Renewable and Sustainable Energy Reviews 59 (2016) 1170–1184

Contents lists available at ScienceDirect

Renewable and Sustainable Energy Reviews

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

Mitigating methods of power fluctuation of photovoltaic (PV) sources – A review

S. Shivashankar [a], Saad Mekhilef [b], Hazlie Mokhlis [a,*], M. Karimi [c]

[a] Department of Electrical Engineering, University of Malaya, 50603 Kuala Lumpur, Malaysia
[b] Power Electronics and Renewable Energy Research Laboratory (PEARL), Department of Electrical Engineering, University of Malaya, 50603 Kuala Lumpur, Malaysia
[c] Faculty of Engineering, Computing and Science (FECS), Swineburne University of Technology, Sarawak Campus, Sarawak, Malaysia

ARTICLE INFO

Article history:
Received 8 October 2014
Received in revised form
7 January 2016
Accepted 13 January 2016

Keywords:
Intermittent photovoltaic
Power fluctuation
Energy storage
Cloud movement
Smoothing PV output

ABSTRACT

Renewable Energy Sources (RESs) particularly photovoltaic (PV) and wind are becoming important sources for power generation. Frequently varying output of PV and wind caused by clouds movement, weather condition and wind speed make them an intermittent and unreliable sources when connected to grid. Connecting intermittent sources to grid introduces challenges in various technical aspects such as power quality, protection, generation dispatch control and reliability. In this context, leveling intermittent source's output is necessary inorder to maintain grid's stability. This paper is aimed at bringing out the latest comprehensive literature review on problems associated when the intermittent PV is connected to grid and the methods of smoothing the output power fluctuation from PV. This paper also briefly discusses control strategy built for battery energy storage pertaining to this issue.

Contents

* Correspondence to: Department of Electrical Engineering, Faculty of Engineering, University of Malaya, 50603 Kuala Lumpur, Malaysia. Tel.: +60 3 79675238; fax: +60 3 79675316.
E-mail address: hazli@um.edu.my (H. Mokhlis).

http://dx.doi.org/10.1016/j.rser.2016.01.059
1364-0321/

1. Introduction

Renewable Energy Sources (RESs) like solar, wind, hydro etc., contribute for today's electricity generation. By the end of 2014, RES contributed 22.8% of global electricity production in the world. The PV installed capacity rose by 27% from 139 GW in 2013 to 177 GW in 2014. Grid connected PV is the fastest growing RES power generation technology [1]. The global PV capacity for the last 10 years (2005–2014) is shown in Fig. 1.

The quantity of electricity produced from PV directly depends on intensity of sun light. PV and wind when connected to the grid have positive impact on the network. At the same time, they also can have a negative impact. The PV penetration relies on solar radiation which fluctuates daily, hourly and over a shorter period of time (minutes and seconds). Fig. 2 shows a typical output power from PV plant due to changes in solar radiation.

Estimating solar radiation is essential to determine the power generated by the PV. Predicting solar radiation using mathematical models based on artificial neural network (ANN) is found to be more accurate compared to the regression model, empirical regression model, empirical coefficient model, angstrom model and models based on fuzzy logic [3]. A neural network model for predicting system output is done in [4] for a PV system connected with battery storage. The model can accurately predict the system output and the amount of battery capacity needed to compensate the PV output power fluctuation with the help of weather information and cloud pattern as inputs. Changes in weather conditions, rain fall and movement of clouds affect the output power from PV. The primary reason for output power fluctuation in PVs is due to movement of clouds [5].

Given below are some of the issues of PV output power fluctuation caused by cloud movement as reported by the investigators,

(i) When PV penetration increases, it is not easy for conventional generators in the system to track the quick change in PV generation [6].
(ii) When PV output power changes rapidly, the area control error of two or more interconnected area may exceed its prescribed limit [6].
(iii) Large uncontrolled PV penetration may change dispatch of regulating units in the utility causing a violation in dispatch regulating margins [6,7].
(iv) Frequent changes in PV output caused by changes in cloud pattern increases overall operating cost of the system [7,8].

Due to these negative impacts, some power utilities had imposed ramp limits to control output power from intermittent renewable generation. Puerto Rico Electric Power Authority (PREPA) for example has suggested limiting the ramp-rate from wind turbines and PV to be within 10% of rated capacity per minute [9]. By having this limit the impact of voltage and frequency fluctuation in grid side could be minimized.

High penetration of intermittent PV cause voltage fluctuations in grid, voltage rise and reverse power flow, power fluctuation in grid, variation in frequency and grounding issues. PV penetration in low voltage distribution network also causes harmonic

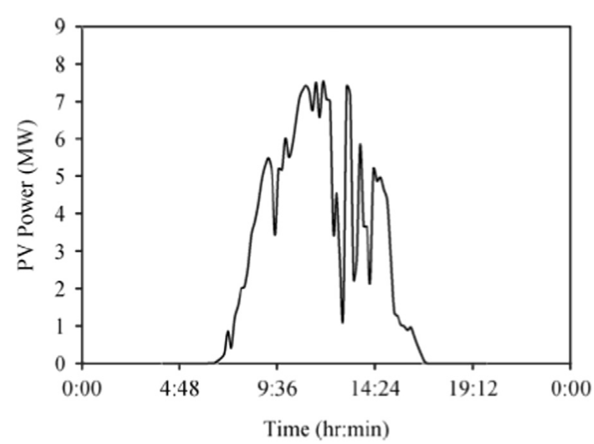

Fig. 2. Typical output power from PV [2].

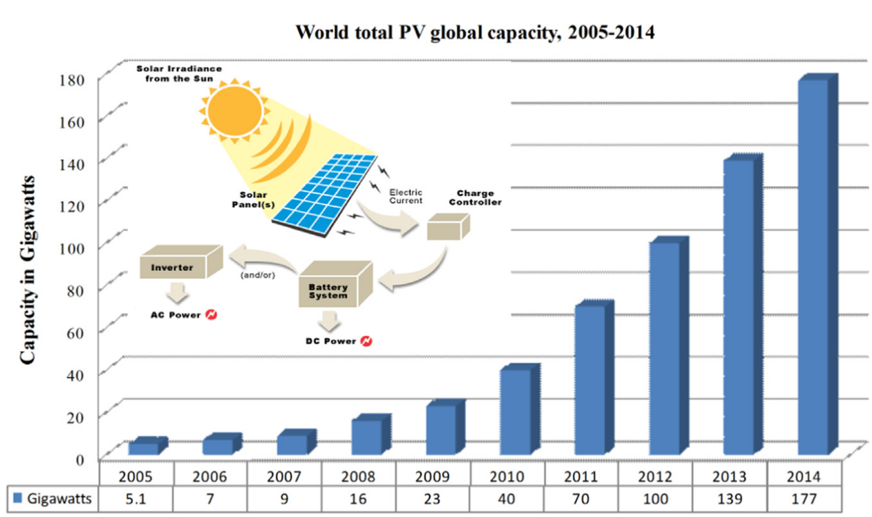

Fig. 1. Global PV capacity between 2005–2014.

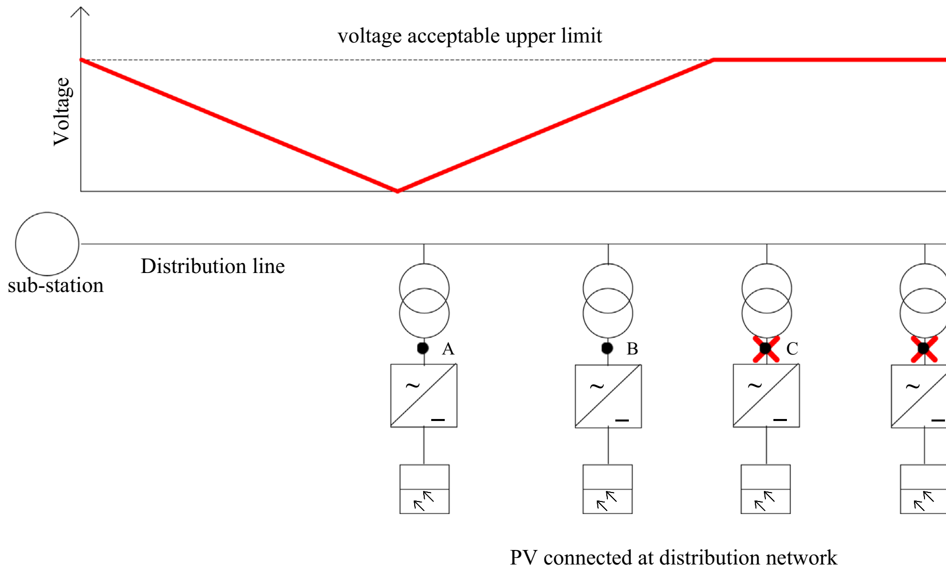

Fig. 3. Problem of voltage rise at distribution network [18].

distortion in current and voltage waveforms [10]. PV inverters are the main source of injecting current harmonics into the distribution system. The injected current harmonics can cause voltage harmonics and increases total harmonic distortion level in the system. These harmonics can increase the losses in the distribution system. A review on dynamic and static characteristics on integrating very large scale PV plant with utility is carried out in [11]. It was found that fluctuations in output power found in large scale grid connected PV plants can affect the system's primary and secondary frequency regulation resulting from significant real power imbalance on the grid side. Since PV has no inertia, integrating large PV plants as a substitute to conventional generators reduces the effective inertia of the bulk power system, which in turn causes the system to have poor ability to cope with frequency fluctuations caused due to frequent output power changes. A review in [12] also discussed the impact of very large scale PV when integrated with the utility and grid code requirement which would facilitate interconnection of large scale PV system with the utility grid. Since the regulation varies from one system operator to another the authors insist on developing necessary standards globally to facilitate integration of very large MW (megawatt) scale PV plant with utility grid which helps the PV equipment manufacturers and developers to reduce additional manufacturing cost.

