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OPTIMIZING THE INTEGRATION OF PHOTOVOLTAIC SYSTEMS WITH ELECTRIC UTILITIES

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ABSTRACT

This paper introduces a comprehensive simulation package whereby the optimal size, operation, performance and economics of a PV system can be determined in the utility-integrated mode. The central issue that concerns the paper is to present a single definitive optimization model that ties together most ideas in this expansive area of utility integration of PV systems. A stepwise analytical methodology starting at the solar resource and culminating in the value of the PV system in terms of avoided costs is provided. The methodology includes processing of the solar irradiance; identification of the PV system's configuration and operational features; identification of real-time system controls in the presence of PV generations; security assessment in the presence of PV and production costing and capacity expansion analysis with PV. The optimization package is sub-divided into five different sub-groups based on their respective purposes in the context of the overall scheme. The paper describes in detail the functions of each sub-group in the analysis and the interpretation of results from each which can then be tied together to yield important parameters, such as capacity credit, PV penetration, costs, etc.

Keywords: Solar irradiance, economic dispatch, security assessment, production costing, capacity expansion.

1. INTRODUCTION

Since the energy crisis of the 1970s, the electric utility has been interested in non-conventional forms of energy for displacing its fossil-fuel fired generation systems. Photovoltaic (PV) systems are being considered as a viable alternative and past research [1-3] certainly indicate a great deal of advancement in this particular science. The on-going project called Photovoltaics for Utility Scale Applications (PVUSA) is assessing and demonstrating the viability of utility scale PV electric generation systems [4]. Among the factors that have or are still contributing to the increased attention being paid to PV technology are:

- *Improved solar cell technology*: Both flat plate and concentrator module efficiencies have improved over the past few years. Besides, a large variety of semiconductor materials other than the commonly used silicon as well as structures other than the simple P-N junction have been introduced and undergoing research. Amorphous Silicon is at present common for large power applications.
- *Steadily decreasing costs*: Over the years since PV systems first started producing power, the installed cost of the system has come down enormously and is continuing the trend.
- *Improved energy storage technology*: Lead-acid and Nickel-Cadmium batteries are the most widely used energy storage devices with PV applications. In the past, the life of the battery has been limited in terms of duty cycles. In recent years, high efficiency batteries with lifetime usage of up to 30 years may be available for central-station applications. The Nickel-Hydrogen battery offers such an option. Other forms of storage are being considered, e.g., superconductive materials, flywheels, etc.

In spite of the above facts and figures, the widespread utility acceptance of PV has left something to be desired. The main concern has been the random nature of the resource. Logical questions raised by utility planners are regarding i) the effect of such intermittency on the overall reliability of the system and ii) the upper limit of the size of the PV system before reliability conditions deteriorate. Although such questions can be easily answered by use of a widely available long-term utility planning package, the figures obtained from such an analysis alone may not be altogether reliable. These planning packages are normally used to study the effects of the presence of conventional plants on a system with the assumption that these plants can be operated according to a given generation scheduling scheme as determined by the control center.

However, because of the variations of solar irradiance occurring in the minute-to-minute time frame, PV systems cannot be a part of the utility's generation schedule. Therefore, in the presence of PV systems, operational questions must be answered before even attempting a long-term planning study. The basic problem in operating a PV plant arises from the fact that randomly varying sources cannot be dispatched in the same manner as conventional plants. Besides, adding a PV plant on an existing transmission and distribution system may cause additional security problems. The likelihood of a PV plant generating peak power during a system's peak demand condition is rather high, mostly in summer peaking utilities. Under such conditions, transformers and transmission lines may already be close to being heavily loaded and additional generation from the PV plant can easily overload those components. Unless these operational concerns can be effectively addressed, any long-term planning results would be erroneous and unacceptable.

This paper introduces a comprehensive simulation package whereby the optimal size, operation, performance and economics of a PV system can be determined in the utility-integrated mode. Since, quite a bit of research work has been done in the past few years with regard to including PV systems in a utility, some of these are pointed out at appropriate places in the paper. The central issue that concerns this paper is to present a single definitive optimization model that ties together most ideas in this expansive area of utility integration of PV systems.

2. THE OPTIMIZATION METHODOLOGY

Figure 1 shows an overview of the methodology adopted for optimizing a PV system in an electric utility. The objectives of the optimization process are determination of (i) an appropriate PV penetration, (ii) the most effective form of operation of the PV plant in terms of impact on system operating economics and security and iii) maximum capacity credit obtainable for the PV system without negatively impacting system reliability. On close inspection of the Fig. 1, five distinct analytical sub-groups can be identified. These are from left to right:

- Insolation and PV Power Pre-processor.
- System Operational Features Identification.
- Real-time System Controls Identification.
- Power System Security Analysis.
- Production Cost and Capacity Expansion Analysis.

