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Ramp-rate control smoothing methods to control output power fluctuations from solar photovoltaic (PV) sources—A review

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ABSTRACT

Solar photovoltaic generator is an intermittent source and mitigating its output power ramp-rate is crucial as they threaten the stability of the utility grid. This paper is aimed at bringing out the latest comprehensive review on different ramp-rate control smoothing methods under three broad classifications: (i) moving average and exponential smoothing based methods, (ii) filter based methods, and (iii) ramp-rate based algorithms. Application of moving average and low pass filter from filter based methods is widely chosen by the researchers for solar photovoltaic ramp-rate control. Therefore, a detailed analysis on these methods supported by simulation results is carried out to analyze the capability of these methods to control the solar photovoltaic ramp-rate. On application of these methods, it was found that there will be an increase in the energy storage's degradation and size. In addition, reduction in energy storage's operating life can also be found. Later, a detailed comparison on different techniques are summarized in the discussion section, from which it was found that the ramp-rate based algorithms are advantageous than moving average and filter based method. The advantages of the ramp-rate based algorithms are discussed as well. In addition, the disadvantages of the existing ramp-rate based algorithms are also highlighted. Finally, the necessitate for, (i) improvement in ramp-rate based algorithms, (ii) application of dual energy storage for large solar photovoltaic plant, and (iii) regulation in control of solar photovoltaic ramp-rates is suggested in this paper. These suggestions will contribute to decrease in energy storage's capacity and degradation, and increase in its operation life.

1. Introduction

Integrating distributed sources like diesel generators, battery storage, fuel cell, solar photovoltaic (PV), and wind turbine to a grid connected distribution network is the trend in progress. Integrating these distributed sources with the utility grid can postpone investments in the distribution system, minimize the system loss, and increase the reliability of the grid connected distribution system.

Despite the fact that it is advantageous, integrating intermittent sources such as solar PV may jeopardize the stability of the utility grid. Solar PV generators are intermittent sources and when connected to the grid they may induce voltage fluctuation, voltage rise and reverse power flow, voltage flicker, grid side power fluctuation, and frequency fluctuation [1–11]. This negative impact is caused by the changes in solar radiation. Solar radiation, which represents time series data fluctuates at daily, hours, minutes, and sometime even in seconds. Rain fall, movement of cloud and changes in the weather condition causes frequent changes in the solar radiation. Cloud movement is examined as the primary cause for output power fluctuation from PV generator [2,12,13]. Fig. 1 shows the output power observed from PV plant using 1 min radiation data due to the changes in the solar radiation.

Beside from voltage and frequency fluctuations, rapid changes in PV output power may cause complication for conventional generators in following the change in PV generation [14]. In addition, changes in area control error (ACE) exceeding the limit for interconnecting area, and increase in operating cost of the system were also noticed in [14–16] when the PV output power changes rapidly. For example, an increase in operating cost by 1% can be found in conventional generators when large PV plant fluctuates at the rate of 5% of PV capacity per minute [15]. Harmonic distortion in current and voltage waveforms were witnessed when solar PV penetration increases in the low voltage distribution system [17]. The fluctuations in the large PV plant can cause huge imbalance in real power which can affect the system's primary and secondary frequency regulation [18]. The effect of solar PV

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Nomenclature

$\bar{P}_{PV}$	Smoothed output power
P_{PV}	Output power from photovoltaic plant
P_{ES}	Output power from energy storage
$P_{ES,ref}$	Reference output power to energy storage
RR_{limit}	Ramp-rate limit
T_1	Time constant for low pass filter
$P_{BESS,ref}$	Reference output power to battery energy storage
P_{BESS}	Output power from battery energy storage
F	Smoothed output from moving average
X	Input data for moving average
N	Number of relevant data points in moving average
PV	Photovoltaic
ACE	Area control error
LFC	Load frequency control
RR	Ramp-rate
SMES	Superconductive magnetic energy storage
EDLC	Electric double layer capacitors
ES	Energy storage
DES	Dual energy storage
MA	Moving average
SMA	Simple moving average
SyMA	Symmetrical moving average
EXS	Exponential smoothing
LPF	Low pass filter
HPF	High pass filter
LSE	Least square estimator
SOC	State of charge
DOD	Depth of discharge
MLSERRC	Mixed least square estimator ramp-rate compliant
OCF	Optimal control filter
BESS	Battery energy storage system
DBESS	Dual battery energy storage system
PHEV	Plug-in hybrid electric vehicle
SCB	Supercapacitor bank
VRB	Vanadium redox battery
MPPT	Maximum power point tracking

fluctuations on load frequency control (LFC) can also be noticed in [19,20].

The harmful distress caused by the PV output power fluctuations to the utility grid has made the network operators to enforce ramp-rate (RR) limit to control the fluctuations. For instance, Puerto Rico Electric Power Authority (PREPA) has imposed a ramp-rate limit for PV generators in order to alleviate the negative impact on utility grid [21]. Batteries, superconductive magnetic energy storage (SMES), capacitors, electric double layer capacitors (EDLC), diesel generator, fuel cell, dump load, and maximum power point tracking (MPPT) power curtailment were predominantly used by the researchers to limit the PV output power ramp-rate [22–28].

The use of dump load is not suggested as it will reduce the revenue to the owners. Fuel cell and diesel generators were only used to mitigate slower ramp ups and downs. Generally, they are not used to mitigate faster ramp ups and downs as the response taken by these generators is slow. Rapid energy storage (ES) technologies like batteries, capacitors, or SMESs are best suited to mitigate the fast ramp-rates in the PV output power. These storage technologies also have the ability to mitigate the voltage and frequency fluctuations caused by rapid changes in PV output power [1]. Therefore the PV plant can be equipped with the rapid ES technologies in-order to mitigate the PV output power fluctuations. In order to control the RR, the ES can be charged or discharged which is based on the reference smoothed PV power and actual PV output power. Separate ramp-rate control algorithm or methods based on moving averages (MA) were applied to generate the appropriate reference smoothed PV power. These ramp-rate control methods generally influence the size of ES and its operating life.

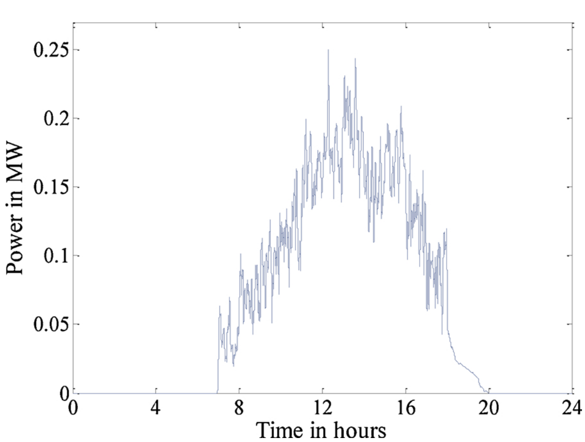

Fig. 1. Typical output power from PV observed using 1-min radiation data.