The movement in cloud influences change in output power which also depends on size of the PV plant. The larger the size of PV plant lower the output power fluctuations. Shorter the sampling time higher the significance of the smoothing effect [13]. In [14,15] authors illustrate challenges faced when large scale PV installations interact with existing grid utility. Due to random fluctuations, it is difficult to prepare the scheduling of PV for electricity generation. The PV output fluctuations can be limited by using additional sources like battery, capacitors, diesel generators, fuel cell, controlling maximum power point tracking (MPPT) to control output power from PV generator or by installing dump load to divert excess power. There has been an intense research activity in the field of RES and the problems associated with it.

The objective of this paper is to provide a comprehensive review on the problem associated with intermittent PV output when connected to the grid and its mitigation methods. Firstly, the paper discusses few important issues caused by PV output variability when PV is connected to the grid. Then a brief explanation on smoothing output power fluctuation by geographical dispersion for PV clusters installed in wide areas is presented. Then a comprehensive discussion on methods of mitigating PV output power fluctuations for individual PV installation using batteries, capacitors, electric double layer capacitor (EDLC), superconductive magnetic energy storage (SMES), diesel generators, fuel cell, MPPT power curtailment and dump loads is reviewed in detail. Based on comparative analysis of these various mitigation methods, it was found that batteries are ideal choice for this fluctuation problem and therefore the control strategy of battery energy storage is also discussed briefly. The paper is organized as follows: Section 2 addresses the problem when the output power of PV fluctuate, Section 3 explains the ways to smooth the output power fluctuations from PV, Section 4 explains control strategy of battery storage technology used for this problem. Discussion is presented in Section 5 and this paper is concluded in Section 6.

2. Problems with intermittent power source

Installing PV in feeder would contribute to problems like frequency deviation and voltage fluctuation in electric power system. In this section important issues such as (i) Grid connected voltage fluctuation, voltage rise and reverse power flow, (ii) unintentional islanding, (iii) power fluctuation in grid and (iv) effect in grid frequency are discussed below.

2.1. *Grid connected voltage fluctuation*

Voltage fluctuation is change in voltage from the prescribed value. It is problematic when it deviates from the specified limit. PV is not only affected by the change in grid voltages but also sometimes cause voltage fluctuation themselves. Movement of clouds is also a source for induced voltage fluctuation however, the magnitude of voltage fluctuation is independent of cloud cover [16]. The impact of voltage fluctuations has been explained in [5,16,17].

2.1.1. *Voltage rise and reverse power flow*

Voltage regulation is an issue when power from intermittent sources increases during grid operation. When PV penetration increases the voltage level at the substation also increases. The voltage level at the substation may violate the limits in presence of capacitor bank or voltage regulating devices which are normally installed in substations to boost the voltage. The possible way to

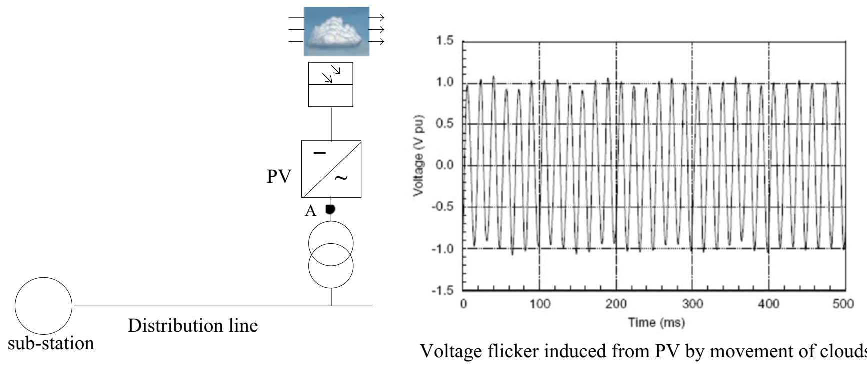

Fig. 4. Problem of cloud induced voltage flicker.

solve this issue is to limit the PV real power generation. When cluster of intermittent PV are connected to low voltage (LV) distribution network, the voltage will raise with the reverse flow of power from the intermittent source towards the substation. During this voltage rise the power output from the PV should be restricted and continuing with this problem the intermittent power source has to be disconnected from the LV network [18]. Fig. 3 depicts the problem of voltage rise locally. The voltage across the distribution line decreases from sub-station until it reaches the point of PV connection. The voltage rises immediately after connecting PV at points A and B. To avoid further voltage rise beyond its acceptable upper limit the PVs at point C and D are disconnected. In addition to it reverse power flow destabilizes the control system of voltage regulators since they are designed for unidirectional power flow and also trigger the protection relay which may possibly disconnect the load.

Authors in [19] have recommended ways to handle the reverse power flow problem in the distribution network. The authors recommended the use of phase balancing from the utility side to mitigate single phase reverse power flow and use of bidirectional regulators to maintain voltage regulation and check three phase reverse power flows. Reactive power control for PV inverter was suggested by authors in [20] to improve distribution system operation. The reactive power control method mitigates distribution system voltage magnitude fluctuation caused by short term solar power fluctuation. Literatures also suggested the use of dump load and energy storage devices to mitigate the voltage rise problem. Authors in [21] suggested curtailment of both active and reactive power by locally controlling the PV inverter to avoid voltage rise.

2.1.2. Voltage flicker

Another important problem pertaining to variable power output from PV is voltage flicker. Fig. 4 illustrates voltage flicker where the variation in voltage peaks (waveform inserted in Fig. 4) caused by PV output power variation induced by movement of clouds.

This problem occurs when rapid changes in PV occurs due to clouds passing which will lead to sudden change**s** in voltage level. Literature has suggested many ways to handle the voltage rise problem [22].

2.2. Unintentional islanding

Unintentional islanding occurs when a fault occurs in distribution level, during which the power generated from PV is equal to load demand. The power interruption from the grid side cannot be sensed by the PV system and PV continues to generate power to the load. However for safety concerns PV system has to stop generating power. This state is called “Unintentional Islanding” [18].

Remote, active and passive are the methods used to detect unintentional islanding. Remote islanding technique is associated with utility side and is based on communication between PV inverter unit and utility. Although it is more reliable than active and passive techniques, it is are expensive to implement and involve complex communication techniques [23]. During active method the islanding is detected by inducing an intentional disturbance such as active or reactive power fluctuations to the grid. However these disturbances also contribute to power quality issues. These intentional disturbances may also affect the performance of PVs when connected in cluster. The passive island detection method works on examining a sudden drift in parameters like voltage, current, frequency, active power or reactive power when islanding occurs. The passive method works well for large power system where the huge drift in parameters are easy to detect.

2.3. Power fluctuations in grid

Industries are widely affected when there is a grid disturbance. One of the main causes of disturbance is intermittent power output from PV and wind power. These sources do not deliver constant power continuously like nuclear, thermal or gas-fired plants. It is the challenge for the grid operator for the ability to predict the power produced from these intermittent sources. The fluctuation in the grid changes the voltage and frequency parameter which affects sensitive equipments in manufacturing units. Due to this problem battery backup and local generators are commonly used to protect sensitive equipment and control systems.

2.4. Effect in grid frequency

Frequency is one of the important factors in power quality. During grid interconnection frequency must be maintained uniformly. Usually load variation causes frequency deviation in the grid and it becomes worse when PV output power changes due to quick change in radiation level [24]. Control of intermittent source output is necessary since increasing share of PV will affect power quality during grid interconnection. At present, frequency deviation due to PV penetration is less as compared to wind turbines since the installed capacity of wind units is higher than PV. The frequency can be regulated by installing energy storage devices. Distributed storage can be used to regulate system frequency for the area by charging or discharging the storage on operators command. In future, the frequency deviation due to increase in PV penetration will be noticeable.