The order of each sub-group in the general scheme of the methodology should be maintained in the same order as listed above as the execution of any sub-group depends on the results of execution of the previous sub-group. The flow of information from one sub-group to another is exactly as depicted by the arrows on the diagram. The methodology provides options of system modification at several strategic points of the analysis. As a matter of fact, the analysis should not proceed unless the user backtracks with modified data to a point in a previous sub-group. Each sub-group can be identified by rectangular blocks bearing specific numbers between 1 and 5. Hence Sub-group I is shown in blocks numbered 1, Sub-group II by blocks numbered 2 and so on. The oval blocks signifying inputs and outputs belong to a specific sub-group.

The following sections describe in detail the function of each sub-group in the analysis.

2.1 Insolation and PV Power Pre-processor

Determination of the value of PV systems to electric utilities begins with modeling the solar resource itself. The sub-group is concerned only with the processing of irradiance data for further use in subsequent analysis. Availability of long-term observations of insolation, temperature, wind speed and cloud cover at a particular site is of vital importance. Processing of such data can proceed in two directions as can be seen by appropriate blocks in Fig.1: statistical characterization and 3-10 minute data prediction. Inputs required and outputs obtained by this sub-group are:

Inputs: Long-term irradiance data, ambient temperature data, cloud cover data.
Outputs: Capacity factors, chronological PV plant output for a year.

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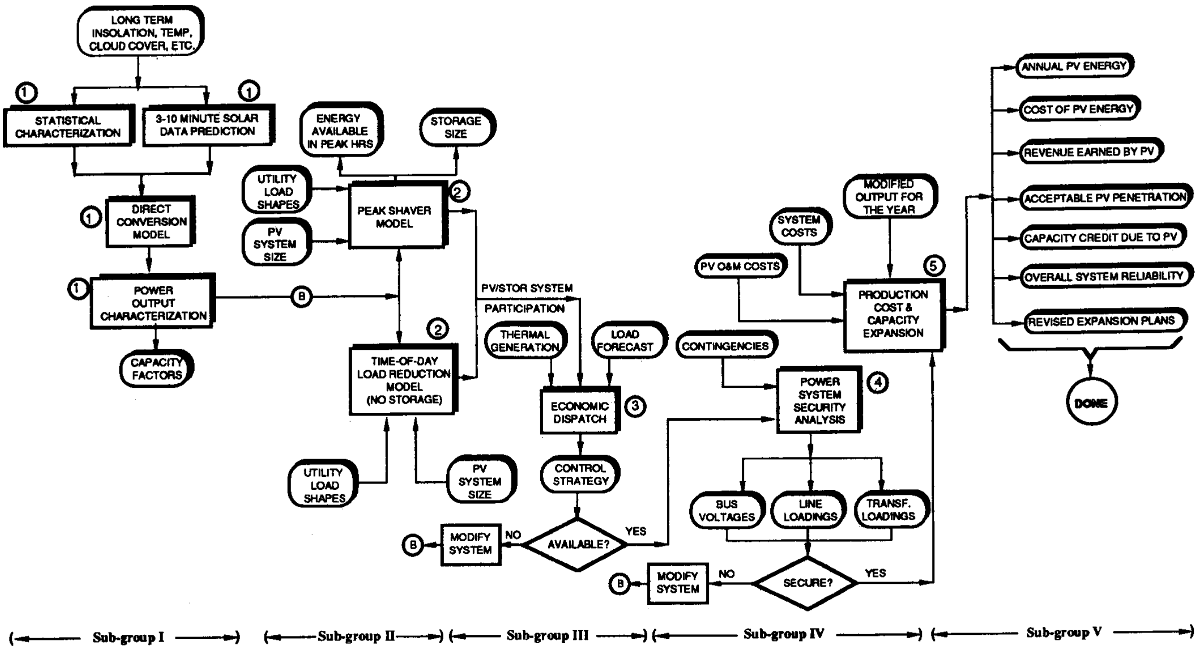

Fig. 1. An overview of the methodology.

Several authors over the past few years have attempted to statistically model the solar irradiance. Most of the models are derived on hourly, daily, or monthly time scales. Much of the available literature is based on correlation of the unknown components of solar radiation with known or deterministic factors such as sunshine hours or cloud cover data [5,6]. An equally large concentration of research work is in the area of modeling solar irradiance components through parameterizations of atmospheric phenomena [7,8]. Parameterization include modeling Rayleigh and Mie scattering and aerosol effects. These existing statistical models can be used to determine the expected solar irradiance components vis-a-vis direct and diffuse radiation on a horizontal surface at any particular hour of the day. The estimated irradiance values are then used by the direct conversion model to produce corresponding PV outputs.