The objective of this paper is to bring out the comprehensive review on different solar PV ramp-rate control methods using rapid ES technologies to mitigate the PV output power fluctuations and the problem associated with these methods. Initially this paper briefly discusses about short term variability and ramp-rate from practical solar PV generators. Then a comprehensive discussion on different RR control smoothing techniques under three classifications: (i) moving average (MA) and exponential smoothing (EXS) based methods, (ii) filter based methods, and (iii) ramp-rate based algorithms are presented. It was found that, moving average and filter based methods are widely used by the researcher to mitigate the fluctuation problem in PV output power. Even though these methods are easy to implement, they contribute to increase in ES capacity and decrease in its operating life. In order to highlight this, a sample simulation on implementation of the MA and low pass filter (LPF) methods to mitigate varying PV output power is analyzed. In addition, the ability of these methods to mitigate the RR of PV output power to the prescribed limit is also analyzed. Then the overall summary explaining the merits and demerits of all the methods is presented from where it is found that the RR based algorithm methods is advantageous than the other two categories. The demerits of the existing RR based algorithms are also highlighted. At last, suggestions related to the solar PV ramp-rate control are also made. The paper is organized as follows: Section 2 briefly discusses the short term variability from some practical PV generators, Section 3 provides a comprehensive review on existing PV RR control smoothing techniques, Section 4 highlights the limitation of MA and LPF filter, discussion for this paper is presented in Section 5, and the paper is concluded in Section 6.

2. Solar PV variability and ramp-rate

Short term variability of PV output power use seconds to minutes data to investigate the impact of PV plant variability in the utility grid. With the projection of new PV plants in the near future, this PV short term variability can introduce ramp-rates that can affect the utility grid's voltage and frequency regulation. Large variations in ramp-rates up-to 90% and 70% of rated capacity per minute were noted in 1 MW and 10 MW PV plants in Spain [29]. A variation in PV output power of 63% of rated capacity per minute was recorded in 1.2 MW PV plant in La Ola Island [30]. Similarly, a variation in PV output power from 8% up-to 50% of rated capacity per second was noticed by researches in [31–33]. These high ramp-rates from the PV plants can induce voltage fluctuation in a weak grid [34]. Therefore a ramp-rate control strategy or method is essential to control the PV output power ramp-rate in-order to reduce the adverse impact caused due to fluctuating PV power. It should also be noted that the level of fluctuation in PV plant decreases as the size of the plant increases [29,35,36].

The ramp-rate (RR) of the PV output power for the time instant '*i*' is shown in Eq.(1) and can be defined as the change in PV output power between two successive time instances ('*i*' and '*i-1*'),

$$RR(i) = \left|\frac{dP_{PV}}{dt}(i)\right| = \left|\frac{[P_{PV}(i) - P_{PV}(i-1)]}{t(i) - t(i-1)}\right| \tag{1}$$

RR can be either positive (up) or negative (down) and depends upon the PV output power. The RR of PV output power should be maintained within the ramp-rate limit (RR_{limit}). For example, in [21] PREPA has suggested RR_{limit} of 10% of PV rated capacity per minute for PV plant operators to counter the harmful impact caused by PV fluctuation into the utility grid. A typical imposition of RR limit on PV output power for instant '*i*' is shown in Eq. (2),

$$RR(i) \leq RR_{\lim it} \tag{2}$$

Rapid ES technologies are highly efficient and likely choice for this solar PV RR control application. In addition, they can also be used for shift peak generation, load leveling, spinning reserves, energy arbitrage, and power backup during outage applications. The general operation of ES technology relevant to the PV RR control application is shown in Fig. 2. The difference between the solar PV smoothed output power ($\bar{P}_{PV}$) and actual PV output power (P_{PV}) is generally specified as the reference power to the ES ($P_{ES,ref}$) sources. The ES source's output power (P_{ES}) follows the specified reference value to mitigate the PV output power fluctuation problem. The ES technologies are either charged or discharged to limit the PV output power RR. Despite the fact that, limiting the PV output power RR or smoothing PV output power contributes to the stability of the utility grid, on the other hand, the increase in the overall capital cost of the system, operating cost, and cost of power produced by the PV is unavoidable.

3. Standards and guidelines followed by local utility on solar PV ramp-rate (RR)

There are different critical issues that arise from fluctuations caused from solar PV plant interconnected to the distribution system. The primary issue from fluctuating solar PV output is voltage fluctuation and voltage flicker. Higher ramp-ups or downs during fluctuation are found to be the major cause of voltage fluctuation at the point of interconnection at grid side. There is no international standard on RR limit as, 90% of RRs are of smaller magnitude. However with the growing number of large scale solar PV plants it is necessary to introduce RR control limits. Local government or regulatory bodies in many countries are becoming aware of the negative impact of higher RR and have recommend to impose stricter RR limit [21]. For instance Hawaiian electric company (HECO) suggests limiting the ramp ups or downs from renewable generators within ± 2 MW per minute for projects less than 50 MW. In Germany the system operator had imposed 10% of rated capacity limit for ramp ups and there are no limitations for ramp-downs [21]. However any significant ramp-rates influences voltage fluctuation and have to adhere any international or local standards regulated by the respective utility operators. IEC 60038 standards are commonly used in most of the countries where the distribution voltage is 230/400 V and the low voltage may vary up to ± 10% from nominal value [37]. In addition to it, the voltage fluctuation issues is addressed through IEEE 1547, IEEE 1547–2003, IEEE 929 standards [38,39]. Table 1 shows the allowable voltage deviation for different countries when renewable energy is interconnected to grid under normal power production scenario [40].

4. Ramp-rate (RR) control smoothing techniques using ES

Control of PV ramp up/down is essential to mitigate the negative impact on the weaker grid. There are several methods used in the literature to generate the PV smoothed output power ($\bar{P}_{PV}$). In general, the smoothing techniques are categorized as (i) MA and exponential smoothing based methods, (ii) filter based methods, and (iii) RR control algorithms based methods. The categorization of RR control smoothing techniques is shown in Fig. 3. In this section a review of the different methods explained in detail.

4.1. Moving Average and exponential smoothing based RR control smoothing techniques

MA and exponential smoothing (EXS) are methods used to limit the RR of output power from solar PV plant. However, MA is extensively used for PV output power smoothing application because of its simplicity in implementation and less computational effort. In [22] a symmetrical MA is applied to control the RR from the PV generator. Lead-acid battery storage is used to smooth the PV output power in-order to control the PV output power RR within the limit. A RR control method based on MA is proposed for a PV plant in [23]. The EDLC absorbs or discharges to control the rapid fluctuation from PV plant, allowing it to change its output at a limited RR. The use of both MA and EXS methods are analyzed in [41] to limit the fluctuation produced from the solar PV plant. EDLC is used to limit the fluctuation produced by the PV plant. It was confirmed by the authors of [41] that both MA and EXS were effective in limiting the fluctuations from PV plant however, EXS utilizes reduced capacity of EDLC than MA method. In [42] Euler type MA method is proposed to control the PV output power fluctuations. Here the PV output power RR is controlled using EDLC and battery source. In [43] an algorithm based on MA is proposed to operate 1 MW h battery energy storage system (BESS) in response to PV fluctuation and load variability. Here a 15 min. MA window is applied to limit the PV fluctuation problem for a 500 kW PV plant.

A generalized implementation of smoothing method is shown in Fig. 4 where MA or EXS maybe implemented for limiting the RR from solar PV plant. Here the reference to the BESS ($P_{BESS,ref}$) is based on the actual PV power (P_{PV}) and the smoothed output from a smoothing module. The power from the BESS (P_{BESS}) is summed with P_{PV} to obtain the smoothed power ($\bar{P}_{PV}$).

