Electrical Power and Energy Systems 96 (2018) 296–305

Contents lists available at ScienceDirect

Electrical Power and Energy Systems

journal homepage: www.elsevier.com/locate/ijepes

Ramp-rate control approach based on dynamic smoothing parameter to mitigate solar PV output fluctuations

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ARTICLE INFO

Keywords:
Energy storage
PV smoothing
Ramp-rate control
Solar PV

ABSTRACT

In this paper a new ramp-rate control strategy based on exponential smoothing (ES) method is proposed. Different from conventional ES, the proposed method varies the smoothing parameter 'σ' according to PV ramp-rate. The proposed smoothing parameter is used to determine the switching status of the battery energy storage (BES). It is also used in determining the amount of power to be injected or absorbed by the BES in order to smooth the PV output power. The proposed ramp-rate control strategy is compared with moving average (MA) and conventional exponential smoothing (CES) methods. It has been found that MA and CES method exhibit memory effect that caused BES to operate all the time. The proposed ramp-rate control strategy overcomes this limitation by operating the BES only during significant fluctuation. As a result, the size of the BES capacity can be reduced and increasing its life span.

1. Introduction

Output power generated from solar photovoltaic (PV) is variable in nature, due to frequent change in solar radiation level caused by cloud passing. Mitigating solar PV fluctuation is a challenge since solar PV penetration with high ramp-rate introduces significant voltage fluctuation in weak radial distribution network [1]. These negative effects have prompted utilities like Puerto Rico Electric Power Authority (PREPA) to impose ramp rate limit to be 10% of rated capacity per minute for both wind and PV generation [2]. There are many ways suggested in the literature such as use of dump load, operate PV below its maximum power point (MPP) and use of storage technology to counter PV output power fluctuation.

Use of (i) battery technology, (ii) dump load and (iii) PV generator curtailment to smooth the output power from solar PV plant is presented in [3]. The authors have also examined the economic aspect of using these methods to smooth out PV output power. On analysing 10 min radiation data, it has been found that combining battery technology and generator curtailment is the most economical solution. Smoothing PV output power using MPPT control is presented in [4]. MPPT controls the PV output power ramp to 1% of PV capacity per minute when solar radiation increases. This method is not effective when the solar radiation decreases rapidly. Use of energy storage technologies such as battery energy storage (BES), electric double layer capacitor (EDLC), superconducting magnetic energy storage (SMES) and fuel cell have been proposed to smooth out short term solar PV output power fluctuations effectively [5–10].

In [5], PV output power fluctuation is smoothed out effectively by dispatching EDLC based on the reference value generated by moving average (MA) method. In [6] a modified euler type moving average method is proposed to mitigate PV power fluctuation using EDLC. A PV output power smoothing algorithm based on average irradiation level is presented in [9]. A smoothing algorithm using fuel cell was designed to smooth the PV output power in [10]. A fuzzy based wavelet transform smoothing filter is used in [11] to smooth PV and wind turbines fluctuations. Least square estimator smoothing algorithm is presented in [12], wherein the BES is used to smooth the PV output power. Application of low pass filter to smooth the PV output power fluctuations using BES can be found in [13]. In [14] a power management module is developed where power fluctuation from PV is taken care by battery source and the power supply to the load is provided by diesel generator and battery. Here moving average smoothing method is used to smooth the fluctuation caused by 5-min solar radiation. In [15] conventional exponential smoothing (CES) method is used to suppress solar PV fluctuation using proton exchange membrane (PEM) fuel cell and electrolyzer. In [16] the ramp rate from solar PV is reduced by applying

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http://dx.doi.org/10.1016/j.ijepes.2017.10.015
Received 3 March 2017; Received in revised form 11 September 2017; Accepted 13 October 2017
0142-0615/

a high pass filter where battery and electric vehicle charging facility were used to mitigate short term PV variability. In [17] BES is used to smooth the output power fluctuation from hybrid system consisting of solar PV and wind turbine. The smoothing functions dynamic filtering controller and dynamic rate limiter proposed in [17] is based on power fluctuation rate from hybrid system. Application of moving average filter and low pass filter to smooth out PV output power fluctuation is presented in [18]. Use of battery energy and natural gas engine generator to smooth the PV output power fluctuation is demonstrated in [19]. The smoothed output is produced using MA method. Simulation results conclude that using gas engine generator along side of battery to smooth PV output power reduces burden of the battery and increases its lifetime. Natural gas engine generator is not fast enough to mitigate higher ramp-rates. Furthermore, if battery is not available, the gas engine generator would not control the ramp-rates. The minimum storage requirement to mitigate worst fluctuations at PV plant is modelled in [20]. Battery is used to follow the smoothed reference waveform produced by moving average method to smooth the PV output from 1.2 MW PV plant [21]. It was recorded that the PV output power varies 63% of rated capacity per minute. The PV penetration into the distribution system is limited to 50% of PV capacity to counter any negative impact of high ramp-rate in distribution system. On analysing the voltage and frequency parameters it was found that the variation in PV does not affect the grid performance. Two ramp-rate control strategies, one strategy based on PV inverter control and other strategy based on battery state of charge (SOC) control and actual power from PV plant is presented in [22]. The advantage of using MA method is that it requires smallest capacity of energy storage. On the other hand it will increase losses and battery cycling degradation [23].