For generation scheduling and dispatch, electric utilities are interested to know whether it is possible to have any advance knowledge about the availability of PV power on a daily basis. Irradiance values can vary significantly in the minute-to-minute interval. Such random disturbances can pose dispatch problems for the utility specially when the PV system penetration reaches 10 percent or above. Results shown in [9] provide evidence contrary to the general belief that because PV power is free of cost, all of the power generated ought to be injected into the power grid. In reality though, high variations in solar irradiance occurring on partly cloudy and windy days restricts acceptance of the total amount of PV power in the grid because of additional operating problems faced by the utility. It seems fairly obvious that the electric utility would be very interested in knowing the transient weather conditions ahead of time so that it can prepare for an imminent contingency. This invokes the need for forecasting solar irradiance in a sub-hourly time frame.

Several authors have discussed models to forecast solar irradiance based on past trends and patterns [10-11]. The model described in [12] makes use of atmospheric parameterizations and a time-series model to forecast sequences of global irradiance in the 3-10 minute time frame.

PV Conversion Systems

Once the insolation is processed, one needs to simulate the electrical performance of a PV system by using a direct conversion model. For maximum effectiveness, the PV system will in all likelihood employ array tilting or constant tracking of the sun. This means that the irradiance measured or estimated on a horizontal surface must be translated on to inclined surfaces. Some of these translation algorithms are discussed in [13]. Computer simulation programs exist today which can evaluate the electrical output of PV systems given insolation temperature and wind speeds at a site [14]. The purpose of such an evaluation tool is to calculate the plane-of-array irradiance, model the PV cell temperature and determine various efficiencies using reference values. DC power is then calculated as a product of these efficiencies and the modular area of the PV array. AC power is computed by using inverter efficiencies.

The output of a PV system depends on the orientation of the array. Three important orientation strategies may be employed:

- *South-Facing Array*: This is the most typical orientation for PV systems in the northern hemisphere. The installation requires only a simple tilting structure. Often, it may be necessary to change the tilt angle on the array based on a monthly optimal output.
- *Optimal-Surface-Azimuth Oriented Array*: Since maximizing PV output at noon (solar) time may not necessarily be of primal importance to a utility with a load shape peaking at another hour besides noon, it is advisable to maximize the PV output at or close to the hour of peak demand. This can be done by changing the surface azimuth angles as required to an angle suitable for maximizing the PV generations at any prescribed hour of peak load. This orientation strategy is of course inherently linked with the fact that the overall energy generated during the day is less than that generated by a south-facing array.
- *Two-Axis Tracking Array*: In this orientation strategy, the array is always facing the direction of the sun for maximum solar radiation at every hour. In other words, the incidence angle is constantly held at 0 degrees. This strategy requires the use of expensive, tracking mechanism in both the horizontal and vertical axis.

Power Output Characterization

The next step in this sub-group of the analysis is PV power output characterization. Owing to the random nature of the solar resource, one needs to determine the expected value of the power output from a PV system over a day, month or a year. If long-term insolation measurements are used in the analysis, capacity factors can prove to be a true indicator of expected power availability. Capacity factor is defined as the ratio of the expected value of output power and the rated power for a particular period.

2.2 System Operational Features Identification

In this part of the analysis, the performance of the PV system in the presence of utility loads is simulated. Blocks numbered 2 in Fig. 1 form the sub-group dealing with this study. Inputs required and outputs obtained by this sub-group are:

Inputs: Expected hourly PV plant output, PV plant size, utility representative load shapes.

Outputs: Storage size and PV/storage energy available during peak hours.

Some of the important questions whose answers are sought in this sub-group are:

- Is it more economical to shift the generation to coincide with the system peak demands?
- Is it at all possible to do the above by using energy storage?
- Can a range or period be specified for a generally consistent PV system operation during the day?
- Given that the optimal daily periods(s) have been found for PV operation, what is the total amount of energy generated in the period(s)?

Two performance models can be used. These are: a peak shaver model and a time-of-day load reducer model.

Peak Shaver Model

With the availability of advanced batteries and other storage technologies, it is now possible to store large amounts of energy during off peak periods of the day for use during the peak periods. The rationale for this entire scheme revolves around the fact that cost of energy during peak periods is more expensive and derived from fossil fuel and therefore the PV system would be considered more valuable to the utility if it could displace expensive fuel required during these periods. An important feature of this model is the investigation of the size of battery system for combined operation with a PV system. Since economy of scale is not very much applicable in battery sizing, the smallest size required to supply the specified period is desired. The authors in [15] discuss the technical and economic feasibility of using a combined PV/battery system for utility peak load leveling.

Time-of-Day-Load Reducer Model

In this model, the power generated by the PV system is added to the system as it becomes available. No storage is considered in this model and therefore the issue of matching of peak demands by the PV generations is no longer one of high priority. It is reasonable to argue that this may not be the most effective form of operation in terms of operating economics because of negative correlations between generation and demand peaks. Besides, it can also be argued that the penetration of the PV system may be limited because the high variability of uncontrolled PV output will definitely constrain the load following requirements of the system dispatchable generations. On the other hand, the peak-shaver model also does not guarantee unlimited penetration, although the high variability of the PV system output can be overcome by storage. The reason is potential transmission line overloadings during peak periods and of course exponentially increasing cost of storage as penetration increases.

