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Modeling the Optimum Solar PV System for Management of Peak Demand

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ABSTRACT

The use of renewable energy systems and mainly solar PV for grid connected applications has grown rapidly internationally over recent years, solar PV systems are potentially well suited to commercial demand side management applications because the solar resource coincides well with the typical weekday load profile of many types of commercial utility customers specially here in Palestine. The paper objective is determining the capacity of solar PV power system that allowed for the storage of solar energy and for the dispatch of that energy during the load peak demand in facilities. The model presented in this paper focuses on the development of a method to obtain the optimal photovoltaic solar PV capacity (kW) and photovoltaic operation time (hours per day) for a given daily load curve (for an electrical peak shaving). This model is for the case of a facility, commercial or industrial, with a constant billing demand rate ($/kW/month) throughout the year. The analysis is based on a linear load duration curve, average solar radiation, and uses a simplified LCC approach.

Keywords: Photovoltaic Power Generators, Peak shaving, Techno-economic Feasibility of PV Systems, Demand Side Management
JEL Classification: O13

1. INTRODUCTION

The use of electricity is growing rapidly, the peak load in many counties is now in summer time and the electricity companies are set to spend a lot of money over the next decade in new generation plant, including significant expenditure on peak load plant, and on new and upgraded network assets. There are opportunities for solar PV and other demand side measures to contribute to point of use energy supply, thereby reducing the need for central generating plant and for costly network upgrades. To do this, however, the wider benefits of solar PV generation need to be valued (SEI, 2003).

The integration of electricity production from fluctuating renewable energy sources such as solar into the electricity system must address the challenge of designing integrated regulation strategies of a complex system of distributed power producers. The PV power generation sources must interact with the rest of the production units in the system to make it possible for the system to secure a balance between sources and demand (Mahmoud and Ibrik, 2006).

Energy side management provided by solar PV power generation systems have been studied extensively. Energy storage is needed in these systems due to the intermittent nature of solar energy. The deep – cycle lead acid batteries has been used as the means of energy storage (Mahmoud and Ibrik, 2006). This paper presents the modeling of peak demand strategy for the peak shaving by using solar PV system.

2. ELECTRIC DEMAND STATISTICAL MODEL

In this section, the statistical and mathematical model for the economical sizing of an electrical peak shaving PV – system

(PSPV) is developed for a given facility based upon the following assumptions (Turner, 2004):

- The load duration curve D (t), is the demand as a function of cumulative time t (i.e., the accumulated daily duration time in hrs/day of a given D (t) load in kW).
- The electrical demand is represented by a linear load – duration curve, as shown in Figures 1 and 2, for a typical day (summer or winter), the facility has a demand D that varies between an upper value (daily maximum) P_{max} and lower value (daily minimum) P_{min}. The facility operates T – hours per day.
- There is an even energy or consumption rate C_e ($/kWh) throughout the year.
- There is an even demand rate C_d ($/kW/month) for every month of the year.
- There is an even energy cost ($/kWh) for the PV system including the amortization unit installed cost and maintenance cost per unit.
- PSPV system is installed to reduce the peak demand by a maximum of P_{PSPV} kW, operating t_{PSPV} hours per day.

2.1. Electricity Daily Cost without Peak – shaving

Based on the above assumptions, consider a facility with the load duration curve shown in Figure 2. For a unit consumption cost C_e, the daily energy or consumption cost (without PV – system) for the facility is:

$$C_{E\text{-}daily} = T.\ P_{min}.\ C_e + ½.\ T.\ (P_{max} – P_{min})\ C_e =$$

$$= T/2.\ C_e\ (P_{max} + P_{min}) \quad (1)$$

Considering a peak demand P_{max} occurs every day, the daily demand cost is defined by:

$$C_{D\text{-}daily} = 1/n\ P_{max}\ C_d \quad (2)$$

Where, C_e - unit energy or consumption cost ($/kWh), C_{d} - demand rate ($/kW/month), n - number of days in a month, T - operating t – hours per day.