From the discussion on previous works, it was found that MA and CES methods are predominantly used by researchers to control PV output power ramp-rate [5,6,14,15,18–20]. These methods give extra importance to the past history data than the present value of the fluctuating value. This problem is referred as "memory effect" as described in [24]. The detailed explanation of memory effect in MA and CES methods is described in Section 2. The memory effect causes the BES to operate even though there are no significant PV ramp-ups/downs. As the results of memory effect when MA or CES methods are applied, the BES is forced to operate all the time decreasing its life span. In addition, the memory effect also causes over smoothing of ramps. The term 'over smooth' is referred as smoothing below the desirable level of ramp rate. As a result of over smoothing, the BES charges/discharges more energy resulting in reduction of ramp-rate below the desirable level which will eventually increase the size of BES capacity.

Based on the above disadvantage, this paper aims to design a ramp-rate control strategy which limits the PV ramp-rate within desirable level and also eliminate the memory effect. The original contributions of this study are: (i) the root cause of memory effect in MA and CES method is analyzed based on its formulation. A detailed study on weights associated to the PV data points for MA and CES methods are conducted, (ii) a sensitivity analysis on MA and CES methods are carried out to analyse the variation of memory effect, ramp-rate control ability and size of battery energy storage required, (iii) a ramp-rate control strategy is proposed which restricts the PV ramp-rate within desirable level thus eliminating the memory effect, (iv) smoothing parameter which is used in proposed ramp-rate strategy has been formulated as a function of ramp-rate. A switching function is also introduced where the BES is switched ON/OFF appropriately only to control PV output ramp ups/downs and (v) the efficiency of the proposed ramp-rate control strategy is compared with MA method and CES method for ramp-up/down events. From the comparison performed it has been found that the proposed ramp-rate control approach is effective in minimising the ramp-rate to desirable level for ramp-rate violation events. In addition, the proposed approach will not allow the BES to operate for ramp-rates which are already within the limit. As a result, BES does not operate all the time thereby increasing its life span. Moreover, larger BES capacity is not necessary when the proposed ramp-rate control approach is applied.

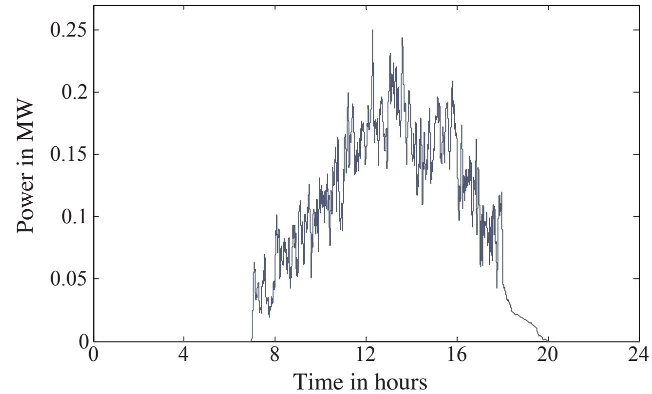

Fig. 1. Solar power output power obtained from 1-min radiation data.

2. Limitations of MA and CES methods

In this section MA and CES methods with their limitations are presented in detail. MA and CES methods are applied to smooth PV output power shown in Fig. 1. Output power from solar PV represents time series data, where the data points consist of successive measurement of PV power over a time interval (see Fig. 1). Average hourly solar radiation for a day in May for a typical location in Malaysia is extracted using HOMER software. Twenty-four hours radiation data have been interpolated to obtain 1440 values by adding normal distribution random noise with '0' mean and standard deviation as '1' [14]. The solar radiation is then redrawn to create 1 min radiation profile (G_n) during a day.

2.1. n-Period Moving Average (MA) method

MA is essentially centered on finding out average for the set of input and the assumption is attributed that it represents a constant or level model. Moving averages is made by assuming that the latest 'n' period is more relevant and others are left out. The principle of operation of MA for 'n' relevant data points for the input having 'k' data points is given in Eq. (1) as,

$$F = \frac{(i(k) + i(k{-}1) + \ldots + i(k{-}n))}{n} \tag{1}$$

where n is number of relevant data points used in MA smoothing, i and F are input (P_{PV}) and smoothed output respectively. For this work 41 data points are used as the moving average window therefore the value of $n = 41$. Expanding Eq. (1) for 41-point MA is given in Eq. (2) as,

$$F = \left[\frac{i(k) + i(k{-}1) + \ldots + i(k{-}41)}{41}\right] \tag{2}$$

As mentioned above for a 41-period moving average, 41 P_{PV} data points which are most relevant for producing smoothed output is used and other data points are left out. A 41-period moving average can be thought of giving weights '1' for the relevant data points considered for producing smoothed output and '0' weights for the points left out.

MA is able to capture the principle that the only relevant data points are important and non-relevant points do not contribute for the smoothing. From the above explanation we would like to highlight two main issues that are associated with MA which causes "memory effect",

(i) MA essentially ignores older data points by giving '0' weights.
(ii) The weights associated with relevant data points are equal which is not logical or acceptable.