2.3 Real-Time System Control Identification

In the preceding analytical sub-group called "System Operational Features Identification," a PV system is assumed to operate on a utility's load demands without concern for generation scheduling or dispatch problems that may result as a direct consequence of "forcing" the PV power on the system. Generation scheduling is in general the science of applying optimization techniques to determine a set of the most desirable generating units to supply the load under certain cost and power constraints. Blocks numbered 3 in Fig. 1 along with its associated input/output blocks form Sub-group III. Inputs required and outputs obtained by this sub-group are:

Inputs: Thermal generation, load forecast, PV plant output transitions in sub-hourly intervals.

Outputs: System control strategies.

The purpose of this sub-group is the development of a strategy for economic dispatch of PV power in the same general sense as that of conventional power generation. Optimal dispatch of PV power requires the development of strategies that allows control of PV plant generations and therefore avoids the penalties due to load following and spinning reserve requirements and other related real-time operational problems. Past research [9,16] have dealt with certain strategies for control of non-conventional generation sources including PV and wind. In dispatching PV power, the dispatcher has to be given information on the general availability of the PV power plant at least 24 hours in advance for unit commitment and the expected fluctuations in plant output 3-10 minutes in advance for economic dispatch. The latter can be done either heuristically by examining present conditions through computer-controlled data management system, or by a statistical forecast model.

Actual observation at various sites around the country support the fact that high amounts of fluctuation may exist in the solar irradiance within a 3-5 minutes interval. This variation translates into constantly fluctuating PV generations posing serious decision-making problems for the dispatcher. In order to quantify the penalties caused by such variations on the power system, one needs to recognize the fact that the randomness found in the global solar irradiance received on earth's surface is caused by changes in the cloud cover. A clear day's (cloudless sky) irradiance data may be estimated accurately by atmospheric parameterization and is therefore deterministic in nature. It is the stochasticity of constant cloud movement which makes the radiation on a partly cloudy day difficult to predict.

In order to determine the specific controls that could be adopted for a problem-free operation of an integrated power system, one should investigate the system operation under certain extreme scenarios. These scenarios are combinations of specific periods of daily load profile and changes in PV plant output from one economic dispatch interval to another. The scenarios are listed below:

- Under peak load condition
  - PV increase by X MW
  - PV decrease by Y MW
- Under medium load condition
  - PV increase by X MW
  - PV decrease by Y MW
- Under low load condition
  - PV increase by X MW
  - PV decrease by Y MW

It is worth mentioning that specific PV plant changes of X MW and Y MW can be found from sub-group I, that is the irradiance pre-processor. A close examination of sub-hourly historical observations of global irradiance may reveal such rapid changes in plant output.

2.4 Power System Security Analysis

The value of a PV plant should be evaluated not only under dispatch conditions as described in the previous section but also under 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 earned by the PV plant. Potential security problem identification in the presence of PV generations has been attempted in [17]. Such analyses should become part of a comprehensive methodology for value determination. Blocks numbered 4 represent 4 in Fig. 1 represent the components of Sub-group IV. Inputs required and outputs obtained by this sub-group are:

Inputs: Selected contingencies, expected PV plant outputs during low, medium and peak hours.

Outputs: Bus voltages, line and transformer loadings.

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. A power flow algorithm is used to determine system conditions under a specific load scenario. Bus voltage magnitudes and angles, branch flows and transformer loadings can be determined. The location of the substation where PV is included is an important aspect of the analysis. The system behavior under contingency conditions is also investigated. This indicates whether the power system can withstand disturbances in the presence of PV power. If security violations are observed, then the analysis returns to Sub-group II for a modified PV/storage system participation. The analysis moves to the next sub-group after finding the maximum PV penetration that does not cause the system to become insecure.

2.5. Production Cost and Capacity Expansion Analysis

The final step in the methodology is the determination of long-term impact of the PV system on the utility. Production costing or predicting expected generations for different power plants as well as the total system production costs is an integral part of quantitative power system analyses. These analysis have to be made prior to making decisions regarding the planning of electric power components, constructing components, continuing or delaying construction, etc. A typical utility generation expansion planning model analyzes alternative expansion plans for a number of years in the future using available generating units. These units may be classified into two categories: scheduled and expansion units. Scheduled units are those units which exist at the beginning of the study period and units which are firmly scheduled for further additions. The expansion units are those candidate units for future addition that are not firmly scheduled at the beginning of the study period but that can be added to the system if selected for optimum system expansion. All possible combinations of new candidate generating units that satisfy certain criteria are evaluated. This evaluation requires simulation of the system energy production and reliability during each year considering both scheduled and expansion units. Subsequently, these combinations of new candidate generating units are compared using a mathematical optimization technique for finding the optimal solution.

Several authors have in the past introduced techniques for long-term value determination of PV system in the utility context [18,19]. These analyses have been attempted without general regard for the shorter-term operational problems pointed out in this paper.