Application of an MA method to control the PV output power RR with less BESS capacity can be found in [44]. In [45], combined natural gas generator (NGG) and BESS were used to control the PV output power RR for a 500 kW PV plant. Here the desired smoothed output is generated using MA average method. NGG is not suitable to mitigate fast ramp up/downs because of its slower response; however, it is used to mitigate slower ramp ups/downs from a solar PV plant. Therefore

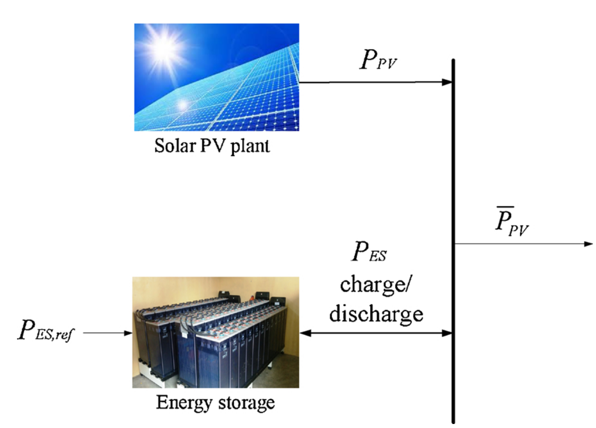

Fig. 2. Operation of ES for PV RR control application.

Table 1
Overview allowable voltage deviation for different countries for renewable energy interconnection [40].

Country	Transmission system operator	Specific power output range	Voltage deviation
Denmark	Energinet	11kW to 25 kW	no requirement
		> 25 kW	± 10%
Ireland	EirGrid	–	± 10%
Germany	EON	–	± 10%
UK	NGET	–	400kV ± 5%
			275kV ± 10%
			132kV ± 10%
			> 132kV ± 6%
Finland	FinGrid	–	0.9 – 1.05 pu
Italy	Terna	–	± 10%
Spain	REE	–	± 10%
Norway	FIKS	> 1 MW	0.93 – 1 pu

NGG alone cannot mitigate the ramp ups/downs from the PV plant. The fast ramp ups/downs from the solar PV plant is controlled using BESS. It was noticed that, the combined operation of NGG-BESS improved the life time of BESS.

A two level ES are proposed to mitigate the fluctuations from a solar PV plant in [46]. Simple MA is used to generate the appropriate reference powers to the ES technologies. MA is also used in [47] to smooth the output of 3.2 kW solar plant and relatively utilizes lead acid battery for smoothing the output power fluctuation. A 20 kW h BESS was utilized to control the RR produced by a 45 kW_p commercial PV plant [48]. High RR variability from 22 kW/minute, to 45 kW/minute was recorded from the plant on cloudy or partially cloudy days. On application of the MA, the BESS is utilized to control PV RR to 0.6 kW/minute. The authors suggested the use of supercapacitors (SCs) to be a better alternative than batteries to smooth out the fast transient due to SC's higher charging rate at low depth of discharge (DOD) and longer operating life. Application of the MA for smoothing the variability caused by 10 MW solar PV plant can be found in [49]. On analysis the maximum RR from the PV plant is found to be 3.68 MW/minute. BESS of capacity 1.07 MW h is used to limit the RR from the PV plant to 0.405 MW/minute. Similar to the above explained works, the application of MA and EXS methods to control the RR of PV output power can also be found in [25,50–55].

4.2. Filters based RR control smoothing techniques

In this section the application of filter based techniques such as low pass filter (LPF), high pass filter (HPF), Kalman and particle filter, least square estimator (LSE), mixed LSE filter, and optimal control filter to mitigate the fluctuation in PV output power is reviewed. Among these filters, application of LPF to smooth the PV output power was followed by many researchers. The schematic diagram on implementation of a simple LPF for smoothing purpose is given in Fig. 5. The fluctuating actual PV power P_{PV} is given as the input to the LPF filter. The output from the filter is the smoothed reference power $\bar{P}_{PV}$. The reference power to the energy storage plant ($P_{ES,ref}$) is calculated using $\bar{P}_{PV}$ and P_{PV}. The power from the ES plant is summed with the actual power from the solar PV plant (P_{PV}) to generate the smoothed power. The LPF filter uses the time constant T_1 and the parameter is user defined. To protect the ES from tracking small excursion from the reference it is desirable to use dead band function and the parameters to the dead band are also user defined.

In [43] a smoothing algorithm is proposed which utilizes LPF filter along side with MA method for smoothing the output power from PV plant. An SOC tracking algorithm is also presented to track the reference state of charge (SOC) and to limit it within the specified range. The RR of the PV output power is limited well below its prescribed level. The proposed smoothing algorithm is simple and does not hold complexity in implementing it in real time. Similarly, application of LPF

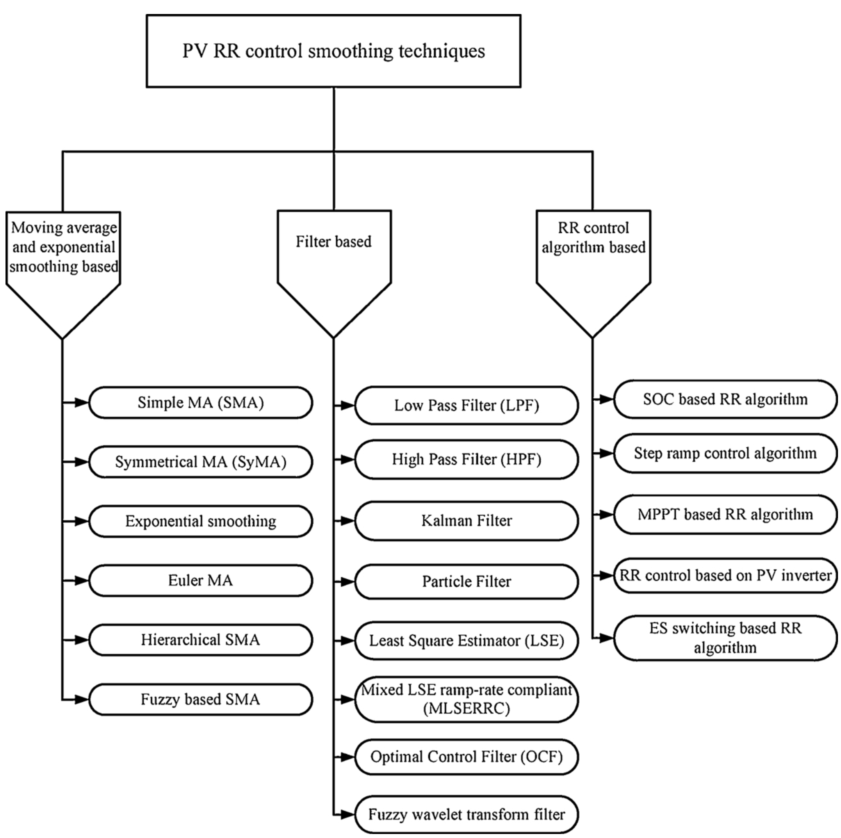

Fig. 3. Categorization of PV RR control smoothing techniques.

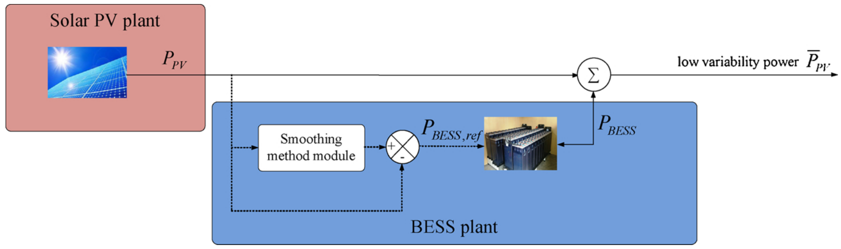

Fig. 4. Generalized implementation of BESS for smoothing PV plant using MA.