Thus, the total daily cost for the facility is:

$$C_{total\text{-}1} = C_{E\text{-}daily} + C_{D\text{-}daily} =$$

$$= T/2\ (P_{max} + P_{min})\ C_e + 1/n\ P_{max}\ C_d\ \$/day \quad (3)$$

2.2. Demand Side Management by using PV

PV systems can generate both energy value (the system's ability to save energy) and capacity value (in the form of coincident peak demand reduction) for utilities (Turner, 2004). Generally the economic viability of such systems depends on the solar resource, the conversion efficiencies of the components of the system, utility prices and customer demand characteristics. There are important differences in the way in which the demand reduction value of dispatchable (i.e. with battery storage) and non- dispatchable (without battery storage) systems are estimated in the model.

A non – dispatchable PV system would achieve demand reductions based on the output of the system at the time that the utility is

Figure 1: Daily load curve

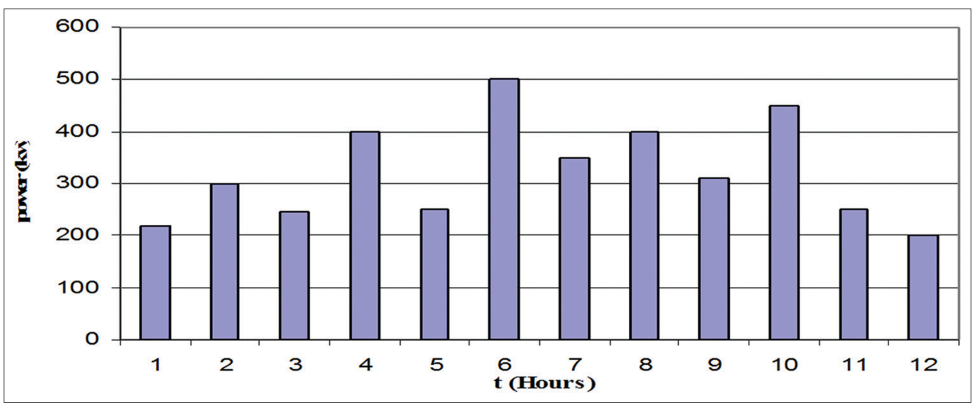
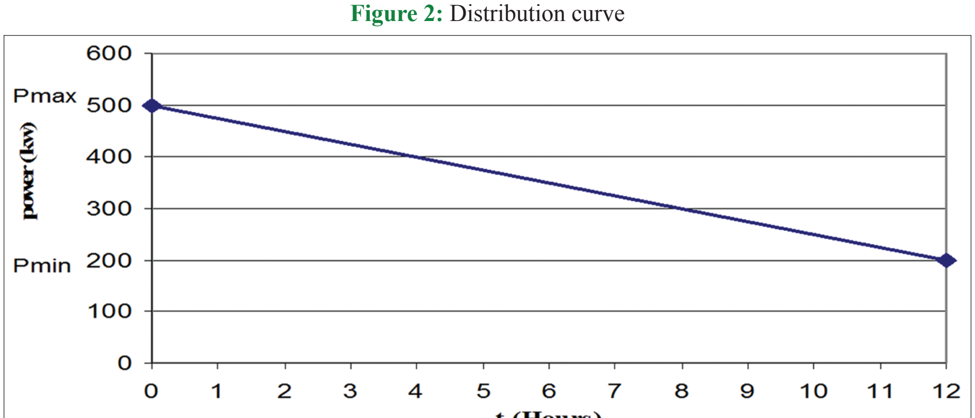


Figure 2: Distribution curve



experiencing peak demand, then the demand reduction value of such a system is estimated as P_{PV} (PV output at time of utility).

A limitation of non-dispatchable system is that the capacity value offered by the system in any given month or year is uncertain. Secondly, the time during which peak demand is experienced may not coincide with maximum solar radiation.

Dispatchable systems, may be deployed for peak - shaving purposes as and when needed, and can deliver a capacity value at least equal to the battery storage value of the system (Archer, 2001).