The value analysis should reach the Production Cost and Capacity Expansion sub-group only when system control strategies have been identified and the system can be considered secure in the presence of PV generations as discussed in the preceding analytical sub-group. The blocks numbered 5 along with its associated input and output blocks in Fig. 1 represent Sub-group V. A list of input parameters required and output parameters sought from this sub-group are shown below:

Inputs: Modified PV plant output, PV O&M costs, system costs.

Outputs: Annual PV energy, cost of PV energy, revenue earned by PV, acceptable PV plant size, capacity credit due to PV, system reliability and revised utility expansion plans.

The modified output for the year shown above refers to PV generations after operating controls have been implemented in the system for both economic dispatch and system security. The items "acceptable PV penetration" and "capacity credit due to PV" found from this sub-group of the analysis can be considered optimal only if the items "overall system reliability" and "revised expansion plans" are optimal in the presence of PV generations. In case of a worse reliability figure and/or higher expenditures arising from a revised expansion plan, the PV system would be unacceptable in its present form and the analysis would retrace to a previous sub-group for modification. Such interaction between the long-term planning model and the short-term operational models, establishes an accurate value of the PV system in a utility-integrated mode and a higher confidence can be placed on PV penetration levels, capacity credits and cost savings.

3. INTERPRETING RESULTS FROM THE ANALYSIS

In order to represent the results from each sub-group of the methodology, the information will be entered into several worksheets. This provides fast identification of the appropriate data, ease of interpretation and convenience in subsequent use in later sub-groups. To study the impact of a proposed PV system on a utility, one needs to examine the various options available. The user of this package who is most likely to be a utility planner will have certain options in mind before executing this package. For example, he/she will select:

1. Type of use for the PV system in the utility either as a load leveling plant or in general a load reduction plant
2. A single site or dispersed sites or have the computer make an appropriate selection. In selecting one or more sites, one must remember that the PV plants be close to one or more of the larger sub-stations in the utility's transmission network. Such substations where the PV plants are integrated will be considered as generating stations, thus changing the network topology during all subsequent power flow analysis.
3. Type of orientation for the PV plant or have the computer make an appropriate selection.

3.1 Execution of Sub-Group I

Worksheet 1 shows the hourly irradiance data on a typical day in a specific month. The typical day is composed from several years of irradiance data at the particular site. Such archived data is normally in the sub-hourly range. An hourly profile can be produced quite easily for this data. A computer program classifies the monthly data into three categories: clear day, partly cloudy and cloudy according to a predefined criteria. Then the monthly irradiance data is averaged for each hour to yield a typical day.

Worksheet 1. Irradiance Data Composition for a Typical Day in a month

BETWEEN HOURS	CLEAR SKY	PARTLY CLOUDY	CLOUDY
7:00 - 8:00 am	120.5	89.6	10.8
8:00-9:00 am	255.2	201.9	88.6
9:00-10:00 am	301.8	285.3	105.7
10:00-11:00 am	..	..	..
..	..	..	..
6:00-7:00 pm	..	..	..

Data entered in Worksheet 1 is composed from actual observations in Northeastern Colorado and is used here only as a sample. Some of the later worksheets in this section also carry data specific to this particular site. Worksheet 2 is used to accumulate information on maximum transitional changes in irradiance levels in a sub-hourly interval. This data is useful for identifying real-time controls during economic dispatch.

Worksheet 2. Irradiance Transition Limits During a Sub-hourly Interval

BETWEEN HOURS	MAX IRRADIANCE INCREASE	MAX IRRADIANCE DECREASE
7:00 - 8:00 am	12.2	9.7
8:00-9:00 am	15.8	19.7
9:00-10:00 am	72	65.4
10:00-11:00 am	..	..
..	..	..
6:00-7:00 pm	..	..

3.2 Execution of Sub-Group II

The analysis now extends into the PV system aspect with such options to be considered as a single site versus dispersed sites, fixed versus tracking arrays and storage versus no storage. Additionally an estimate of the size of the PV system has to be made here keeping in mind that this figure may change during later stages of the analysis.

No Storage Case

PV system output simulation will proceed with hourly data for the typical days in each month which was shown in Worksheet 1. This is merely to get a first indication of the relative impacts on the affected thermal or hydro units present in the power system. Total PV system energy output during an hour will directly affect the scheduled conventional unit operation in terms of potential reduction in plant output. Worksheet 3 shows a sample simulation result when no storage is considered.

Worksheet 3. Hourly PV Plant Output (MW) on a Typical Day

Array Size: 300 MW

BETWEEN	CLEAR SKY			PARTLY CLOUDY			CLOUDY		
HOURS	Fixed	1-axis	2-axis	Fixed	1-axis	2-axis	Fixed	1-axis	2-axis
7:00-8:00 am	35.4	36.3	45.9	23.4	26.4	30.3	5.1	5.7	6.6
8:00-9:00 am	72.6	77.1	94.5	55.2	63.9	71.7	21.0	26.7	27.3
9:00-10:00 am	89.4	93.3	116.1	78.6	87.9	102.3	28.5	30.3	36.9
10:00-11:00 am		..			..			..	
..		..			..			..	
6:00-7:00 pm		..			..			..	