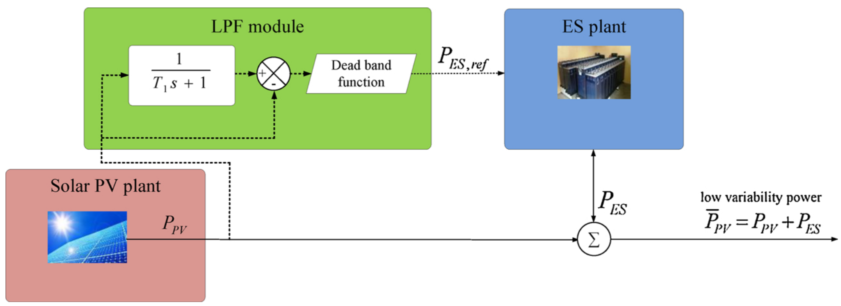

Fig. 5. Typical implementation of LPF filter for smoothing PV plant output power.

to suppress the disturbances caused by variation in PV output power can be found in [56]. A power smoothing filter based on wavelet transform and fuzzy logic is proposed in [57] to smooth the output power from the solar PV and wind hybrid generation. BESS capacity of 300 kW h is used for this smoothing application. Least square estimator (LSE) filter is used to smooth the fluctuation produced from PV plant in [58]. The results were compared with MA method and were observed that, LSE filter utilizes the less BESS capacity to limit the RR of PV output power within the prescribed limit. Li-ion BESS is used to limit the fluctuation of 1.9 MW solar PV plant in [59]. As a result, a mixed least square estimator ramp-rate complaint (MLSERRC) filter is proposed to control the RR of the fluctuating PV power within the prescribed level. The proposed filter is based on parabolic LSE and on comparison with MA and LSE filter, the proposed MLSERRC reduces the size of BESS capacity required for smoothing application. The implementation of MLSERRC filter for smoothing the PV plant's output power is shown in Fig. 6.

The use of optimal control filter (OCF) to mitigate the fluctuation problem of solar PV plant was proposed in [49]. The OCF is enhanced with forecast module and is compared with MA method. The results confirm that the OCF filter utilizes reduced capacity of ES when compared with MA method. That is, for the 10 MW PV farm, MA utilizes 1.25 MW h on the other hand OCF filter utilizes ES of capacity 0.3 MW h only. On further analysis, it was found that the combined use of OCF filter with dump load can contain the fluctuation within the prescribed level with further reduced ES capacity. Application of extended Kalman filter and particle filter to smooth the PV output power is found in [60]. Combined BESS and diesel generator is used to smooth the output power fluctuation from a solar PV plant. Through the combined operation the authors were able to achieve 50% improved operation in diesel generator by minimizing the cold starts, maintenance and overhauls.

In [61] 10 kW h plug-in hybrid electric vehicle (PHEV) battery chargers are proposed as a possible solution for 100 kW solar PV plant's intermittent problem. As a result the proposed integrated PV-PHEV system utilizes first order high pass filter to generate an appropriate reference to PHEV battery chargers. The proposed system guarantees PV-grid integration with reduced RR and fast EV battery operation with high efficiency. A second order LPF is used in [62] to generate appropriate references for battery and diesel systems to smooth the fluctuations from a solar PV plant. The major objective is to reduce the frequency fluctuation caused due to integration of the PV plant with grid. It was found that the combined operation of battery and diesel generator can effectively mitigate the fluctuation from PV plant at the same time maintaining the SOC level of the battery plant at 50%.

Application of filter to mitigate the negative impact of power fluctuation from PV plant is studies in [63]. It is compared with constant output power model, and it was suggested that application of filter is the suitable solution to mitigate the PV variability caused at cloudy days. Application of smoothing algorithm based on LPF for mitigating the fluctuations from 1 MW PV plant can be found in [64]. Hybrid energy storage consisting of vanadium redox batteries (VRB) and supercapacitors bank (SCB) is used to mitigate the PV power fluctuation problem. The smoothing algorithm ensures that VRB and SCB operate within the constraints. The proposed algorithm has resulted in increase of overall system efficiency and maintains the SOC levels of both VRB and SCB within the prescribed limit. Furthermore, it has resulted in reduced power rating of SCB.

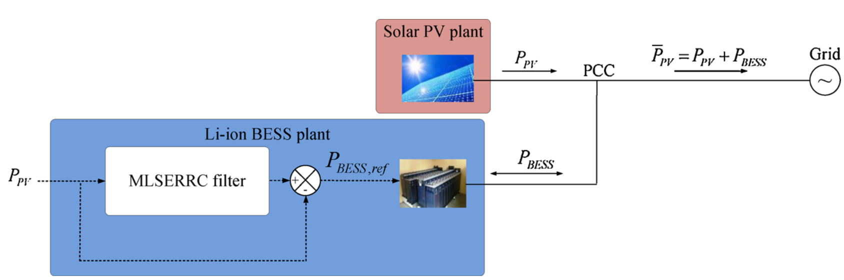

Fig. 6. Implementation of MLSERRC filter for smoothing PV output power [59].

4.3. Ramp-rate control algorithm

The RR control method is used to control the fluctuation of output power from solar PV plant. A generalized implementation of ramp-rate control strategy for limiting the RR of PV output is shown in Fig. 7. The reference to the ES device ($P_{ES,ref}$) is generated by the RR control module. The power from the ES (P_{ES}) following the reference is added to the output power from solar plant (P_{PV}) to generate the RR limited output power ($\bar{P}_{PV}$).

In [65] a RR control algorithm based on BESS SOC is proposed to control the fluctuations on hybrid renewable generation consisting of solar PV plant and wind turbines. Five lithium-ion BESS systems, each having capacity of 200 kW h is operated continuously to smooth the output power 3 MW wind turbine and 1.26 MW PV plant. The proposed SOC based smoothing method prevents the shutdown of BESS due to overcharging and discharging by maintaining the SOC of BESS within the limit. In addition, it also provides adaptive coordination among different BESS systems depending on SOC levels of individual BESS units. A RR control algorithm with SOC control is proposed in [44] to mitigate the PV fluctuation problem. The proposed SOC controller will prevent the BESS from over discharging; as a result the BESS SOC level maintains its reference value. In addition, the authors also proposed step ramp control strategy to contain the RR of PV output power within 2% of PV rated capacity per minute. On analysis it was found that the step ramp control strategy utilizes 20% reduced BESS capacity than SOC based RR control algorithm. A RR control method algorithm based on maximum power point tracking (MPPT) is proposed in [66] to reduce the negative effect caused by fluctuating PV output power from solar plant. Using the PV MPPT the RR algorithm curtails the power from PV generation. Similar application of the RR control algorithm using PV MPPT can be found in [27,67]. The RR control during the ramp down events was not properly addressed.