For this reason, the paper focuses on the economic viability of dispatchable photovoltaic systems in peak – shaving applications and the equivalently demand reduction value will be equal P_{PSPV}:

$$P_{PSPV} = P_{PV} + P_{bat} \quad (4)$$

Where, P_{PSPV} - total peak shaving of PV system, P_{PV} - PV output of utility peak demand, P_{bat} - battery bank output at time of utility peak demand.

The capacity of PV system and the size of battery can be selected according to the optimal value of P_{PSPV} and its operating time.

2.3. Electricity Daily Cost with DSM

If a peak shaving PV system of size P_{PSPV} is installed in the facility to run in parallel with the utility grid during peak – load hours, so the maximum load seen by the utility is (P_{max} – P_{PSPV}), then the electric bill cost is:

$$C_{bill} = T/2\,(P_{max}–P_{PSPV}+P_{min})\,C_e+1/n\,(P_{max}–P_{PSPV})\,C_d \quad (5)$$

In addition, the cost of energy from the PV system ($/kWh) can be calculated using estimates cost of producing electricity by using PV in the facility.

Hence, the daily cost with demand peak shaving is:

$$C_{total-2} = [T.\,P_{min}+½\,(T+t_{PSPV})\,(P_{max}–P_{PSPV}–P_{min})]\,C_e + +1/n\,(P_{max}–P_{PSPV})\,C_d+½\,t_{PSPV}\,P_{PSPV}\,C_{PV}\ (\$/day) \quad (6)$$

Where, $C_{total-2}$ – the daily total cost with demand peak shaving by using PV system, t_{PSPV} – operating hours of P_{PSPV} system/day, C_{PV} – the cost of energy from PV system ($/kWh).

3. ANNUAL WORTH OF DSM BY PEAK – SHAVING PV SOLAR SYSTEM

The annual worth (AW) or net savings $/year of the peak shaving PV system are obtained by subtracting eq. (3) from eq. (6) (Turner, 2004), that is:

$AW = C_{total-1}–C_{total-2}$, so

$$AW = 365\ days/year\ [½\,t_{PSPV}\,P_{PSPV}\,C_e +1/n\,P_{PSPV}\,C_d - ½\,t_{PSPV}\,P_{PSPV}\,C_{PV}] \quad (7)$$

From Figure 2 we obtain:

$$P_{PSPV}/t_{PSPV} = (P_{max}–P_{min})/T$$

So, the expected P_{PSPV} operative time is:

$$t_{PSPV} = P_{PSPV}.\,T/(P_{max}–P_{min}) \quad (8)$$

Substituting the value of t_{PSPV} in eq. (7), we have:

$$AW = 365\,[P^2_{PSPV}.\,T.\,C_e/2\,(P_{max}-P_{min}) +1/n\,P_{PSPV}Cd-P^2_{PSPV}.T.C_{PV}/2(P_{max}-P_{min})] \quad (9)$$

3.1. Optimum Conditions of DSM

For optimal size of P^*_{PSPV} and the corresponding maximum AW (eq.9), with respect to P_{PSPV} and equating it to zero, we obtain necessary condition for the maximum annual worth or net saving per year:

$$AW' = 365\,[P_{PSPV}.\,T.\,C_e/(P_{max}–P_{min}) +1/n\,C_d – – P_{PSPV}\,T.\,C_{PV}/(P_{max}–P_{min})] = 0 \quad (10)$$

If the second derivative of AW with respect to P_{PSPV} is negative, i.e.

$AW'' < 0$, then AW is a strictly convex function of P_{PSPV} with a global maximum point.