Storage Case

In the scenario where storage is considered as an integral part of the PV system, utility peak load leveling or peak shaving becomes the foremost concern. With the availability of advanced batteries, PV energy can be stored efficiently for use during periods of high demand in order to increase the value of the PV system. Sizing a suitable battery for this purpose is a difficult task because it must be done in the light of the following constraints:

- PV power should be used only during the peak period. If PV power is available during the peak region, then it should be used directly to serve the load; if not, then the PV power should be used to charge the battery.
- Usage of PV power outside the peak demand region should be almost nil.
- Cost of the battery is largely dependent on the MWh size than the MW size. Therefore a long period of discharge during peak hours can drive the cost very high.
- Backup power, i.e. power outside of the PV generated power, to charge the battery should be almost nil.
- Battery discharge during peak periods should be such that a reasonable amount of peak shaving is possible and at the same time battery depth of discharge is not very high.

Worksheet 4. PV/Battery Participation (MW) in Load Leveling

PV Array: Rating:- 300 MW; Two-axis tracking; Weather Condition: Partly Cloudy; Month: August

BETWEEN HOURS	UTILITY LOAD	ARRAY POWER TO BATTERY	ARRAY POWER TO LOAD	BATTERY POWER TO LOAD
7:00 - 8:00 am	low	full	0	0
8:00-9:00 am	low	full	0	0
9:00-10:00 am	low	full	0	0
10:00-11:00 am	mwdium	full	0	0
11:00-12:00 pm	medium	partial	partial	0
12:00-1:00 pm	peak	0	full	full
1:00-2:00 pm	peak	0	full	full
2:00-3:00 pm	peak	0	full	full
3:00-4:00 pm	medium	partial	partial	0
4:00-5:00 pm	medium	full	0	0
5:00-6:00 pm	medium	full	0	0
6:00-7:00 pm	medium	full	0	0

Shaded Area -> Peak hours

An iterative computer optimization methodology to satisfy the above constraints is employed to yield desired results. Once the battery size is fixed, simulation can continue in order to determine respective hourly participation from the PV array and the battery for load leveling purposes. Worksheet 4 provides sample information for 2-axis tracking arrays on a partly cloudy day for a particular month. Similar worksheets can be formed for other array configuration options and other weather types and the other months.

3.3 Execution of Sub-Group III

Real-time power controls may be required during economic dispatch because of random variation in the PV output alone. It should be borne in mind that even with a battery storage option, the variations will be due to the PV array and not due to discharge of the battery. From Worksheet 2 one can determine the maximum percentage increase or decrease in PV plant output during a dispatch interval. The function of this sub-group is to identify problems arising out of such short-term PV output transitions during peak load, medium load or low load conditions and to suggest control measures to overcome these problems. Utilities normally operate with a reasonable amount of regulating capacity. It is possible that the inclusion of PV system fluctuations may cause violations in the regulating capacity.

Worksheet 5 shows such possible problems in the system when the PV plant output changes suddenly during the three representative demand periods. The term regulating capacity violation represents the inability of the thermal units to ramp up or down fast enough to cover the PV-induced fluctuations.

Two kinds of conditions might arise. These are described below under two cases:

Case I

Thermal generation increase not possible in the dispatch interval: This situation may arise because of a sudden drop in PV power in the mix causing the cycling thermal generators to attempt to make up the loss.

Case II

Thermal generation decrease not possible in the dispatch interval: This situation is brought about when there is a sudden increase in PV generation in the mix possibly by movement of clouds away from the area. The cycling thermal generators are expected to back-off part of their generations (unload) in order to accommodate the additional PV power.

Worksheet 5 also contains columns for total number of thermal units which have either reached their minimum limit or maximum limit set by their response rates given in percent output per minute. Possible control actions are also listed. These include changes in combustion turbine generations, pumped storage or hydro generations, and starting or shutting unscheduled units. When conditions are such that the possible control actions listed in the worksheet are too expensive, unavailable or even impractical, the analysis retracks to sub-group II for modification to the PV system so that these unaffordable control actions may be avoided.

3.4 Execution of Sub-Group IV

The central-station PV plant would have to be connected to either a single bus or multiple buses depending on whether the PV system is located on a single site or on dispersed sites. To illustrate the executions of algorithms within this sub-group, the 24-bus IEEE Reliability Test System will be used. With the assumption that the PV plant can be located at any bus on the pre-existing network, Worksheet 6 shows how a list of line loadings and voltage problems can be compiled in the case of a single PV site. These are compared to a "base" case where no PV generations are present in the system. The comparisons are shown for a peak demand period. Similar comparisons should be made at the other two representative loading periods and also for multiple PV sites. With the information provided in Worksheet 6, it becomes easy to identify the PV plant location which will cause the most serious security problem in the system under peak load condition. It is quite conceivable that the PV system penetration level could be high enough to cause unacceptable security problems, and in such a case, the analysis will return to sub-group II for system modifications.

