 - 3	11 - 12	8 - 13, 5 - 10 8 - 9
PV Plant at bus 3	11 - 1, 11 - 2 11 - 3	11 - 12, 3 - 2 11 - 3	11 - 12	3 - 2, 7 - 13 8 - 13, 5 - 10 8 - 9
PV Plant at bus 5	11 - 1, 11 - 2 11 - 3	11 - 12, 3 - 2 11 - 3	11 - 12	8 - 13, 5 - 10
PV Plant at bus 10	11 - 1, 11 - 2 11 - 3	11 - 12, 3 - 2 11 - 3	11 - 12	8 - 13
PV Plant at bus 11	11 - 1, 11 - 12 11 - 2, 11 - 3	1 - 3, 11 - 12 3 - 2, 11 - 3	11 - 12	7 - 13, 8 - 13 5 - 10, 8 - 9
PV Plant at bus 12	11 - 1, 11 - 2 11 - 3	1 - 3, 3 - 2 11 - 3	None	8 - 13, 5 - 10 8 - 9

Table 4: Contingency analysis at medium demand period

CASE	LINE OUTAGES			
	1 - 3	11 - 2	2 - 12	9 - 13
	Overloads	Overloads	Overloads	Overloads
Base Case (No PV)	11 - 1, 11 - 2 11 - 3	3 - 2, 11 - 3	11 - 12	8 - 13, 8 - 9
PV Plant generating 18 MW at bus 2	11 - 1, 11 - 3	3 - 2	11 - 12	8 - 13, 8 - 9
PV Plant generating 18 MW at bus 3	11 - 1, 11 - 3	3 - 2	11 - 12	8 - 13, 8 - 9
PV Plant generating 18 MW at bus 5	11 - 1, 11 - 3	3 - 2	11 - 12	8 - 13
PV Plant generating 18 MW at bus 10	11 - 1, 11 - 3	3 - 2	11 - 12	None
PV Plant generating 18 MW at bus 11	11 - 1, 11 - 2 11 - 3	3 - 2, 11 - 3	11 - 12	8 - 13, 8 - 9
PV Plant generating 18 MW at bus 12	11 - 1, 11 - 2 11 - 3	3 - 2, 11 - 3	None	8 - 13, 8 - 9

CONCLUSIONS

This paper presents arguments in favor of the statement that the value of central station photovoltaic power to electric utilities should not be determined without concern for system security. The value of a PV plant can only be useful if the additional power does not cause line overloading and/or bus voltage deviations that would otherwise not occur. The analysis presented in the paper introduces a step-by-step method of determining the optimum PV penetration that would not cause system security violations under any general demand condition.

During the analysis, it was found that the generally accepted notion that peak load matching by the PV plant is beneficial to utility operations, does not entirely portray the true conditions under security assessment. In fact, for some systems, this may even adversely affect system operation. For the test system adopted for the analysis in this paper, the peaks were fairly well matched at the times selected for the simulation. Under peak demands, some of the lines were already carrying 90% of the rated load. With the addition of a PV plant, overloads can occur in those critical lines unless discretion is used in the choice of the bus where the central station PV plant is to be added.

The analysis shows that on an assumption that the PV plant is added to an existing transmission and distribution system, with the right choice of a substation for adding the PV power, line overloads can be avoided under normal system loading conditions and lines can be relieved of additional overloads under single line contingencies.

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