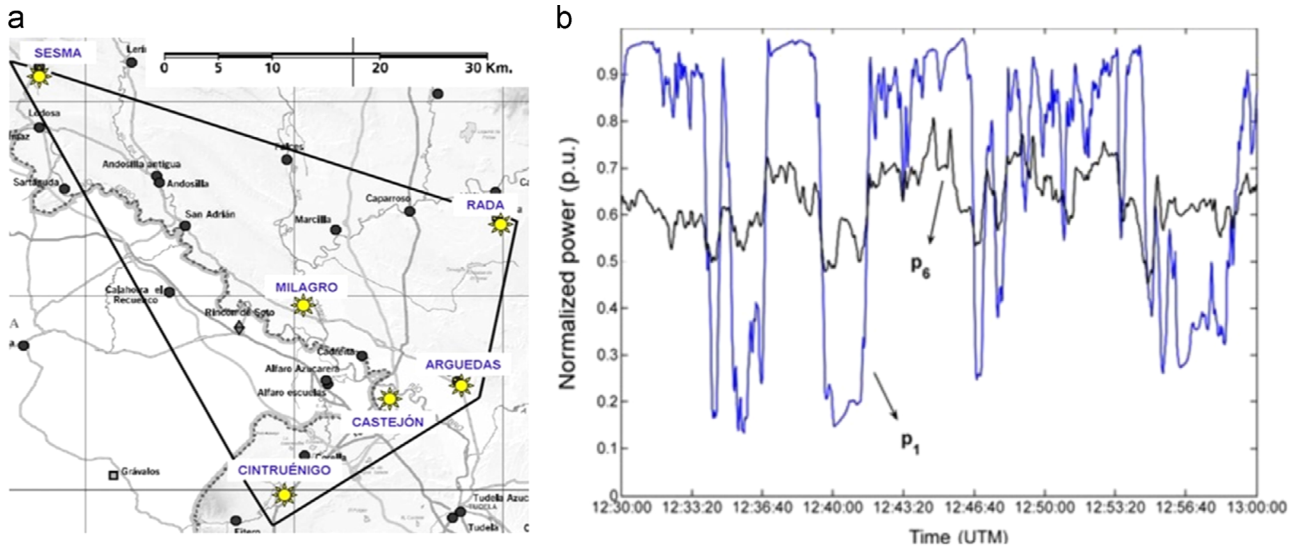

Fig. 5. (a) Six PV plants geographically spread over 1000 sq km, (b) output power from cintruenigo PV plant (P_1) and combined output of six PV plant (P_6) [26].

3. Intermittent smoothing approaches for PV output

To prevent power fluctuations, grid operators generally impose limits on suitable ramp rates. Smoothing PV output power fluctuation increases the overall system cost, operating cost and the cost of power produced by PV. For example, installation and control of dump load, fuel cell or battery sources to mitigate PV variability increases all the aforementioned costs. In order to study the impact of PV penetration on electric network, extensive analysis is necessary which rely on large volume of historical data. In order to mitigate the power fluctuation problem input data of minutes, hourly or weekly radiation of PV is necessary. Predicting the power production from intermittent PV is not 100% accurate. It is clear from [25] that a PV system depends on short term variations of solar radiation since PV system respond to changes in radiation. A study on developing a frequency fluctuation model to calculate the frequency of output power fluctuation and magnitude of fluctuation was carried out **in** [26]. In [27], authors analyzed fluctuations in solar radiation focusing on amplitude and frequency of occurrence instead of focusing on location and time. A wavelet based spectral analysis tool was used for analysis of short-term fluctuation of instantaneous clearness index. The wavelet spectral analysis gives information about frequency of occurrence and fluctuation.

3.1. Smoothing power fluctuation by geographical dispersion

Geographical dispersion is normally used to mitigate the short term output power fluctuations for PV clusters installed in wide area. It is also observed that the protection problem caused by large PV penetration can also be solved by dispersing PV generation [28]. Fig. 5(a) and (b) shows six PV plants geographically dispersed over 1000 sq km in Spain and their outputs.

From the analysis it was found that the effective smoothing depends on grouping PV installations and the corresponding distance between them.

Many methods are developed to forecast the PV power with and without the help of solar radiation. One such method is combining regional forecast technique and principal component analysis (PCA) to forecast PV power generation spread over large area was proposed in [29]. The disadvantage of combining regional forecast and PCA technique is that it is impossible to monitor the PV units spread across the region individually. The proposed method did not use solar radiation measured in the past.

Significant findings were reported in [30] where economic and performance analysis of roof top PV was carried out. The authors were the first to report increase in LFC (Load Frequency Control) when PV contribution increases. It is also found that the break even cost is high when PV contributes less to the power system. Considering economic and LFC requirements, 10% PV penetration to power system as the upper limit is suggested. In [31] the authors used the output from 100 PV distributed in Germany to calculate the stability and long-term predictability of the dispersed PV generation. It is found that power fluctuations were suppressed significantly but could not smooth short-term fluctuations effectively. Incidentally, when number of PV system decreases it contribute to increase in fluctuations. In [26], short term output power fluctuation of a geographically dispersed PV is reduced against individual PV. In addition, it is possible to calculate largest fluctuation of individual PV from a PV group by applying convolution technique to the frequency fluctuation model. The reduction in output power variability by integrating many PV stations is achieved in [32]. It is also confirmed that the magnitude of smoothing effect depends on capacity of tie-line available for electricity transfer between PV stations and grid. Strong decrease in fluctuation was observed by applying wavelet transform to clear sky index of separate PV installation or average of geographically dispersed six locations [33]. Hoff et al. [34] developed a model to calculate the output variability of PV group by computing the standard deviation of change in fleet output power, relative output variability and dispersion factor. The results closely matched with the measured 20 s irradiance data. The fleet computation is valid but difficult to implement practically since the multiple system calculation involves heavy mathematical calculations and insufficient data on solar irradiance.

By spreading the resources, the fluctuations and the transient related interconnection issues such as voltage problems, tripping issues at the sub-stations or distribution level are reduced considerably but cannot be eliminated [35]. The problem of voltage fluctuation in a grid connected dispersed PV is also addressed in [36]. There are literatures about detailed study on fluctuations in irradiance [37,38]. A correlation among distance between PV inverters, wavelet time scale and daily fluctuation is established in [39] for a 45.6 MW PV plant spread over 2.8 km. [40] focuses on reducing variability in PV power generation by geographic dispersion. It is concluded that, increased dispersion reduces variability indicated by standard deviation and pearson correlation coefficient analysis. Furthermore small reduction in energy generation with increased dispersion above 800 km and step up in system performance with increase in dispersion of solar PV panels was found. The authors of [41] recommend the operator to forecast the cloud pattern and predict PV generation to maintain system reliability and to reduce system operating cost since the efficiency of the scheduling also depends on accuracy of the forecast.

3.2. Smoothing by using energy storage technologies

Storage devices assist in performing one or more important tasks such as (i) smoothing power fluctuation, (ii) shift peak generation period, (iii) protection during outages when installed along with large PV generation [2].

3.2.1. Battery energy storage

The usage of energy storage technologies is inevitable as the PV penetration increases in the grid. Battery energy storage (BES) consists of many batteries connected in series–parallel combination to produce required power for the application. Batteries are cost effective and can store energy in the form of electrochemical process. They have quick response in charging and discharging mode. There are many types of batteries used for BES applications**,** some are (i) flooded lead acid (LA) batteries, (ii) valve regulated lead acid (VRLA) batteries, (iii) nickel cadmium (NiCd) batteries, (iv) lithium ion (Li-ion) batteries, (v) sodium sulfur (NAS) batteries and (vi) vanadium redox (VRB) batteries. Lead acid (LA) batteries are widely used for this application due to low cost and market availability. Increase in maintenance cost and frequently adding distilled water are few disadvantages of LA batteries. VRLA is alternate choice since they are maintenance free, operating life of VRLA is higher than normal LA and achieve 70–80% efficiency. Compared to LA batteries NiCd, NAS, VRB, Li-ion batteries are efficient, have high energy density, require less maintenance. High energy density, more operating life and less maintenance cost also make sodium–sulfur (NaS) batteries a better choice than LA batteries for large scale power applications. It is important to estimate the power and energy rating of the battery storage.

It is estimated that battery is 17 times more effective in providing frequency regulation services than traditional resources [42]. Fig. 6 shows solar PV and battery source connected to the grid through separate voltage source converter.

Control strategy for a grid-connected PV, battery energy system (BES) is proposed in [43] to smooth output power fluctuations from PV. The optimal size of the BES is estimated by optimizing a multi-objective function using genetic algorithm for a 1.2 MW PV plant. Operating efficiency of the proposed controller is reported as 84% and the state of charge (SOC) control reduces the size of battery by 2% from 300 kWh to 294 kWh. It is also observed that the non-linear parameters like battery impedance, self-discharge

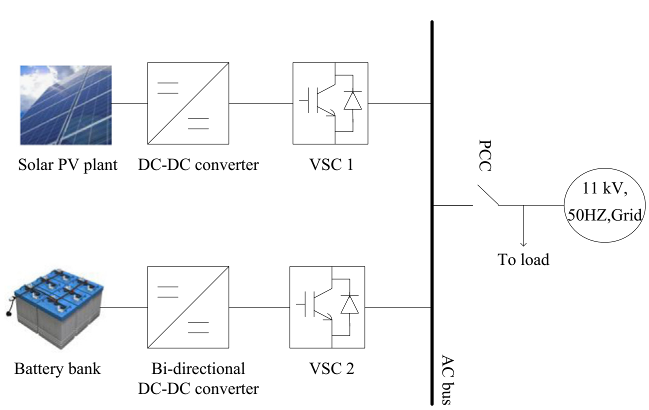

Fig. 6. Battery station for smoothing PV output connected with grid.

