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OPTIMIZATION OF CLEANING PERIODICITY OF SOLAR PHOTO-VOLTAIC POWER PLANTS

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ABSTRACT

One of the major concerns leading to reduction in delivery of power and hence loss of revenue from solar photovoltaic (PV) plants is the deposition of dust on the panel surface. Solution to this problem lies in cleaning the panels frequently. Both events dust accumulation and cleaning entail cost which become significant as the size of the plant becomes large. Plant management often encounters a question as to what must be the periodicity of cleaning the panels that ensures maximum delivery of power to the grid. This study answers this question by determining optimum cleaning periodicity on the basis of maximum net energy delivered. The methodology is illustrated by an example of a 40 MW_p PV plant. It is demonstrated that the optimum periodicity of cleaning for a 40 MW_p PV plant comes out to be 7 days at which the annual energy delivered by the plant will be maximum at 60.53 GWh /year. The proposed methodology is simple, accurate, has a general applicability with no dependence on the capacity of the plant. However, the methodology requires experimental data on the rate of degradation in the output due to dust and dirt accumulation on the panels at the plant site.

Keywords: Dust accumulation loss of PV arrays; optimum cleaning periodicity; dust; module soiling

NONMENCLATURE

Abbreviations

PV	Photo Voltaic

Symbols

n	Number of days in a year
p	Cleaning periodicity, days
E_n	Net energy generation, kWh
G	Gross generation from the plant, kWh
D	Fraction of annual energy lost due to soiling, %
R	Rating of the PV plant, kW
S	Number of sunshine hours per day, h
K_1	Energy loss coefficient due to soiling
K_2	Energy consumption coefficient of RO plant, kWh/y
K_3	Energy consumption coefficient of the pumping system, kWh/y

1. INTRODUCTION

Photovoltaic plants are subjected to de-rated operation due to accumulation of dust, dirt, moss, sand, scaling, snow, bird droppings or other pollutants on the panel surface. The average reduction in power output can be 0.2% per day on days without rainfall in a dry weather [1]. The need for proper and periodic cleaning of the panels is thus mandatory. Based on their study of soiling losses on residential PV systems in Australia, Tanesab et al [2] point out that the standard dust de-rating factor of 5% need to be revised considering the geographical location of the PV plant. Periodicity of cleaning is defined as the number of days between two consecutive cleaning activities. Determination of the correct dust de-rating factor and the associated cleaning periodicity is a major concern for utility scale power plant operators.

The periodicity of the cleaning activity is governed by the geographical location, cost of cleaning, cost penalty for generation loss and availability of water and manpower at the site. Hammad et al. [3] predict the optimal cleaning frequency for arid climate typical to Jordan using a multiple linear regression and artificial neural network model by minimizing the revenue loss due to soiling. Jiang et al [4] have developed a simple model to estimate the cleaning periodicity as a function of environmental variables such as dust accumulation density (g/m^2) and the particle mass concentration in the atmosphere (µg/m^3). However, no consideration was given to the cost of cleaning the PV array and income from lost energy. Further, as environmental parameters are location specific, such a determination of cleaning frequency cannot be generalized. Jones et al. [5] proposed a formulation to determine the optimum cleaning periodicity by minimizing the ratio of total cost of cleaning to the value of energy sold. Though this approach considers economic parameters, the cost coefficients viz., electricity rate, cleaning cost, may change from time to time limiting the validity of the results for a future time. In this manuscript, a novel yet simple method to determine the unknown the optimum cleaning periodicity is determined based on maximization of net energy delivered. The net annual energy generation from the photovoltaic plant is maximized by treating the energy used in cleaning and energy lost due to soiling as optimization variables.

2. METHODOLOGY

Figure 1 shows a schematic diagram of a typical automated cleaning system. Automated cleaning is quicker and controllable and hence preferred by most MW scale power plants. The methodology adopted for determining the optimum cleaning periodicity consists of two parts. First being, characterizing the energy losses due to soiling and energy consumption for cleaning activity. Secondly, the expression for the optimum cleaning frequency is derived by maximizing the net energy generation from the PV plant. The following section describes the mathematical formulation for determination of energy losses during cleaning activity.

2.1 Mathematical Modeling

Net energy (E_{net}) delivered by the power plant over a year is the algebraic sum of the gross generation (G), the energy lost due to soiling (E_p), the energy consumed by the Reverse Osmosis (RO) plant (E_{ro}) the energy consumed by the pumping system (E_{po}) and associated parasitic energy consumption (PA) of the plant other than cleaning

$$E_{net} = G - E_p - E_{RO} - E_{PO} - PA \qquad (1)$$

Estimated gross generation (G) depends upon the plant peak rating (R), number of peak sunshine hours