Two separate RR control strategies based on PV inverter control and SOC control is devised in [68]. PV inverter based method is proposed to reduce the BESS capacity required for mitigating the fluctuations from solar PV plant. The PV inverter is used to control only the ramp up while the downward fluctuation is mitigated using BESS. On comparison, PV inverter based method incurs more system loss than SOC based method. It was also concluded that the SOC based RR control method is easier to implement with less cost when compared with filter based RR control method. RR control strategy based on SOC is introduced in [69,70] for single and fleet of PV plants to control the RR of PV output power within the limit. A switching function based RR control algorithm is proposed in [71] to control the RR of PV output power within the desired level. BESS is utilized to control the fluctuation and the use of ultra capacitors is also suggested by the authors for efficient operation. The implementation of the proposed strategy for PV-BESS integrated system is shown in Fig. 8. The RR control strategy is designed in such a way that the BESS is operated when there is a RR of PV output power violates the limit, otherwise the BESS power is maintained zero. The proposed method utilizes reduced BESS capacity for smoothing application when compared to MA method. In addition, the proposed method can also mitigate the voltage fluctuation on the grid side.

5. Problem associated with MA and LPF RR control smoothing techniques

A review of different smoothing techniques to control the RR of PV plant within the limit has been conducted. Fig. 9 shows the number of articles reviewed based on different smoothing techniques. It was found that, MA method is mostly used by the researchers to mitigate the PV fluctuation problem. In addition to this, the application of LPF or other filters is also found to be a favorable solution to mitigate the PV fluctuation problem than the RR control method. The main reason behind the researcher's choice on these techniques is that, MA and LPF filters are very easy to implement and requires very less computational effort to calculate the smoothed output.

There are limitations on application of the MA and LPF filters for solving the PV output power fluctuation problem. MA method does not use the current fluctuating value and depends on past history data which is referred as "memory effect" by previous researchers in [71]. In addition, MA and LPF filter exhibit "over smoothing", an event where these methods smoothes the RR of PV output power well below the desirable level. As a result, on application of these methods will eventually increase the size of ES's capacity and decreases its operating life.

A clear explanation on the limitations of these methods is presented in the next section. In-order to clearly explain the limitation, simulations is performed on application of MA and LPF filter methods on a fluctuating PV output power from a PV plant. The fluctuating PV output power from the 200 kW PV plant shown in Fig. 1 is taken as an example case for this analysis.

5.1. Limitation of MA method

For a given input data, MA will essentially find the average of relevant data point present within the considered window. The data points that are not within the window are left out. In other words, for a given input data, it can be considered of giving weights '1' for the relevant data points that are present within the considered window. On the other hand, '0' weights are given for the points which are not within the considered window. The principle of operation of MA for the 'x' input data is given as,

$$F = \frac{(i(x) + i(x-1) + \ldots + i(x-n))}{n} \tag{3}$$

where 'n' is number of relevant data points used in MA smoothing, i and F are input PV output power (P_{PV}) and smoothed output respectively. For example, if 51 data points is used as MA window, the value of $n = 51$ and elaborating eq.(3) for 51 point MA can be given as,

$$F = \left[\frac{i(x) + i(x-1) + \ldots + i(x-51)}{51}\right] \tag{4}$$

Generally the value of 'n' is chosen depending on the level of smoothness. For our simulation, we consider 51 point MA as it can eventually smooth the PV output power effectively. ES technology such as BESS is used to mitigate the fluctuation problem. Fig. 10 shows the output power from PV plant smoothed using 51 point MA method. To

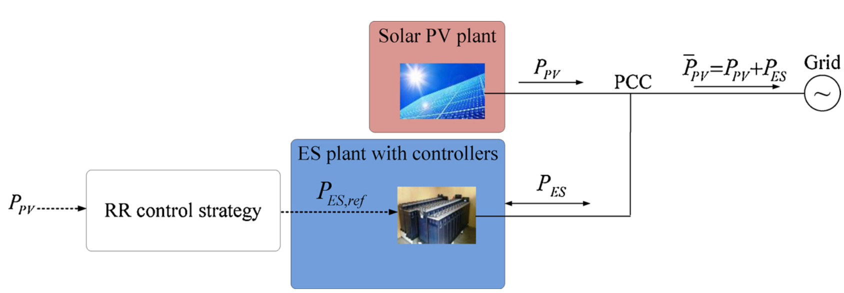

Fig. 7. Typical implementation of RR control strategy.

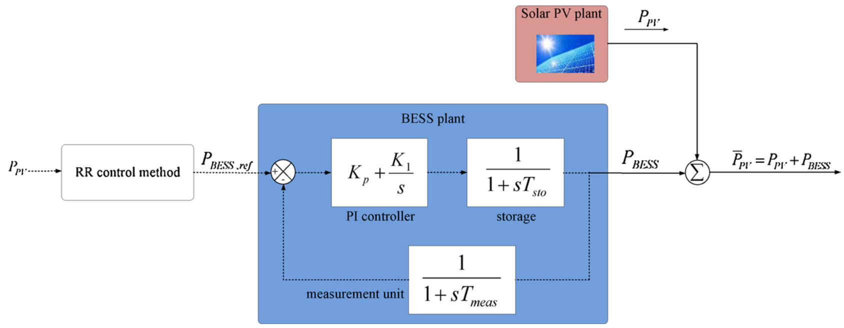

Fig. 8. Implementation of RR control strategy through dynamic model of PV-BESS system [71].

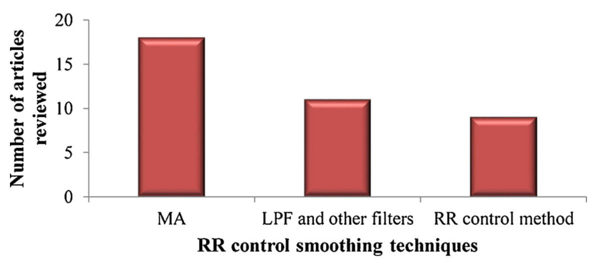

Fig. 9. Articles reviewed based on different smoothing techniques.

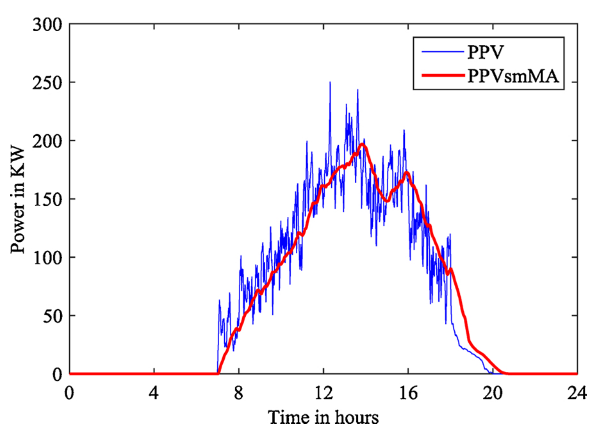

Fig. 10. PV output power smoothing using 51 point MA method.

clearly illustrate the negative effect of memory effect in MA method, the output power waveforms are plotted in Fig. 11 for hours between 17 h and 21 h. The corresponding BESS utilization for the specific hours is shown in Fig. 12.

It can be noticed from Fig. 11, particularly after 18.2 h where there is no significant fluctuation or RR violation in actual PV output power (P_{PV}). Since there is no significant fluctuation in actual PV output power, the use of BESS can be avoided. Nevertheless, on application of MA method the BESS is forced to discharge power to smooth the actual PV power (P_{PV}). The discharge from BESS after 18.2 h can be noticed in Fig. 12 and this unnecessary operation of BESS is due to memory effect.

During the MA application, there are many instances in the PV operation where there is no significant fluctuation in actual PV output power (P_{PV}) for which the BESS is unnecessarily operated. As a result, the size of BESS capacity required for MA application will eventually increase. In addition to it, MA method forces the BESS to operate continuously which may decrease its lifetime [72].