So, by taking the second derivative of AW with respect o and evaluating AW'' as an inequality (<0) we have:

$$AW'' = T.C_e/(P_{max}–P_{min}) – T.\,C_{PV}/(P_{max}–P_{min}) <0 \quad (11)$$

Multiplying this equation by $(P_{max}–P_{min})/T$, we have the sufficient condition for a maximum AW is:

$$C_e–C_{PV} <0 \text{ Or } C_e < C_{PV} \quad (12)$$

Therefore, for a global maximum AW exist, the energy rate C_e must be less than the energy cost from PV C_{PV}. Since this is the case for most utility rates, we can say there is maximum AW and an optimal P^*_{PSPV} for the typical electrical demand case.

From eq. (10), we can solve for P_{PSPV} and find the optimal size P^*_{PSPV} (in kW output):

$$P^*_{PSPV} =1/n\,Cd\,(P_{max}-P_{min})/T\,(C_{PV}-C_e) \quad (13)$$

Equation (13) estimates the optimum capacity of power necessary for DSM by using PV system and it is a function of photovoltaic output and battery output.

4. SIZING OF PEAK SHAVING SOLAR PV SYSTEM

The primary objective is to determinate the size of solar PV system that allows for the storage of solar energy and for the dispatch of that energy during the utility's peak demand.

The system can be sized according to the electricity needs eq. (13), the PV system would have to produce the total E_{PV} (kWh) per day. From Figure 2 the PV system kilowatt - hrs/day, is:

$$E_{PV} = ½ P_{PSPV} t_{PV} \quad (14)$$

4.1. Sizing of the Solar PV – Generator

The peak power of the PV generator to cover such a load (P_{PV}) is obtained as follows:

$$P_{PV} = \frac{E_{PV}}{\int_V \int_B \int_R PSH} S_f \quad (15)$$

Where E_{PV} – (daily electricity needs – kWh/day): PSH – Peak sun hours = 5.4 (Mahmoud and Ibrik, 2003); $\int_B$ – efficiency of battery; $\int_R$ – efficiency of regulator; S_f – safety factor for compensation of resistive losses and PV – cell temperature losses S_f = 1.15; $\int_V$ – efficiency of inverter.

The number of the necessary PV modules (N_{PV}) is obtained as:

$$N_{PV} = \frac{P_{PV}}{P_{MPP}} \quad (16)$$

Where P_{MPP} – maximum peak power of selected PV module for the system.

4.2. Sizing the Battery Block

The storage capacity of battery block for such system is considerably large. Therefore, special lead – acid battery cells (block type) of long life time (>10 years), high cycling stability – rate (>1000 times) and capability of standing deep of discharge should be selected.

The ampere hour capacity (C_{Ah}) and watt hour capacity (C_{Wh}) of the battery block, necessary to cover the load demands for a period of 1.5 days without sun (autonomy days), is obtained as follows (Mahmoud and Ibrik, 2003):

$$C_{Ah} = \frac{1.5 \times E_{PV}}{V_B \times DOD \times \int_B \times \int_V} \quad (17)$$

$$C_{wh} = C_{Ah} V_B \quad (18)$$

Where V_B and $\int_B$ are voltage and efficiency of battery block, DOD – is the permissible depth of discharge rate of a cell.

4.3. The Charge Regulator and Inverter

The charge regulator (CR) is necessary to protect the battery block against deep discharge and over charge. Input/output ratings of CR are fixed by the output of the PV system and battery voltage.

The input of inverter have to be matched with the battery block voltage while its output should fulfill specifications of the electric grid of the system (ERC, 2014).

5. CASE STUDY

NABCO company plant in the city of Nablus in Palestine operates 12 h/day, and has a fairly constant electrical (billing) peak demand every month (Figure 1). The actual load varies widely between a minimum 200 kW and a maximum 500 kW (Figure 2). The demand charge is 10 $/kW/month and the energy charge is 0.15 $/kWh. The PV generator cost in Palestine is about 0.25 $/kWh (ERC, 2014).

The optimal P_{PSPV} size is calculated using equation (13),

$$P^*_{PSPV} = \frac{1}{30} 10(300)/12(0.25 - 0.15) =$$

$$= 100/1.2 = 83.3 \text{ kW}$$

The potential annual savings are estimated using equation (9),

AW = 365 (20.66+27.66–34.44) = 5064 $/year

The value of AW at different sizes of P_{PSPV} are shows in Figure 3.