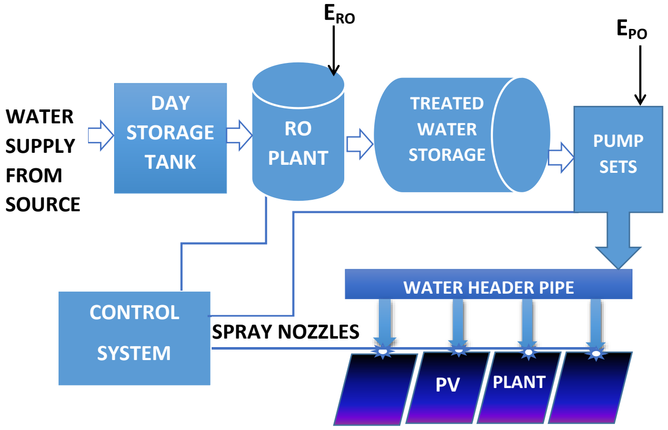

Figure. 1. Schematic of automated cleaning system

per day (S) for the location and number of days of plant operation in a year (n). G can alternatively be evaluated if capacity utilization factor for the plant is known.

$$G = RSn\,. \qquad (2)$$

E_p is the energy lost annually due to dust accumulation on the panels with cleaning periodicity of p. For instance, if the panels are cleaned every 13 days(p=13) and the plant operates for 260 days a year, implies this loss will occur 20 times (frequency f = 260/13) in a year. This loss can be evaluated if the cumulative annual degradation in the output due to dust deposition is known. This data can be experimentally obtained from the plant location. Let D be the total energy lost annually due to dust accumulation on the panels without cleaning over the year expressed in terms of percentage of the estimated annual generation (G). If the panels are not cleaned over the year then the total energy lost annually (E_n) due to dust deposition on the panels can be evaluated as follows.

$$E_n = DG = DRSn \qquad (3)$$

E_n may alternatively be evaluated as follows. Let E be the energy lost per day due to dust accumulation, then the energy lost over the year without cleaning is an arithmetic series given as:

$$E_n = \frac{n}{2}(1+n)E \qquad (4)$$

The energy lost over the year (E_n) due to dust accumulation for n days without cleaning can be obtained by equating (3) and (4)

$$E_n = \frac{2DRSn}{1+n} \qquad (5)$$

Now, a cleaning periodicity of p days means dust accumulation for p days. If the panel is being cleaned every p days (e_p), the energy lost due to soiling in p days will then be

$$e_p = \frac{p}{2}(1+p)E = \frac{p(1+p)DRS}{1+n} \qquad (6)$$

This loss will occur (n/p) times in a year. Therefore, the total energy lost annually due to dust accumulation with a cleaning frequency of p days can be expressed as follows.

$$E_p = e_p \frac{n}{p} = \frac{1+p}{1+n} DRSn \qquad (7)$$

Equation (7) may be alternatively expressed as:

$$E_p = K_1(1+p) \quad where\ K_1 = \frac{DRSn}{1+n} \qquad (8)$$

The term e_{RO} in (1) relates the power consumption coefficient of the RO plant expressed in kWh/m^3. If m_c is total water requirement for single time cleaning of the power plant in m^3 and the cleaning operation is done (n/p) times in a year, then the annual energy consumed by the RO plant (E_{RO}) is

$$E_{RO} = \frac{e_{RO} m_c n}{p} = \frac{K_2}{p} \qquad (9)$$

Where $K_2 = e_{RO} m_c n$ is the energy consumption coefficient of the RO plant. Similarly, the annual energy consumption by the water pumping system (E_{PO}) is determined as follows:

$$E_{PO} = \frac{c_{mp} m_c}{60} \frac{n}{p} = \frac{K_3}{p} \qquad (10)$$

Here, $K_3 = (c_{mp} m_c n)/60$ is the energy consumption coefficient for the pumping plant and c_{mp} is the consumption of pump on the basis of water discharge, kW/ m^3/ min (kW/LPM).

2.2 Optimum cleaning periodicity

In this section, the basis for determination of optimum cleaning periodicity is discussed. The net energy generation as given by equation (1) can now be expressed in terms of the cleaning periodicity p and the energy consumption coefficients (K_1, K_2, K_3):

$$E_{net} = G - K_1(1+p) - \frac{K_2 + K_3}{K_1} - PA \qquad (11)$$

In order to maximize the net-generation from the plant and determine the optimum value of p Equation (11) is differentiated with respect to p while treating G, K_1, K_2, K_3 and PA as constants for a given plant. This yield:

$$p = \sqrt{\frac{K_2 + K_3}{K_1}} \qquad (12)$$

Equation (12) is an analytical optimum cleaning periodicity in days corresponding to delivery of maximum power to the grid by a Photo-Voltaic plant. It is noted that the optimum cleaning periodicity is a function of the energy consumption coefficients related to cleaning activity and the energy loss coefficient due to soiling. The discussed methodology is applied to an illustrative case as described in the subsequent section.

3. ILLUSTRATIVE EXAMPLE

The methodology is demonstrated with the illustrative example of an existing 40 MW$_p$ PV plant of M/s. Enrich Energy Pvt. Ltd., Pune India installed at village Mandrup of Solapur District, Maharashtra, India [6]. The plant is spread over 100 hectares. Plant related specifications shown in Table 1 have been obtained by visit to the plant and after discussion with the plant personnel.