In-order to illustrate the over smoothing of RR by MA method, Fig. 13 has been plotted. In Fig. 13 the RR of actual PV power and MA smoothed power is shown in detail for specific time period of 17 h and 21 h. The main objective of any RR control technique is to limit the RR of PV output power within the limit. The RR limit for this analysis is taken as 10% of PV capacity/minute. Therefore for a PV plant of capacity 200 kW, the RR has to be limited by ± 20 kW/minute.

From Fig. 13, point ‘a’ (encircled in red) the case of over smoothing can be illustrated. At point ‘a’, a negative RR of value -41.35 kW/minute in actual PV output power is recorded at 18.01 h. The RR should be controlled to the desirable level of −20 kW/minute and in-order to achieve it, the BESS has to discharge exactly 21.35 kW. However the BESS excessively discharges 40.192 kW to over smooth the RR to -1.158 kW/minute. Actually, this operation of BESS is unnecessary and in-order to control the RR below the desirable level the BESS power is excessively utilized which will eventually increase the BESS size. In addition to the over smoothing event, MA allows the BESS to operate for RR of actual PV power which is already within the limit and an example of that is shown in Fig. 13 (encircled in black). For this instant the BESS is unnecessarily charged or discharged and this will eventually contribute to increase in BESS capacity. Therefore it is clear that the MA method exhibit the phenomenon of memory effect and over smoothing, which will eventually result to increase in the size of BESS capacity and decrease in BESS life time.

5.2. Limitation of using LPF

LPF uses the time constant and the parameter is user defined. Generally, the value of time constant is chosen in such a way that it effectively smoothes the fluctuating PV output power. As a result, for this analysis the value of time constant is chosen until the smoother waveform of PV power is produced. The resulting PV smoothed power from application of LPF is shown in Fig. 14.

To clearly illustrate the negative effect of LPF method, the output power waveforms are plotted in Fig. 15 for hours between 17 h and 21 h. The corresponding BESS utilization for the specific hours is shown in Fig. 16.

It can be noticed from Fig. 15, particularly after 18.2 h where there

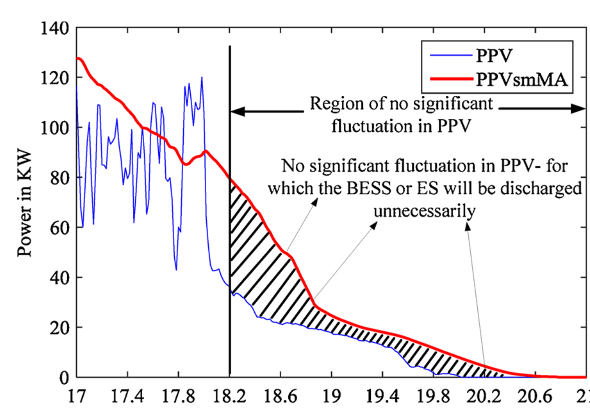

Fig. 11. PV output power smoothing using 51 point MA method for specific hours.

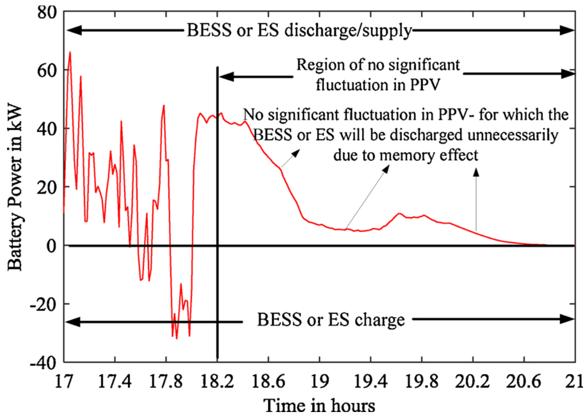

Fig. 12. BESS utilization for 51 point MA method for specific hours.

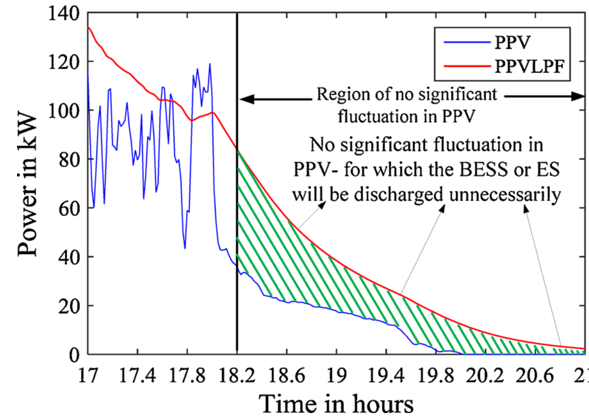

Fig. 15. PV output power smoothing using LPF method for specific hours.

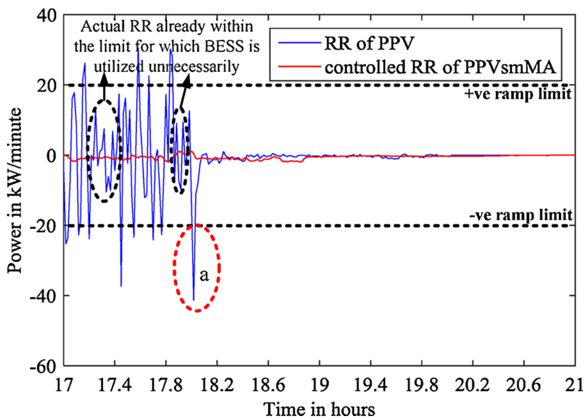

Fig. 13. RR control ability of MA method for specific hours.

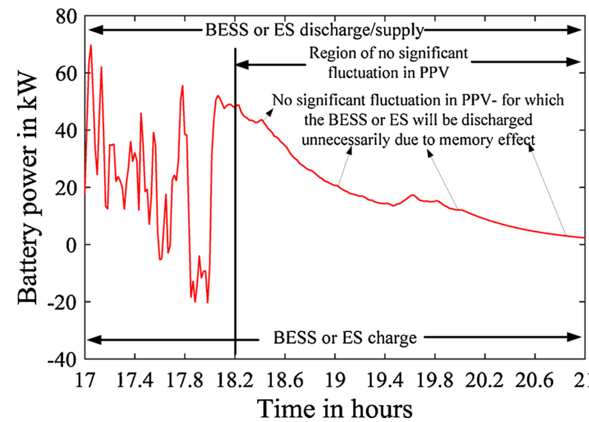

Fig. 16. BESS utilization for LPF method for specific hours.

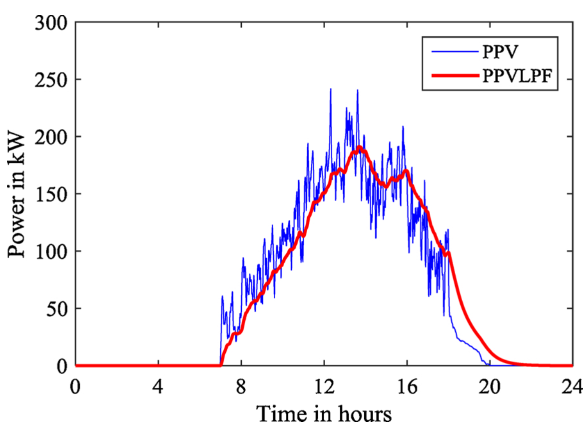

Fig. 14. PV output power smoothing using LPF.