The expected daily operating time for the P_{PSPV} is estimated using equation (8):

t_{PSPV} = 83 × 12/300 = 3.3 h/day

The energy generated from PV for DSM is calculated using equation (14):

$$E_{PV} = \frac{1}{2} P_{PSPV} t_{PSPV} = \frac{1}{2} \times 83 \times 3.3 = 136.95 \text{ kWh/day}$$

The most appropriate PV system to cover the energy needs for DSM is obtained using equation (15):

$$PV = \frac{136.95 \times 1.15}{0.92 \times 0.9 \times 0.85 \times 5.4} = 41.4 \, KW_P$$

To install this power, a mano – crystalline PV module rated at 36 V_{dc} and a peak power of P_{mPP} = 330 $_{WP}$ is selected. The number of the necessary PV modules (N_{PV}) is obtained by equation:

N_{PV} = 41.4/0.33 = 126 PV modules

Each 7 modules will be connected in series to build 18 parallel strings.

The ampere hour capacity (C_{ah}) and watt hour capacity (C_{wh}) of the battery block, necessary to cover the DSM for a period of 1.5 days without sun, are calculated using equations (17,18):

$$C_{AH} = \frac{1.5 \times 136.95 \times 10^3}{220 \times 0.75 \times 0.85 \times 0.9} = 1627.4 \text{ Ah}$$

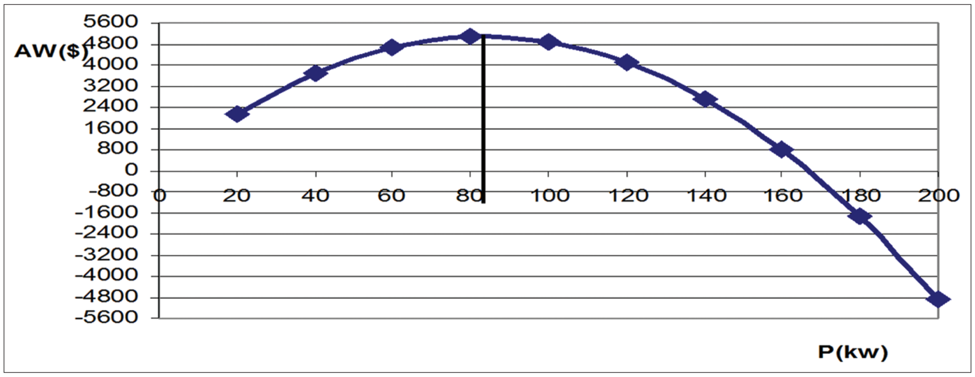
C_{wh} = 1627.4×220 = 358 kWh

To install this capacity, 110 battery cells (each cell rated at 2 V/1600 Ah) have to be connected in series to build a battery block of an output rated at 220 V_{dc} 1600 AH (Archer, 2001).

6. CONCLUSION

This paper provides the mathematical relationship necessary to perform a solar PV – DSM analysis from customer's perspective. A complete set of match design method for PV – peak shaving system is introduced. In this method optimum size of solar PV and

Figure 3: The relation between AW and PPV size



battery are adopted the optimum configuration which meets the load demand with the minimum cost can be uniquely determined by this method.

The correct sizing of solar PV is important part of designing a PV system for DSM, over sizing and under sizing the PV system makes it more expensive also optimum sizing is important because it ensures maximum annual worth as well as reliable system. This arrangement offers all the benefits of PV systems with respect to low operation and maintenance costs and also ensures that PV electricity is not wasted. If a solar PV system is interconnected on the customer side of the meter, this translated into energy and demand charge savings. On the utility side of the meter, distributed generating resources such as solar PV which provide power during peak load hours can defer costly and under – utilized additions to generation and transmission capacity. In addition, every kilowatt – hour generated by a solar PV system reduces utility fuel and variable operation and maintenance costs.

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