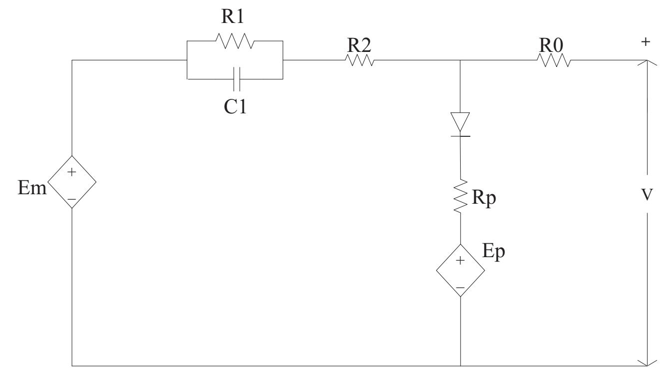

Fig. 7. Third order model of battery [46].

resistance affect the charging and discharging of batteries. It is also suggested that the proper representation of BES contribute to accurate SOC estimation and improve**s** controller design. A day ahead dispatching smooth model is optimized using linear programming for a PV, wind, battery hybrid system when connected with the grid connection [44]. The combined output of PV and wind is smoothed effectively by charging and discharging the battery system.

A rule based controller for battery is designed in [45] for optimal use of lead acid BES. The authors achieved effective smoothing of PV output where the battery is dispatched on hourly basis. A third order model of battery was considered for accurate representation of battery charging/discharging level [46]. The third order model of battery is shown in Fig. 7 where the R_p and E_p are parasitic branch for self-discharge and R_0 is overcharge resistance. It was reported that the controller is effective in dispatching the set points most of the time.

A power management system is developed in [47] which balance real and reactive power independently with current controller and is capable of smoothing the output power fluctuations from PV. A microgrid consisting of diesel power plant, PV and BES is considered in this study. The power management system works on operator decision. The design and size of the lead acid battery is accurately found by following the developed guideline algorithm. The authors observed the reduction in computational burden and the effective smoothing was carried out by applying moving average filtering method. They also reported applying droop mechanism for excitation control of diesel plant enables reactive power sharing between diesel plant and BES. Hill et al. [48] presents challenges of operating PV in grid connection mode and explains different modes of operating the BES in solar-grid connected mode. The authors focused on ramp rate control, frequency response and reactive power support for a BES integrated with PV installed on Hawaiian Islands. They reported that by coupling PV with battery will improve the economics. PV-BES also provides voltage and frequency regulation services. The BES act as a centralized storage installed in distribution feeder since the control of battery in centralized storage is easy. Daud et al. [49] evaluated the dynamic performance of BES with grid connected PV system under step change in solar radiation and fault in the grid. A control strategy was developed to maintain DC bus voltage constant at 500 V and efficient operation of BES. Authors used parameters of VRLA battery for the simulation. They also suggested using lithium batteries than lead acid batteries for large scale applications considering the economic point of view. The authors of [50] minimized the line loss**es** in distribution system considering variation in PV and load operation. The optimal scheduling problem was solved using genetic algorithm. It was reported that the line loss were reduced to 390.41 kWh from 523.5 kWh in summer season and in the winter season the line losses were reduced to 81.5 kWh from 117.31 kWh. The authors also reported that the line loss would go up to 467.4 kWh and 169 kWh in summer and winter respectively if the BES is not scheduled. The proposed optimal scheduling method has improved the system performance. The authors did not address the effectiveness of proposed method in smoothing the output power fluctuation of PV. NAS batteries were used to suppress PV output power fluctuations**,** where hybrid method involves moving average and fluctuation center to produce reference set point for NAS battery bank [51]. Results show the performance of hybrid suppression method is almost same when compared to moving average method and it is also estimated hybrid suppression method requires battery with low power capacity and high energy capacity.

The optimal control strategy of VRLA BES by optimizing the control parameters of state of charge feedback (SOC-FB) control scheme by genetic algorithm, gravitational search algorithm (GSA) and particle swarm optimization (PSO) for smoothing the output power from PV farm is presented in [52]. They used an improved BES model and also evaluated the optimal size of BES. The proposed control strategy has improved the operating efficiency of SOC-FB controller to 90% from 37.6% (by using conventional SOC-FB). In summary the obtained results show that (i) high power fluctuations were reduced by optimal control and operation of BES, (ii) BES size has been minimized and (iii) the use of optimization technique increases efficiency of the controller. Fuzzy wavelet filtering method is proposed to smooth the output power variation of a wind turbine and PV system [53]. The effectiveness of the proposed control method is tested to smooth the output fluctuation from wind and PV by maintaining the SOC of battery within its limit. The fuzzy wavelet filtering method efficiently levels the output power fluctuation without adding energy storage capacity.

In [41] optimal power management of PV, BES in grid operation is presented where a predictive power management supervisor is designed in three stages. The authors formulated an objective allowing intense PV penetration into grid by proposing peak shaving at lower cost. Dynamic programming was used to achieve the objective function. Authors considered economic view of owner to minimize the cash flow as objective function and compared it with rule base management approach. Battery SOC, state of health (SOH), battery power limits are taken as constraints and are maintained within the limits to prevent battery from degradation and ageing. The cash flow is minimized effectively using predictive power management strategy than rule base management. Predictive power management strategy minimizes the electricity bill of owners by 13%. The article [54] discusses on smoothing the output power from single PV and multiple PV generators located in different locations. A control method is developed based on fuzzy logic which balances the output fluctuation by charging/discharging the BES. The optimal size of BES is also estimated. The fuzzy control method is validated by analyzing the frequency deviation. It is observed that the fuzzy control method is effective in smoothing PV output than MPPT control and maintains the frequency deviation within ± 0.2 Hz.

Use of lithium ion phosphate battery energy storage is demonstrated to smooth the output power fluctuation from PV and wind hybrid system [55]. The SOC smoothing control method is designed by considering (i) power distribution among BES, (ii) coordination among BES for smoothing, (iii) individual BES SOC level. Optimal design of storage considering intermittent wind and PV has been presented in [56]. The aim is to reduce the size of the storage device and it was concluded that the PV power is more predictable than wind power. Improved cycle VRLA battery is used to charge/discharge power to smooth the power fluctuation from PV inverter output [57]. The smoothing is based on average solar irradiance and the results show the smoothing algorithm reduces the ramp-rate. The experiment demonstrates the increase in operating life of improved VRLA battery. Battery is used to smooth PV output by using a smoothing and SOC tracking algorithm [58]. Combining natural gas engine generator with battery for smoothing PV output was demonstrated by [59]. Smoothing algorithm developed by authors of [58] was used. The smoothing algorithm can respond to (i) PV output fluctuation, (ii) Area control error and (iii) load variability. It was found from the experiment that the (i) natural gas engine generator responds to slow ramp-rates, (ii) battery responds to quick ramp-rates, (iii) reduction in battery size and low ramp-rates.

In [60] integration of electric vehicle DC–DC bi-directional chargers for charging electric vehicle is carried out. In addition to it the size of the battery is also evaluated. They analyzed the effectiveness of the charger to smooth the PV output by limiting the ramps within the prescribed limits by charging of battery. Result shows reduction of ramp-rate by efficient battery operation. Model predictive control (MPC) framework is proposed for a grid connected PV-BES system [61]. The objective of the system is to shift the output to match the load profile and smooth the intermittent output from PV. The forecast model in MPC frame work is self-correcting in nature which involves linear error correction. MPC framework is dynamic and it involves computational method, where less computational time is required to solve the optimization problem. Thus, the cost of the system is minimized extensively.

A method where the ramp-rate of PV inverter is controlled to desired level by employing battery energy source is proposed in [62]. The proposed method is effective to mitigate the fluctuation problem and to control the ramp-rate independent of PV output historical data. They designed an algorithm for controlling the energy storage by observing the inverse relationship with PV output ramp-rate. The authors recommended usage of energy storage devices such as BES and capacitors to limit the PV ramp-rate. The problem of voltage rise with the increase in PV penetration is reduced by coordinate control of distributed lithium ion iron phosphate batteries and OLTC (on-load tap changing) transformers [63]. The problem of voltage fluctuation and reverse power flow in distribution network is addressed when a roof top PV is connected with BES [64]. The battery storage is used to store excess power flow during peak PV penetration and discharge during peak evening load. In addition, the storage also discharges for short term during PV output fluctuation caused by change in weather conditions. The proposed charging/discharging method is tested practically in distribution network and is effective in maintaining voltage profile, reverse power flow and **to** match excess PV power with evening load profile.