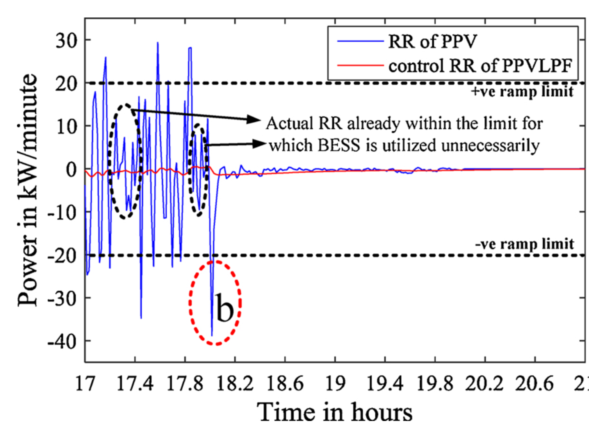

Fig. 17. RR control ability of LPF method for specific hours.

is no significant fluctuation or RR violation in actual PV output power (P_{PV}). Since there is no significant fluctuation in actual PV output power, the use of BESS can be avoided. However, on application of LPF method, the BESS is forced to discharge power to smooth the actual PV power (P_{PV}). This unnecessary discharge of BESS after 18.2 h can be noticed in Fig. 16. During the application of LPF method there are many instances in the PV operation where there is no significant fluctuation in actual PV output power (P_{PV}) for which the BESS is unnecessarily operated. This type of BESS operation for no significant fluctuation in actual PV power can be found during entire operating hours of PV operation. As a result, the size of BESS capacity required for LPF application will increase. Like MA method, LPF method also forces the BESS to operate continuously which may decrease its life time.

Similar to MA, LPF method too exhibit the phenomenon of over smoothing of RR. Fig. 17 is plotted to illustrate the over smoothing of RR by LPF method.

In Fig. 17 the RR of actual PV power and LPF smoothed power is shown in detail for a specific time period of 17 h and 21 h. The main objective is to limit the RR of PV output power by ± 20 kW/minute. From Fig. 17, point ‘b’ (encircled in red) the case of over smoothing can be illustrated. In point ‘b’, a negative RR of value -41.35 kW/minute in actual PV output power is recorded at 18.01 h. The RR should be controlled to the desirable level of -20 kW/minute and in-order to achieve it, the BESS has to discharge exactly 21.35 kW. However the BESS excessively discharges 41.05 kW to over smooth the RR to -0.3 kW/minute. Actually, this excess BESS discharge is unnecessary

Table 2
Comparison on different RR control smoothing techniques.

Category	Reference	RR control method	Type of source used	Strength	Weakness
MA and EXS based	[22] [23,52] [41] [42] [43,44,47,48,49,50] [45] [46] [25] [53] [54]	Symmetrical MA (SyMA) Simple MA (SMA) SMA and EXS Euler type MA SMA SMA Hierarchical SMA SMA + fuzzy control SMA + fuzzy control SMA	BESS EDLC EDLC BESS + EDLC BESS BESS + Natural Gas Engine Generator BESS BESS + Diesel BESS SC	In general, SMA, SyMA, EXS, Euler MA are, ● Easy to implement. ● Utilizes less computational effort in calculating the PV smoothed output. ● Low cost in real time implementation.	SMA, SyMA, EXS, Euler MA, ● Exhibit memory effect and over smoothing phenomenon. As a result, the size of ES is increased. ● Force the ES to operate continuously which will reduce its operating life. ● Causes large ES degradation than RR algorithm and filter based methods.
LPF and filter based	[43] [56] [62] [64] [61] [60] [58] [59] [49] [57]	LPF + MA LPF LPF LPF High Pass Filter (HPF) Kalman and Particle filter LSE MLSERRC OCF Fuzzy wavelet transform filter	BESS BESS BESS + Diesel BESS + SC PHEV- BESS chargers BESS + Diesel BESS BESS BESS BESS	LPF, HPF, Kalman and Particle filter: ● Utilizes less computational effort in calculating the PV smoothed output. ● Low cost in real time implementing. ● Easy to implement. ● Easy to implement. ● Low cost in real time implementation. ● Reduce the size of BESS when compared to MA and LPF filter methods. ● More suitable for second life BESS. ● MLSERRC filter reduces the size of ES than MA and other filter based methods. ● Uses less BESS capacity than MA. ● Uses time horizon to prepare solution for the future. ● Reduces the BESS cycle degradation. ● Regulates the SOC of the BESS.	LPF, HPF, Kalman and Particle filter: ● Force the ES to operate continuously which will reduce its operating life. ● Causes over smoothing of RR. As a result, the size of ES is increased. ● Large ES degradation than RR algorithm based methods. ● Unnecessary BESS operation for non-significant PV fluctuations. ● Force the BESS to operate continuously which will reduce its operating life. ● There are instances where LSE does not have ability to control the RR within the limit. ● MLSERRC filter method is unable to control few RR within the limit. ● Utilizes more computational effort than other filter based methods. ● Forces the BESS to operate continuously. ● Utilizes more computational effort than other filter based and RR based algorithm methods. ● Does not guarantee to control the RR within its limit. ● Forces the BESS to operate continuously. ● The size of BESS is larger than RR control algorithm methods. ● The BESS is continuously operated. ● Increases the size of BESS. ● Does not guarantee to control the RR within its limit.
RR control algorithm	[65,68,69,70] [44] [66,67] [27] [68] [71]	SOC based RR algorithm Step ramp control algorithm MPPT based RR algorithm BESS-MPPT based RR algorithm BESS-RR control based on PV inverter BESS switching based RR algorithm	BESS BESS – BESS + MPPT BESS BESS	● Regulate the SOC of the BESS. ● Reduce the size of BESS compared to MA and filter methods. ● Less BESS degradation compared to MA and filter based methods. Less energy loss from BESS. ● Reduce the losses in BESS when compared to SOC based RR algorithm and MA method. ● Less cost in implementing real time. Easy to implement in small PV plants ● Less cost in implementation. ● Easy to implement in small PV plants. ● Reduces the size of BESS. ● Less BESS degradation compared to MA and filter based methods. ● Since the BESS is used only for ramp down events, the size of BESS can be reduced. Regardless of PV plant size it can be implemented.	● Does not guarantee to control the RR within its limit. ● Utilizes more computational effort to calculate the PV smoothed output. ● Does not guarantee the control of RR within the prescribed level. ● Utilizes more storage size than MA method. ● More BESS degradation than RR algorithm and MA method. ● Used to limit ramp ups, while the control of ramp downs using MPPT method is not addressed. ● The use of BESS to mitigate ramp downs is unavoidable. ● Does not guarantee the control of RR within the prescribed level. ● Does not guarantee the control of RR within the prescribed level. ● PV inverter control used only for ramp ups events. For ramp downs BESS should be used.

(*continued on next page*)

Table 2 (*continued*)

Category	Reference	RR control method	Type of source used	Strength	Weakness
				● Less BESS degradation compared to MA and filter based methods. ● Does not force the BESS to operate continuously which may contribute to increase in BESS's operating life. ● The size of BESS is reduced considerably compared to other RR algorithm. ● Mitigate the voltage fluctuation at grid side. ● Less BESS degradation compared to MA and filter based methods.	● High energy loss due to inverter limitation. ● Does not guarantee the control of RR within the prescribed level. ● Does not guarantee the control of RR within the prescribed level. ● Utilizes more computational effort in calculating the PV smoothed output.

and as a result BESS power is excessively utilized which will eventually increase the BESS size. In addition to this, LPF method allows the BESS to operate for events where the RR of actual PV power is already within the limit and an example of that is shown in Fig. 17 (encircled in black). For these events the BESS is unnecessarily charged or discharged and this will eventually contribute to increase in BESS capacity. Therefore, it is clear that the LPF method exhibit the phenomenon of over smoothing, which will eventually result to increase in the size of BESS capacity and decrease in BESS life time.