Worksheet 5. System Regulating Capacity Violations

WEATHER	LOADING	PV INCREASE BY A MW => CASE I			PV DECREASE BY B MW => CASE II		
		# of Units Affected	Remarks	Possible Control Action	# of Units Affected	Remarks	Possible Control Action
Clear	Low	2	No system problem	No action required	1	No system problem	No action required
	Medium	7	Thermal unloading problem	Decrease hydro gen.	5	No system problem	No action required
	Peak	12	Thermal unloading problem	Decrease CT gen.	8	Thermal loading problem	Increase CT gen.
		PV INCREASE BY C MW => CASE I			PV DECREASE BY D MW => CASE II		
Partly Cloudy	Low	..	..	..	..	..	..
	Medium	..	..	..	..	..	..
	Peak	..	..	..	..	..	..
		PV INCREASE BY E MW => CASE I			PV DECREASE BY F MW => CASE II		
Cloudy	Low	..	..	..	..	..	..
	Medium	..	..	..	..	..	..
	Peak	..	..	..	..	..	..

Contingency analysis with and without PV under different loading conditions should also be done. Line outages can cause major security problems in the system and this phase in the analytical sub-group analyzes the impact of the presence of the PV system during contingencies. Worksheet 7 shows a sample of such an analysis during the peak demand period.

Worksheet 6. Security Assessment at Peak Demand Period

CASE	LINE LOADINGS		VOLTAGE DEVIATIONS	
	LINE	LOADING	BUS #	CHANGE
Base Case: No PV	1 - 3 1 - 2 8 - 10 3 - 9 9 - 11	92.40% 92% 92% 90.30% 90%	-	-
PV Plant generating 30 MW at bus 2	2 - 6 2 - 4	95.70% 92%	All load buses	Slight increase
PV Plant generating 30 MW at bus 3	2 - 12 1 - 3 3 - 24	90.50% Overload 90%	All buses	No change

Worksheet 7. Contingency Analysis at Peak Demand Period

CASE	LINE OUTAGES			
	1 - 3	11 - 14	2 - 6	12 - 23
	Overloads	Overloads	Overloads	Overloads
Base Case (No PV)	1 - 5, 3 - 9 9-11, 2 - 6	..	..	..
PV Plant at bus 2	1 - 5, 2 - 6 9 - 11	..	..	..
PV Plant at bus 3	1 - 5, 3 - 9 9 - 11	..	..	..

3.5 Execution of Sub-Group V

In the presence of any new power generation technology, the power system has to be examined from the standpoint of reliability. A PV system is no exception. In the case of a displacement/deferment of either a scheduled or unscheduled conventional unit, resulting directly from inclusion of the new PV plant, system reliability figures even more prominently in any planning decisions.

Reliability evaluation studies are made with conventional generation first, considering both scheduled and expansion units to determine operating costs, total energy demand, total generation, unserved energy and loss of load probability (LOLP) for each year of the study period. Later this process is extended to include PV power in order to meet a load modified by the PV power output. At this stage of the analysis, the proposed PV system will have withstood the rigorous operational requirements test applied in the preceding sub-groups and is therefore "fine-tuned" for being added to the power system. What is yet required to be tested of the PV system is its ability to provide net savings in fuel cost and construction expenditures and at the same time maintain a reliability figure of at least no worse than the base case. Worksheet 8, on completion will show long term reliability effects of adding PV in a system.

In this worksheet the PV system is brought on-line in 1992 and at the same time a conventional unit of X MW is taken off the list of scheduled plants for study period. The LOLP column will show the effect of such a replacement on system reliability. The capacity credit can only be accepted if the LOLP for each year is within the allowable range.

As part of the optimal expansion policy determination, potential candidates of different plant types need to be identified. This is done in two steps: first without the PV system and then with the PV system included in the form of either a single site or dispersed sites. Worksheet 9 tabulates the effect of PV on construction costs in terms of present worth.

3.6 Example Illustrating Use of the Methodology

The following example is developed so as to demonstrate the functionality of and relationship among the sub-groups except Sub-group V of the methodology. It is felt that the latter is reached after a thorough iterative analysis in the preceding stages wherein the initial PV system selected for integration may be subjected to modifications. Therefore, when the optimization analysis reaches Sub-group V, the proposed PV system characteristics will be in their final states acceptable to the utility for addition to its operations scheme. Sub-group V only investigates the PV system capacity credit and overall system reliability given a particular PV system size.