3.2.2. Use of capacitors and superconductive magnetic energy storage (SMES)

The ramp-rate of PV generators connected to grid can be controlled by electric double layer capacitor (EDLC) where the reference is generated using moving average method [65]. The capacitors absorb the difference of power between PV and inverter output. The expression for calculating the capacitor size was developed and it was found that the capacitor size decreases when ramp-rate decreases. Moreover the size of the capacitor is reduced by 10% to its projected size when the PV output is smoothed using moving average method. The moving average method depends on older data points. When there is no significant fluctuations in PV output the reference waveform produced using moving average method deviates wider. This is because the moving average method heavily depends on previous or older data points which is termed as “memory effect”. Therefore due to this reason the energy storage will operate unnecessarily even thought there is no significant fluctuation in PV output power. Power modulation of

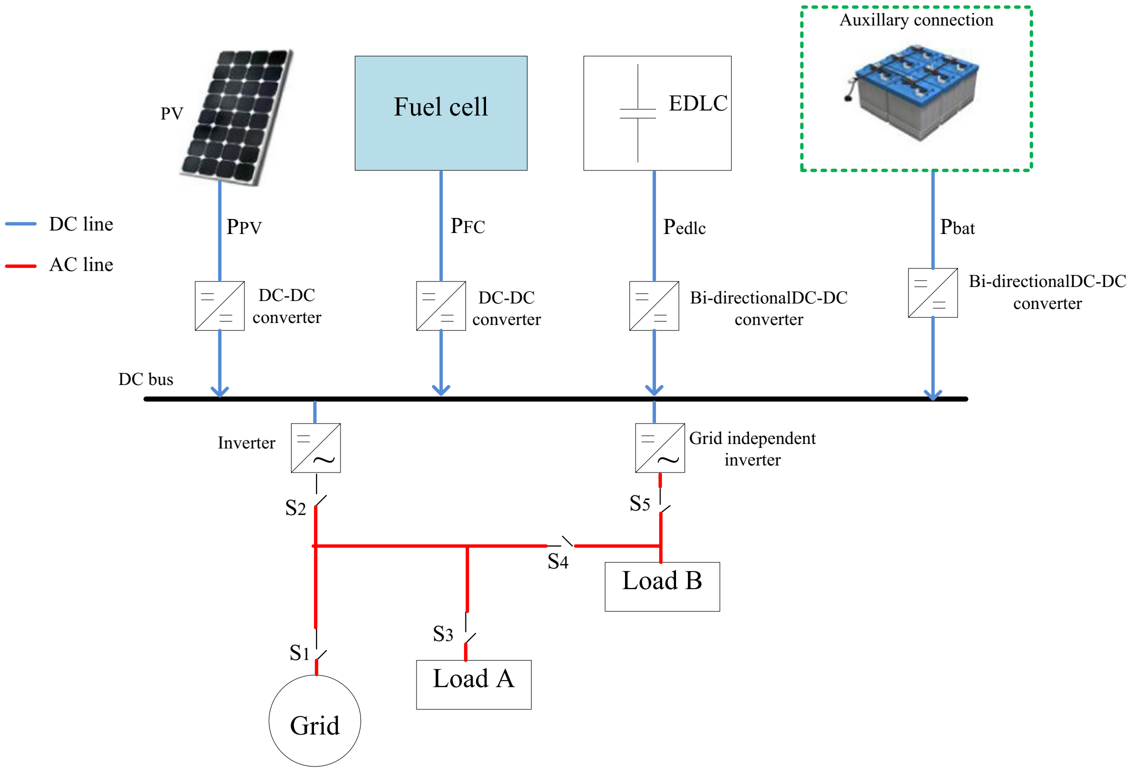

Fig. 8. Structure of PV, EDLC, FC dispersed system [68].

photovoltaic sources for frequency regulation is proposed in [66]. The frequency deviation is minimized by modulating the PV generator's output limited to 3% of the rated power is achieved. The effect of PV penetration on OLTC transformers was examined in [67]. Results show increase in tap changing frequency and voltage violation as PV penetration level increases (0–90%). They also reported that tap changing frequency and voltage violation is reduced by installing DSTATCOM (Distribution static compensator) in the feeder. Consequently, this will minimize the maintenance cost and increases the life span of OLTC transformers. They also estimated the size of DSTATCOM needed for voltage regulation. The increase in the size of DSTATCOM significantly reduces the voltage violation.

Moving average prediction method predicts the exact value with time delay. The exact value can be found after $(N-1)T_s/2$ s where N is sampling number and T_s is sampling interval. This demerit is overridden by applying Euler moving average prediction (EMAP) method. EMAP method is applied to a system consisting of PV, fuel cell and EDLC, where the following objectives were achieved**:** (i) meeting customer power requirement, (ii) effective use of fuel cell, (iii) EDLC to compensate PV output, load demand and to (iv) maintain voltage stability [68]. System topology is shown in Fig. 8.

EMAP is an effective method for optimal power sharing between fuel cell and EDLC. Furthermore, the size of EDLC is also reduced by 77% when compared to moving average prediction method.

The problem of voltage flicker caused by variability in PV output is mitigated by installing super capacitors [69]. The use of superconducting magnetic energy storage (SMES) with intermittent sources shows its effectiveness in maintaining load side frequency [70]. It was found that the increase in SMES capacity maintains the frequency within the limit. The SMES is combined with 4 kW PV facility to show that the PV output is fully utilized and is effective in leveling the PV output power fluctuation**s** [71]. The experimental results conducted at different weather conditions demonstrate that the PV output is effectively enhanced by using SMES. Active/reactive power control for current sourced-EDLC connected inverter for solving the PV or wind output fluctuation problem is proposed in [72]. The effectiveness of the proposed control method is tested when connected to wind turbines. Terminal voltage fluctuation and fluctuation in tie-line power is effectively reduced. The use of current controlled ultra capacitors and battery energy storage connected to PV in grid connected mode is examined in [73]**,** to minimize the PV output fluctuation and to meet load variations. Ultra capacitors and battery through dual active bridge (DAB) converters connected in series and parallel combination are used to meet the DC bus voltage. A proposed topology for DAB converter enables power sharing between battery and ultra capacitor as presented in [73]. The characteristic feature of the proposed control strategy and DAB controller are: (i) power distribution among batteries is flexible without affecting normal operation, (ii) upgrade of energy storage is done by connecting the battery or ultra capacitor directly to the group through DAB converter without disturbing the existing order, (iii) dynamic allocation of steady state power and transient power demands to batteries and capacitors and (iv) the battery with high SOC is discharged till the SOC level of all batteries are same. The PV output is smoothed by installing electric double layer capacitors [74]. The power exchange between capacitor and PV is enhanced by controlling buck-boost controller as illustrated in Fig. 9. The power injected or absorbed by the capacitor is done by turning on and off the pulses G_1 and G_2.

In [75], a novel idea of voltage management in distribution system by cooperation between distribution network operator and commercial customers is demonstrated. Voltage regulation in distribution network due to PV output fluctuation is done by installing Static Var Compensator (SVC). PV output based on minute by minute irradiation data is used for analysis.

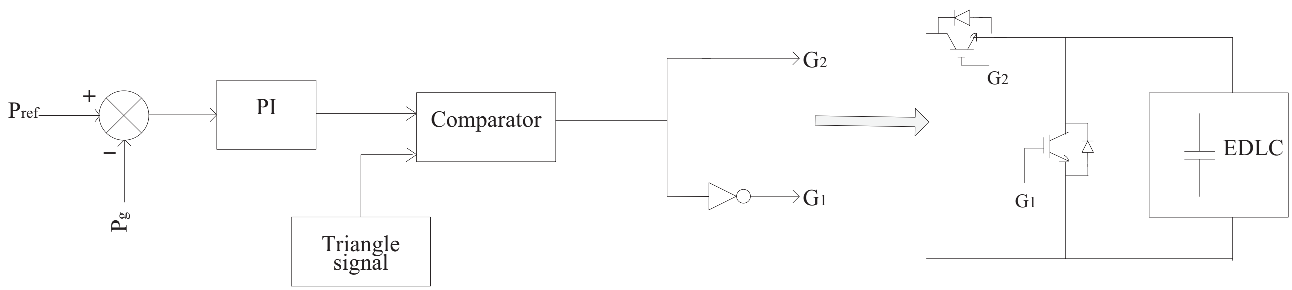

Fig. 9. Buck-boost converter control [74].

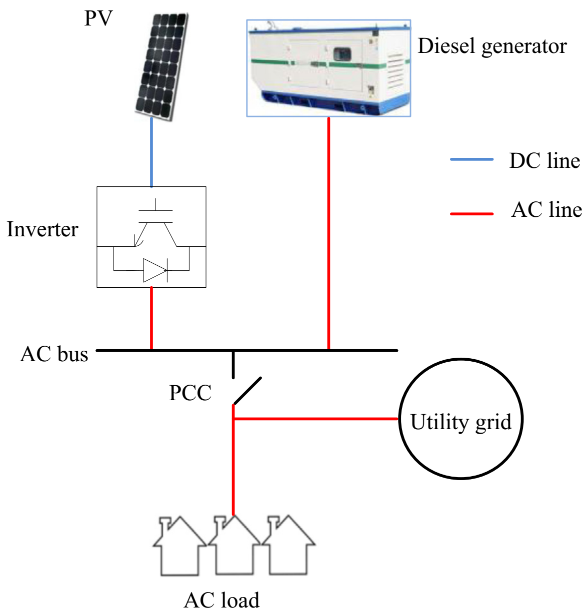

Fig. 10. PV, diesel generator hybrid system.

3.3. Diesel generator

Integrating diesel generators with PV for mitigating fluctuation has gained user's trust in early years. However, the difficulty of using a diesel generator for the PV power fluctuation problem are due to (i) slow response during continuously changing PV and (ii) decrease in operational efficiency when it is made to run at low output levels during high level of oscillation in PV. These problem have prompted the users to focus on fast response technologies with more operational flexibility like battery energy storage, capacitors and fuel cell [76]. Fig. 10 shows the connection of PV and the diesel generator hybrid system with grid.