Table 1. Specifications of the PV Plant [6]

Parameter, Unit	Notation	Value
Capacity or Rating, kW	*R*	40000
Number of days of operation of the plant	*n*	260
Annual average peak sunshine hours	*S*	6
Energy lost per day due to dust accumulation without cleaning, percentage of the daily generation	*d*	0.2%
Energy lost due to dust accumulation on the panels without cleaning over the year, percentage of the annual generation	*D*	52%
Total water requirement /cleaning, m^3	m_c	7500
Power consumption coefficient of the RO plant, kWh/m^3	e_{RO}	3
Consumption coefficient of pump for 100 LPM, HP	c_{MP}	1.25
Consumption coefficient of pump based on water discharge, kW/ m^3 /min	c_{MP}	9.325

When equation (11) is solved for varying p with parasitic losses assumed to be negligible, the net energy delivered from the plant can be obtained as shown in Figure 2. It is to be noted that the net energy delivered is maximum at 60.52 GWh (capacity factor= 17%) when the periodicity of cleaning is 7 days. If an ad-hoc periodicity such as once in 30 days was adopted, the energy loss amounts to 2.19 GWh /annum. This can lead to saving of about 3, 12 857 US$ assuming a tariff of US$ 0.14/ kWh [7].

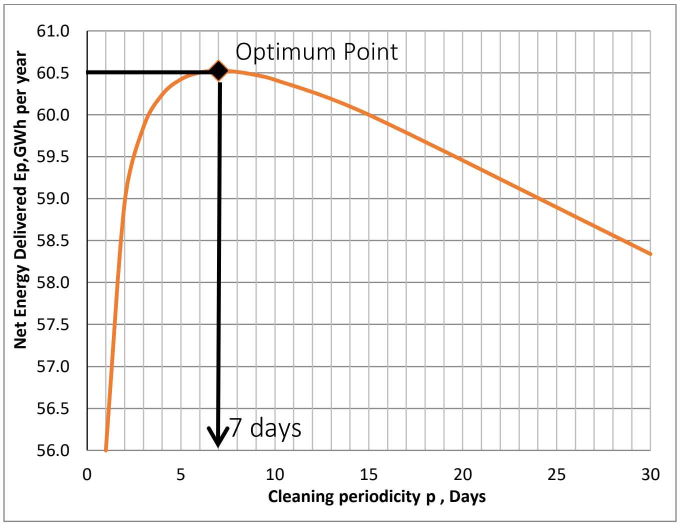

Figure 2. Net energy generation for varying cleaning periodicity at Solapur, Maharashtra State, India

The fractional annual energy loss due to soiling (D) is a vital parameter governing the optimum cleaning periodicity. For relatively low dust accumulation, D is lower and the cleaning periodicity is relatively higher. The effect of D on the optimum cleaning periodicity is shown in Figure 3. This is done by solving equation (12) for varying values of 'D'.

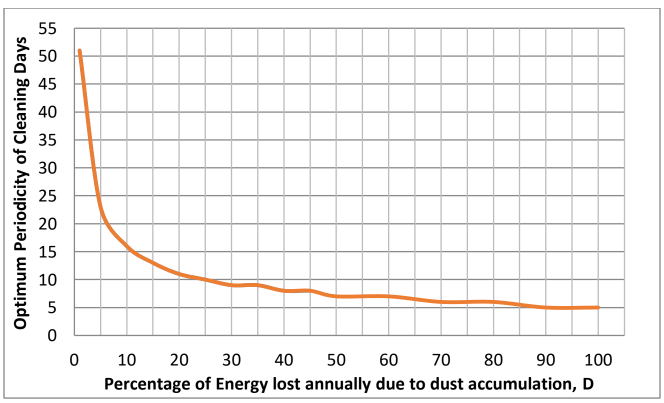

Figure 3. Variation of optimum cleaning periodicity with percentage energy lost annually

Maximum rate of dust accumulation without cleaning corresponds to a situation when the plant does not deliver any energy at the end of the year. Optimum cleaning periodicity for such power plant is 5 days which is the least (Fig .3). The net energy delivered in this case will be 59.7 GWh i.e. 1 % reduction as compared to the base case of wherein 60.52 GWh is delivered. The highest cleaning periodicity of 51 days is obtained for a situation wherein the fractional soiling energy loss is least (about 1%).

4. CONCLUSION

Accumulation of dust and dirt on the PV panels forms one of the major causes of loss in the power plants. This loss need to be controlled by cleaning the panels periodically. A methodology for optimization of the periodicity of cleaning on the basis of maximum net energy delivered by the PV plant has been presented. The methodology is demonstrated with an illustrative example. It is shown that if ad-hoc cleaning norms such as once in 30 days are adopted, the loss in energy can be about 3.5% of the gross generation which is considerable.

The novelty of the proposed methodology is that it is a quick yet accurate method for any plant size. Further, it is based on optimizing the energy generation rather than an economic parameter which changes from time to time or an environmental variable which is location specific.

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