<u>System Description at start of optimization:</u>

PV system:	Size:		700 MW
	Array configuration:		2-axis tracking
	Storage option:		None
	Main anticipated use:		Load reduction
Site:	Single/dispersed:		Single site
	Location:		Southeastern U.S.
Utility:	IEEE Reliability Test System (somewhat modified)		
	Total generation capacity:		10,850 MW
	Peak load:		7,500 MW (August)
	Dispatchable load:		4,000 MW
	Generation mix:	Thermal cycling:	24 units (5,060 MW)
		Base load units:	6 units (5,200 MW)
		Comb. turb. (CT):	17 units (590 MW)
		Hydro:	None
		Tie lines:	None

Worksheet 8. Long Term Reliability Effect of Adding PV

YEAR	OPERATING COST	ENERGY DEMAND (MWH)	TOTAL GENERATION (MWH) (CONVENTIONAL)	PV GENERATION (MWH) (SINGLE SITE)	LOLP	PV GENERATION (MWH) (DISPERSED SITES)	LOLP
1992	..	..	..	..	..	..	..
1993	..	..	..	..	..	..	..
..	..	..	..	..	..	..	..
2001	..	..	..	..	..	..	..

Worksheet 9. Effect on Construction Costs of Expansion Units

YEAR	# UNITS	CONSTRUCTION COST NO PV	# UNITS	CONSTRUCTION COST SINGLE SITE	# UNITS	CONSTRUCTION COST DISPERSED SITES
1992	..	..	..	..	..	..
1993	..	..	..	..	..	..
..	..	..	..	..	..	..
2001	..	..	..	..	..	..

Using sub-hourly interval irradiance data available at some southeastern U.S. sites, it was possible to arrive at estimates of the maximum irradiance increases and decreases during specific hours of the day in the month of July. Worksheets similar to Worksheet 2 was formed for the clear, partly cloudy and cloudy sky conditions. The most severe irradiance transitions (for July) were observed in a sub-hourly interval between the hours 10-11, and 11-12. These values are 595 W/m^2 decrease and 385 W/m^2 increase which translate into a PV power generation change of respectively 550 MW decrease and 360 MW increase for the size of the PV system selected. Using these values of PV plant output transitions, Sub-group III was entered. Table 1 shows results of execution of the computer program within this sub-group.

Table 1. Economic dispatch simulation results

CASE	IMPACT ON SYSTEM OPERATION	CONTROL ACTIONS	SUCCESS/ FAILURE
PV decrease by 500 MW. Net effect on demand: Increase	# Thermal unit response constraint limit violations in 20 units # Generation deficit= 110 MW	Unscheduled CT units started.	Control actions inadequate to make up deficit.
PV increase by 360 MW. Net effect on demand: Decrease	# Thermal unit response constraint limit violations in 14 units # Unloadable gen = 110 MW	Scheduled CT units shut down.	Not enough capacity was on schedule for backing off

Suggested Reduction of PV Plant Size: 200 MW

On repeating the above procedure with a modified PV plant size of 500 MW, control actions were found to be available and adequate to deal with sudden PV output transitions.

With the analysis now advancing to Sub-group IV, security conditions in the presence of PV were investigated. Using the procedure outlined in Section 3.4 of the paper, and with the assumption that the PV plant could only be added at a generator bus, it was found that the worst security violations under peak load occurred when PV was added to bus 7 of the network. As many as four line overloads and two bus voltage violations were observed. Bus 13 on the other hand was the safest location for the PV plant judging from a minimum number of security violations. However, on running a contingency analysis with the PV plant located at bus 13 at peak load condition, a high number of security violations could be observed in the system which would otherwise not be present without PV. This invoked the need to reduce the size of the PV plant again and returning to Sub-group II.

After several trials, a PV plant size of 320 MW was found acceptable in both Sub-groups III and IV. The PV system was then in its final state of approval. Programs in Sub-group V could therefore be initiated in order to determine the long-term impact of the plant in the utility.

4. CONCLUSIONS

The paper contributes toward fulfilling the need for a single definitive optimization package by which the optimal size, operation, performance and economics of a PV system can be determined in the utility-integrated mode. A stepwise analytical methodology starting at the solar resource and culminating in the value of the PV system in terms of avoided costs is provided in the paper. The methodology includes processing of the solar irradiance; identification of the PV system's configuration and operational features; identification of real-time system controls in the presence of PV generations; security assessment in the presence of PV and production costing and capacity expansion analysis with PV. The optimization package is sub-divided into five different sub-groups based on their respective purposes in the context of the overall scheme. Each sub-group is related to another by way of information exchange. The user is led through the sub-groups in the methodology and at certain points of the analysis, given the option of modifying the PV system before continuing forward. Without such modifications in effect, the proposed PV system can become an expensive liability rather than a valuable generation option to the utility.

The analysis is data-intensive to say the least. Therefore, it is very important to maintain a large data base on short term historical solar irradiance values at the site/s where the PV plant/s is/are to be located.

The entire analysis is done using standard practices followed by the electric utility industry. This includes generation scheduling and dispatch, power flow, security assessment and capacity expansion analysis. Therefore, the results obtained from the analysis should be meaningful and sound.

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