Authors in [77] developed a fuzzy controller for PV generator to control the frequency of a PV-diesel hybrid system. The PV generator controlled the output produced and effectively maintained the frequency deviation within ± 0.2 Hz. The results were satisfactory when compared with PV with MPPT control. The diesel generator acted as a backup source which will follow the changes caused by variation in PV output and load. A similar work was carried out by authors in [78]. The authors developed fuzzy reasoning control based on (i) average insolation, (ii) variation in solar insolation and (iii) frequency deviation. In addition, a proportional integral controller was installed to control the PV inverter. Operating PV-battery-diesel engine generator installed in a ship was analyzed in [79]. In this work, a coordinate operation between the PV, battery and diesel generator considering changes in solar radiation was achieved by minimizing the fuel consumption of diesel generator and maintaining constant output from the generator with high efficiency. In [80] frequency deviation is maintained within its limit by prioritizing the PV using fuzzy rules. A coordinate control based on fuzzy reasoning of multiple PV connected with diesel generator in isolated power system is developed in this work. Central and local controllers have been proposed. The central controller produce the output power leveling command based on fuzzy reasoning. The local controller is responsible for maintaining coordination. The proposed two level coordinate controls are effective in minimizing frequency deviation when compared with MPPT control. A control strategy for coordinate operation of PV and diesel generator is proposed by the authors in [81]. When PV power production increases or decreases the power production of diesel generator decreases or increases respectively, where the coordination is maintained by exchange of information. Coordination method for multiple PV systems has not been suggested. The problem of voltage and frequency stability at the grid side has also not being addressed. A two level coordinated control considering frequency deviation was proposed in [24] to smooth the output power fluctuation of multiple PV system operated along with diesel generator. Frequency deviation not more than ± 0.2 Hz was observed. The objective of (i) smooth output fluctuation and (ii) minimize frequency deviation were achieved in order to maintain the reliability of the system. The benefit of coordinated control is shortage of power can be compensated by nearby generator.

3.4. Fuel cell

Operating fuel cell plant along with intermittent source is gaining its emergence due to following reasons; (i) high integrating efficiency with RES, (ii) high reliability and low maintenance cost, (iii) fast response, (iv) fuel cell can be installed near to the load with reduced noise and emission. Feasibility of using fuel cell to smoothing the PV output power is demonstrated in [82]. In [76] hybrid operation of fuel cell with PV is studied. The authors reported that it is realistic to use this hybrid system in grid connected and standalone modes as the variations in load and PV output are fulfilled by fuel cell. It is worth to mention that the fuel cell have registered an increase in ramp-ups up to $+5.4$ MW per min and ramp-down up to -4.5 MW per min. However the authors did not discuss about the use of fuel cell for voltage or frequency mitigation problems arising due to intermittent PV. Smoothing algorithm was developed based on exponential smoothing to dispatch power from proton electron membrane (PEM) fuel cell as a solution to suppress short term PV fluctuation was conducted in [83]. The proposed system is as shown in Fig. 11.

The average of irradiance data in 1 minute resolution measured for 20 years is used for this work. The work does not involve any forecasting methods and rely heavily on the measured PV data from the past. The work can be carried out with PV forecast technique. Fuzzy logic based self tuning PI controllers is proposed in [84] to compensate the power change in microgrid consisting of PV, wind and tie line power when microgrids are interconnected. The system is operated in islanded and grid connected mode where the controllers are effective in reducing frequency deviation

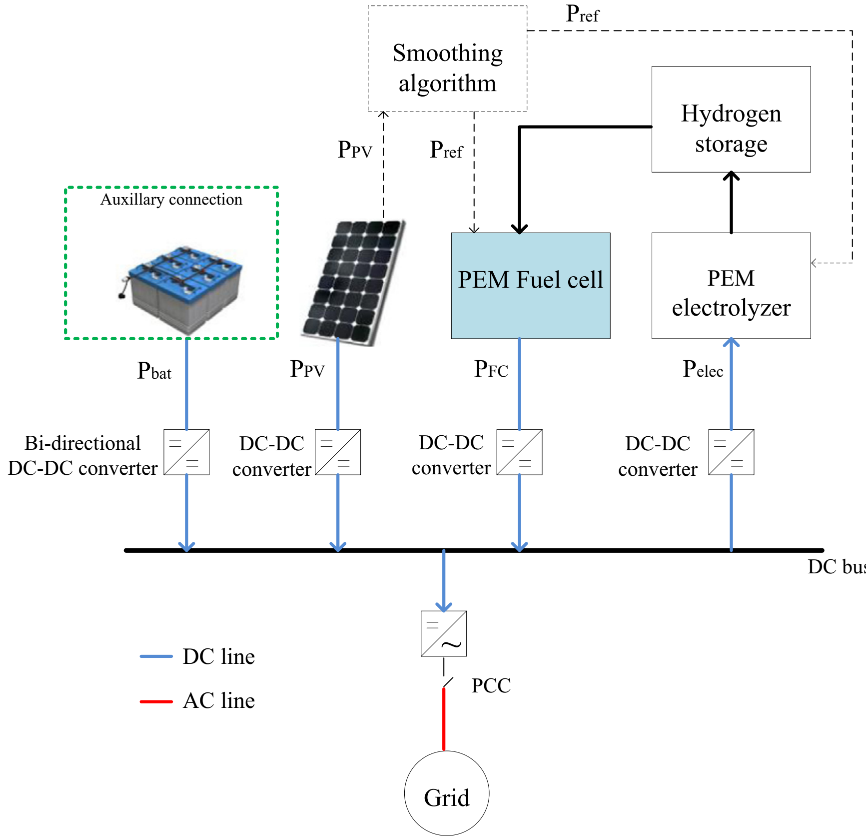

Fig. 11. PV connected to fuel cell [83].

caused by random variation in PV, wind power generation and tie line power. The problem of frequency deviation caused by power fluctuation from intermittent source is addressed in a system containing PV, wind and micro turbine with fuel cell by balancing the real power between generation and load is carried out in MATLAB in [85]. However the problem of smoothing output power from intermittent sources is not addressed. A power management system is developed in [86] for a stand-alone system containing PV, wind generator and fuel cell as a primary energy source and battery back-up as secondary source. The output power of the PV and wind is controlled by MPPT and pitch angle control. The effectiveness of proposed energy management system for fuel cell to supply the power deficit during winter and summer season considering real irradiance and wind speed data is demonstrated by the authors.

3.5. Curtailment of active power by MPPT control and dump load

Curtailing power from PV is a conventional method to suppress the output power fluctuations. In [87], authors limit the output power from PV by controlling its MPPT (Maximum power point tracking). The smoothing effect is created by limiting the PV ramp-ups by 1% of PV rated capacity per minute. This proposed method does not address limiting PV's output when radiation decreases. It is reported that ***the*** output fluctuation is reduced by 28%. The condition of changes in frequency and voltage deviation is not considered. In [88], authors controlled the system frequency by a novel method of utilizing “PV reserve” by operating the PV after MPPT point. The frequency control capability of the system with PV and rotating machine is only demonstrated and no energy storage technology is used. The cost of the system is reduced when compared with using storage technologies. When batteries usage is combined the size of battery is reduced very much.

Table 1
Change in revenue for different methods [2].

	Method			
	Battery	Dump load	MPPT	Battery+MPPT
Change in revenue in % with fluctuation ±400 kW/10 min	−18.5	−14.7	−9.0	−7.8
Change in revenue in % with fluctuation ±250 kW/10 min	−22.4	−19.9	−13.7	−10.6
Change in revenue in % with fluctuation ±100 kW/10 min	−28.2	−32.6	−25.9	−16.4
Change in revenue in % with fluctuation ±0 kW/10 min	−34.5	−51.0	−43.8	−24.5

In [2], the authors performed linear programming to investigate the economical benefits of three smoothing methods (i) use of battery storage, (ii) use of dump loads and (iii) operating below MPPT method. NAS batteries are economical for long term applications are used for the simulation. From economic point of view, the loss of revenue from its base value is less (base value is calculated as $23,666,808) by operating below MPPT method when compared to the usage of battery storage and dump loads because operating below MPPT method do not require any additional installation [2] as shown in Table 1. From the table, it can be clearly noticed that operating battery together with MPPT method is more economical.

PV connected to utility grid through dump load is shown in Fig. 12.

The main objective of installing dump loads is to smoothen the fluctuation by absorbing excess power generated by PV system. The dump load consists of resistance with a controller to control the power flow through the load. It is logic to say that dumping a part of power generated is a loss. In [5], authors examined the impact of voltage fluctuation and flicker when cloud pass above PV panels. Results showed passing clouds induce large voltage flickers in the distribution network. The flickers are greater than the prescribed level. Authors showed from the experimental results that the load controllers can be used to reduce short-term and long-term flickers effectively. Unity flicker severity curve method is used to calculate the level of voltage flickers in the proposed control algorithm. The control algorithm acts as a central controller which controls the load controller. The effectiveness of load controller can be viewed from the published results, where all the short-term flickers are reduced and maximum long-term flickers are maintained within the prescribed limit. In addition, they noticed that flicker in phase A also contributes to flicker in phase B and C due to capacitive linkages between the phases. Increase in PV capacity also increases the short-term and long-term flickers. Curtailment of PV output power using dump load was recommended in [89] to ensure voltage of the system is within its acceptable limits.