6. Discussion

The main focus of this paper is to discuss the capability of different RR control smoothing method's ability to mitigate the fluctuations in PV output power. A summary on different RR control smoothing techniques with its advantages and disadvantages is presented in Table 2.

From the table it is clear that the PV RR control smoothing technique can be categorized as MA and EXS based, filter based and RR control algorithm based methods. MA based methods are mostly chosen by researchers and many implement SMA method for mitigating PV output power fluctuations. Researchers have used BESS, SC, EDLC, and ES with other source when they implement SMA method. Irrespective of type of MA method, they exhibit the phenomenon of memory effect and over smoothing. As a result, the ES is forced to operate unnecessarily even thought the RR of PV output power are within the limit. In addition, the ES is forced to charge or discharge excess power to over smooth the RR which will eventually result to increase in the size of ES. MA based method allows the BESS to perform more cycles with a large depth of discharge (DOD) than other strategies which will make the ES to degrade. Therefore, when MA based methods are applied the degradation of ES will take place in a faster rate. On the other hand, the degradation of BESS or any ES is lower on application of RR based control algorithms. For example, the RR control algorithms proposed in [27,65,69,71] does not allow the BESS to operate continuously or perform more cycles with large DOD eventually contributing to the less BESS degradation. However, the problem of over smoothing of the RR is not addressed clearly in these references. Generally, some RR based control algorithm [65,68,71] utilizes the less ES capacity than filter and MA based methods. This is due to the fact that these algorithms allow the ES only to operate for significant fluctuation and limit their operation during the non-significant fluctuations. In addition, these algorithms are equipped with ES's SOC regulation which is one of the aspects contributing to reduction in size of ES. The SOC based RR algorithms also contribute to less losses in ES. The application of MPPT based RR algorithms in [27,67,68] and PV inverter control based RR on [68] is generally not suggested because, the curtailment of PV output power can generate a loss in revenue to the owners. These methods can guarantee the control of ramp ups in PV output power while the use of ES to control ramp downs is inevitable. Even though it is easy to implement MPPT based methods with BESS with less capacity, but it does not guarantee to control the RR within the prescribed level. Moreover the PV inverter based method will incur high energy loss due to inverter limitation than any other RR control smoothing methods.

Calculating the smoothed PV reference power with less computational effort is one of the important characteristic for the RR control smoothing method. RR control algorithm based methods take more computational effort in calculating the reference. On the other hand MA and filter based methods can calculate the reference smoothed power effortlessly with less cost. Most of the filter based methods force the ES to operate continuously which may affect its operating life. In addition, on application of filters like LPF, HPF, LSE, OCF, Kalman and Particle filters the size of the ES is increased. On the other hand, MLSERRC filter can mitigate the PV fluctuations with reduced ES capacity compared to other filter based and MA methods. In addition, on analyzing its RR control ability; there are few instances where MLSERRC is unable to control the PV RR within the prescribed limit. Almost all the filter based method force the ES to operate continuously. In particular, methods like LPF, LSE, HPF, Kalman and Particle filters utilize excess ES power to charge or discharge in order to mitigate the PV fluctuation leading to over smoothing and more degradation of ES.

From the table it is also clear that, the usage of ES technologies is ideal for solar PV RR control applications because they have the ability to mitigate fast ramp ups and downs. The usage of capacitors, ultra-capacitors, and SMES was suggested to mitigate RR of small PV plants. On the other hand, battery storage technology was suggested to mitigate RR of large PV plants [1]. In addition, there is also literature which used the ES with the other slow response generating sources like diesel generators and natural gas engine generators in [27,45,60]. Here the slow response generators are used to mitigate slow ramp ups and downs and ES is used to mitigate fast ramp ups and downs. This will eventually reduce the operation of ES which will contribute to increased operating life and less ES degradation. In addition, since the ES is used only to mitigate fast ramp ups and downs the size of the ES can be reduced significantly.

The objective of any RR control smoothing method is to control the RR to the prescribed level in order to avoid voltage and frequency fluctuations at the grid side. By analyzing the existing literature on different smoothing techniques the following research gap was found. Of all the three categories of smoothing techniques, RR based smoothing algorithm like SOC based and BESS switching method is found to be advantageous. These methods can mitigate the fluctuation problem with less ES's capacity and degradation effect which will contribute to prolong its operational life. However, these methods do not guarantee to limit the PV RR exactly to the prescribed level, which is one of the important characteristic for smoothing technique. Advancement in RR control algorithm based smoothing technique is suggested to identify only the significant RRs in PV output power for which the ES can be charged or discharged. For non-significant fluctuation the ES is not allowed to operate unnecessarily, which will contribute to less ES capacity. The suggested method should depend on the current fluctuating value and should be able to control the significant RRs exactly to the prescribed limit thus eliminating the possibility of memory effect. By limiting the RR of PV output power exactly to the prescribed level (for example, 10% of PV rated capacity/minute), the size of ES can be reduced further with the possibility of over smoothing being eliminated. This will eventually contribute to the less ES degradation and extended operating life. In addition, an analysis on voltage deviation, frequency deviation, and power quality issues is also needed on application of these RR control algorithms based smoothing techniques.

The application of dual ES (DES) can be realized for mitigating PV fluctuation problem for large solar PV plants. This will eventually contribute to further less degradation of ES technology. An application of dual BESS (DBESS) is realized to facilitate the integration of wind turbines in [73]. As said before, the application of ES with slow response generators can be used for this PV RR control problem. This will contribute to a reduction in the size of ES and the increase in its operating life. In addition, to the best of our knowledge there are no standards available to control solar PV ramp-rates. With the integration of more solar PV installation in the distribution system in the future, there is a burning need to develop regulations or standards on control of solar PV ramp-rates.

7. Conclusion

In this paper a review of different ramp-rate control smoothing techniques to mitigate the fluctuation in PV output power is presented. First a short analysis of variability and ramp-rate from practical solar PV generators is presented. Then a detailed review on different ramp-rate smoothing techniques is conducted under three classifications: (i) moving average and exponential smoothing based methods, (ii) filter based methods, and (iii) ramp-rate based algorithms. It was found that MA and LPF filter based method were used by researchers to address the fluctuation problem. Application of MA and LPF to solve the PV output power fluctuation problem leads to increase in ES's capacity and also contribute to decrease in its operating life. In order to give more clarity on this issue, simulation was performed and results on application of the MA and LPF filter to mitigate the PV output power fluctuation problem is presented in this paper.

Later, a summary of different smoothing techniques with its advantages and disadvantages is presented. On analyzing the merits and demerits of different techniques, implementation of RR based algorithms is found to be advantageous in solving the PV output power fluctuation problem. Therefore, the advantages of RR based algorithms over MA and filter based techniques are explained clearly. However, there are few disadvantages in using the RR based algorithms and is also highlighted as well. At last the need for, (i) improvement in RR based algorithms, (ii) application of DES for large PV plant, and (iii) regulation in control of solar PV ramp-rates is suggested. The paper will be useful for PV plant owners, utility grid operators, and planners.

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