In addition to MPPT control and dump load, curtailing active power using PV inverter control was demonstrated in [90,91]. Power curtailment using PV inverter control is achieved by frequency-power droop control when PV is connected to diesel generator dominated system [90]. Frequency deviation is reduced and fuel consumption of diesel generator is minimized during peak PV penetration and low load. Droop active power curtailment control is used to limit the PV output from inverter to maintain the voltage within specified limit [91]. The droop active power curtailment works on relating the system frequency and active power of the generators.

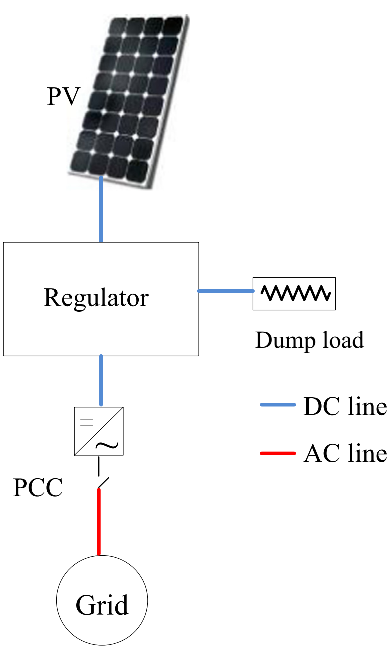

Fig. 12. PV connected with dump load.

4. Control strategy for BES

Understanding battery modeling is necessary for developing control strategy of BES. Utilizing simple battery model for BES implementation is easy but less accurate. Vice-versa, computational burden and mathematical complexity increases when accurate battery model is considered for BES implementation. The rule based control of battery in [45] is developed considering battery SOC limits, charging/discharging current limit and battery life time. The rule based control is considered as closed loop optimal controller as it continuously gets feedback from BES. This controller is easy to implement since it does not involve mathematical equations and the computation time is less when compared to other controller which is its advantage. The proposed controller can be used for any energy storage technology by incorporating its constraints.

The control parameters of a SOC feedback (SOC-FB) controller proposed in [43] is shown in Fig. 13. I_{dref} and I_{qref} are direct and quadrature axis reference currents generated by the outer control loop. The SOC feedback controller is used generate the battery reference power (P_{BESref}) which is used as the input to outer control loop. Here the SOC time constant (T_{SOC}), SOC margin rate (M) and BES energy rating (C_{BES}) in the SOC feedback controller are optimized using genetic algorithm. The primary objectives achieved in this work are (i) to minimize the BES size, (ii) to decide optimal charge/discharge level for BES and (iii) safe operation of BES.

The difference between the rule based controller [45] against genetic algorithm optimized SOC-FB controller is the BES dispatch ability depends on the hourly set point that reflects effective smoothing. On the other hand the dispatch ability of the rule based controller depends on the controller's time constant. In [47], the authors designed a current control algorithm to maintain charging/discharging current within its limits. The SOC limits, current limits, load forecast, PV forecast were considered for the design. The authors noticed that the AC network is less stressed in implementing the current control algorithm where the BES responds within the acceptable time. In [49], discharge/charging of BES is achieved by SOC and voltage control algorithm implemented on DC–DC buck boost controller of BES. The internal current control loop controls the charge/discharge current considering SOC level of battery. The authors developed algorithm for optimal operation of BES based on SOC level and DC bus voltage. In the absence of BES, when solar irradiation increases or decreases in step the voltage at DC bus also fluctuates by 5% and the power

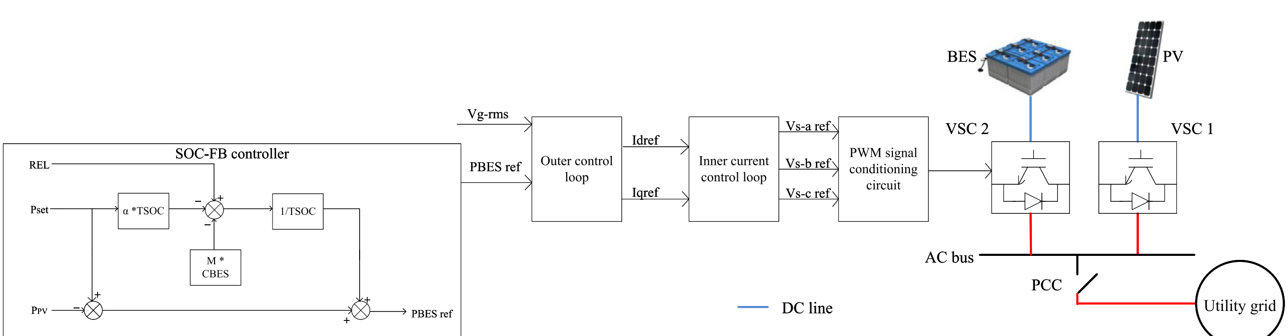

Fig. 13. SOC-feedback controller [43].

transfer to utility grid also changes between ±20%. With the presence of BES during step change in irradiation the voltage fluctuation at DC bus is limited to 1–2%. It was also reported that when the system is subjected to faults, the controller minimizes the transient settling time by optimally operating the BES.

In [50], authors minimized the line loss by scheduling the BES using genetic algorithm. The authors proposed a battery model and estimated the SOC of the battery using piecewise constant current (CC)–constant voltage (CV) method. The CC–CV method is simple and considers the heating effect caused by electrochemical reaction in battery which is a drawback of coulometric method and Advanced Vehicle Simulator (ADVISOR) model. The authors claimed the proposed piecewise CC–CV is realistic and less complicated. There are many algorithms in the literature [92–95] which are used to estimate the SOC of the battery. The SOC-FB control scheme is used to control the BES in [52]. Operational constraints such as (i) SOC limit, (ii) depth of discharge (DOD) limit, (iii) voltage exponential limit and (iv) battery current limits are included for control of BES. SOC-FB controller normalizes (i) SOC at appropriate level, (ii) charge/discharge current level within limits and (iii) BES terminal voltage. In [54], the BES is controlled based on the designed fuzzy controller where the output power command is generated from PV on the basis of (i) average insolation, (ii) absolute average of frequency deviation and (iii) variance in insolation. The output power command is given as an input to energy storage system which produces smoothing effect by charging/discharging the batteries. For coordinated control an addition parameter “tuning factor” is designed with the MPPT which produce output power command. Implementing artificial intelligence (AI) methods in control of battery energy storage can alleviate power quality disturbances in the grid tied PV systems [96]. The review conducted by the authors show that implementing AI control schemes in energy storage devices outperforms the conventional control methods in terms of controllability and response time for the PV power fluctuation events. Apart from that the authors also highlighted the drawbacks of it as AI method takes more time in training the data and the system will not perform to it maximum efficiency if the AI control schemes are tested with new unseen data sets. Model predictive control (MPC) framework in [61] dynamically responds to system changes and external signal from the operator. Two types of BES are used: (i) large BES for shaping output power profile and (ii) small BES to smooth PV output fluctuations. The MPC framework integrates the control algorithm with the forecast models. The control of BES is modeled as a convex optimization problem.

The control of charging/discharging power from BES is developed based on (i) PV output power, (ii) load profile and (iii) current SOC level of battery [64]. Reduction of reverse power flow depends on battery size. Optimal size of battery for mitigating voltage fluctuation and reverse power flow is also found. The controller is designed such that it can compensate the charge drained by adjusting the charging rate to maintain the desired level of SOC. Fuzzy wavelet filtering control strategy is effective in smoothing the output by not compromising the deviation in SOC level of lithium-ion battery [53]. The charging/discharging command for the battery energy sources is sent from the coordinate controller which is based on battery SOC level and voltage at bus bar [63]. Authors found that by coordinate control the life span of OLTC transformer is increased by minimizing the frequency of tap changer. A four stage SOC smoothing control strategy is proposed in [55] for lithium ion phosphate BES which is based on (i) SOC level of individual BES units and (ii) charge/discharge power constraint of each BES units. The SOC smoothing control strategy is found to be effective in minimizing the wind, PV combined output power fluctuation on extreme SOC levels. It is also reported the operating life of BES is extended since the battery units share the burden. Two novel battery energy storage control strategies to smooth PV ramp-rates with half the battery requirement is proposed in [97]. These control strategies are tested with real time data acquired from 38.5 MW PV fleet in Portugal. In the first strategy the ramp ups are limited using inverters and the ramp downs are met by battery storage. The second strategy is based on accurate SOC control. The first strategy presented by the author has two disadvantages: (i) total energy loss in the system is up to 9% due to inverter limitation and (ii) practical implementation is hard due to complexity in inverter control. However advantage of second control strategy is that it is easy to implement. The authors also claim that both control strategies can be implemented irrespective the size of PV plant.

5. Discussion

Curtailment of output power is not recommended since it limits the revenue of the owners even though it is found to be an economical method for smoothing PV output. Effects like voltage fluctuation, reverse power flow and frequency deviation produced due to PV output fluctuations can be reduced by complementing PV with rapid energy storage technologies such as batteries, fuel cell, capacitors with more effective control.

Performance comparison among different mitigation methods are summarized in Table 2. On comparing the performances based on vital characteristics it was found that diesel generator, fuel cell and natural gas engine generator were not able to mitigate fast ramp ups and downs. This is because the time taken by these sources to respond to this sudden change is slow. They were

Table 2
Comparison of characteristic features among different mitigation methods for mitigating PV power fluctuation.

Characteristics	Battery	Capacitors/SMES/ EDLC	Diesel generator	Fuel cell	MPPT method	Dump load	Natural gas engine generator
Response time of the source for mitigation problem	Fast	Very fast	Slow	Slightly slow	Fast	Fast	Slow
Short/long term storage application	Short	Short	Long	Long	Long	Long	Long
Ability to mitigate fast ramp ups and downs	Yes	Yes very rapid	No	No	Yes	Yes	No
Efficiency in mitigating short term PV fluctuations	High	High	Low	Low	High	High	Low
Ability to control voltage/frequency fluctuation due to PV power fluctuation in grid side	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Reliable in mitigating PV fluctuations	High	Very high	Low	Low	High	High	Low
Cost	High	High	High	High	Low	Low	High
Size of PV plant	0- large MW scale	0-few MW scale	0-MW scale	Few kW–MW scale	0-very few kWs	0-very few kWs	200 kW–few MW scale

capable in supporting relatively slower ramp-ups and ramp-downs. On the other hand other mitigating methods were fast enough to mitigate PV ramp-ups and downs. MPPT control method and use of dump load is highly reliable but is not recommended to mitigate PV power fluctuations in large PV plants since it limits the revenue of the owners even though the cost is relatively very low. But they can be applied for relatively smaller PV installation of residential levels or up to community level.

Energy storage devices like battery, capacitors or SMES are suitable candidates for PV power fluctuation problem. Rapid changes in PV output power may induce unwanted voltage or frequency fluctuation at the point of interconnection. These changes can be efficiently mitigated with the help of battery or capacitors. Battery energy storage is most preferred for MW scale PV installations since batteries have high energy density, it can discharge power for longer duration that is even for hours. On the other hand capacitors or SMES are high power density devices which can discharge power only for few seconds and can be used to mitigate power fluctuation for smaller PV installations. In addition, the capacitors/SMES have clear advantage over batteries as they are cost effective, have faster charging time and have longer life which proves to be an ideal candidate for small PV installation up to commercial scale. For capacitors or SMES, increasing the energy density is the key and this limitation hinders them from being implemented in multi MW scale PV projects. From the above discussion it can be seen that the battery energy storage is the ideal choice for mitigating PV output power fluctuations for PV installations of any size. In addition to it, when using fuel cell for power mitigation problem, the processing time taken by the fuel reformer to convert the necessary input to hydrogen to deliver required power is slow. Therefore this makes the fuel cell the second best choice for the power mitigation problem. Improvement in fuel cell reformer can eliminate the time delay where fuel cell technology can be a potential alternate to batteries in the future.

Fig. 14 shows battery storage was preferred by researchers as a source for mitigating PV output power fluctuations.

Lead acid batteries are economical for short term (2 years) applications. Installing sodium sulfur batteries for a term of 4 to 6 years is economical for BES applications. Fuel cell technology can be a potential alternative to batteries as (i) it can be used for long term applications (15–20 years), (ii) have prolonged discharge time at rated capacity and (iii) parasitic loss is almost negligible. Employing optimization technique on SOC-FB controller for batteries is found to be effective for PV output power leveling application. Optimizing the control parameters of SOC-FB controller for battery is effective in minimizing the PV output fluctuation and increases operational efficiency of the controller. Based on the review it can be seen that the control of battery is based on SOC level, therefore accurate battery modeling and estimation of SOC and depth of discharge (DOD) is necessary.

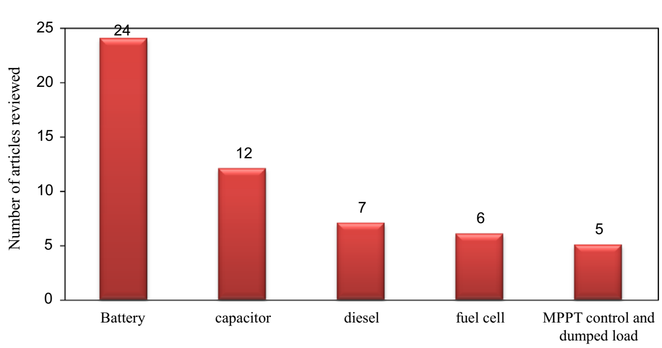

Fig. 14. Articles reviewed based on source used of smoothing PV output.

It is found from the literature that use of optimization technique and control algorithm for battery or capacitor controllers (i) increases overall efficiency of the controller, (ii) minimizes the size of battery/capacitor by optimally charging/discharging, (iii) increase the operating life of battery/capacitor. It is evident that combining a secondary energy supply or an additional power generating unit with battery will increase the operating life and reduces the size of the battery. Combining energy storage technology with other methods like varying MPPT or dump loads proves to be more effective in smoothing PV output and also reduce the size of the energy storage technology. However, combining rapid response technology with diesel generators, natural gas engine generator is more effective in reducing transient and slow ramp rates. However when PV penetration is low the use of storage technologies is not essential to mitigate PV variability. With increase in PV penetration, rapid storage technologies like batteries and capacitors are crucial for mitigating variable PV generation when connected to a weak grid.

Recent advancement for the PV power mitigation problem is actively researched and work published by authors in [98,99] shows that flywheel and compressed air energy storage (CAES) can be a good alternate source for mega-watt scale PV plants. In [98] the authors modeled MW scale CAES system for a 100 MW peak power PV plant. The objective of this work is to do a feasibility study on CAES systems to absorb or produce the power difference from the target power supplied to the grid and the power produced from the PV plant. The authors demonstrated CAES dynamic response to sudden PV ramp ups and downs. A detailed thermodynamic model on PV farm and CAES system considering real conditions is reported. Authors highly recommend the construction of large PV farms equipped with CAES systems in the areas where the solar energy potential is high. It should be noticed that CAES systems is a good alternate for battery bank because of its lower capital cost. Since no previous literatures have been reported on this topic yet the feasibility of CAES system for small PV plants has to be researched. A smoothing method is presented in [99] where the performance of battery energy storage, fly wheel and ultra capacitors connected to single large PV plants are examined. These sources are used to limit the PV ramp rate within 10% of PV rated capacity per minute. It was found that increase in size of these energy storage contribute to decrease in ramp violations. The model also demonstrates the importance of PV forecast, assuming a perfect forecast scenario it was found that the ramp-rate violation is reduced by 24%. Optimum value of power to energy ratio for battery, ultra capacitors and flywheel systems were found and used for further analysis. The power to energy ratio of ultra capacitor is very large and therefore to mitigate 99% of PV ramp violations the power capacity required by the ultra capacitor is very large compared to battery or flywheel systems. Due to this reason the capital cost of ultra capacitors is very large. It was also found that limiting the ramp limit to 5%/min increases the energy rating of the sources than the power rating, due to this reason the power to energy ratio decreases. In this paper moving average method is used as the reference to dispatch the required power to control the PV output power ramp within the limit. On analyzing the cost of different energy sources it was noticed that the capital cost of batteries is cheaper than fly wheel installations but the operation and maintenance expenses for the fly wheel is cheaper than batteries. The usage of flywheel is limited to multi MW scale PV plant and implementing flywheel system to mitigate PV output power fluctuations should be researched for small PV plants. The cycle life of flywheel system is more than batteries therefore even though with higher capital cost it may be economical to operate flywheel system parallel with large PV fleets for longer run.

6. Conclusion

In this paper an updated review on various techniques for mitigating output power fluctuation from PV sources is presented. Since intermittent sources are connected to the grid, the usage of storage technologies like batteries, capacitors and fuel cell are indispensable and found to be very effective in minimizing the PV output variations. The use of fuel cell for this problem is in the early stage of research. Utilizing batteries or capacitors are also appropriate for power quality applications.

Literatures related to the use of battery/capacitor or any additional sources placed individually or centralized for reducing PV variability for geographically dispersed PVs is less and its impact on grid can be experimented by researchers. Well placed energy storage devices can help to solve other issues like voltage fluctuation, voltage flicker caused due to PV output variability, therefore strategic placement of energy storage technology for distributed PVs can also be researched.

Studies focusing on grid connected power quality issues created when PV output varies are limited. Large part of the literatures concentrates on smoothing PV output. More focus on voltage flicker, voltage at grid side, reverse power flow and frequency deviation is needed when leveling PV output power. Special attention has to given on solving these power quality issues. The effectiveness of these mitigating methods depends on forecast of solar radiation. Simplified and more accurate technique is needed to forecast the solar radiation from which PV output power is estimated. These methods will be useful for plant operators where they can plan the scheduling of conventional generator**s**. Increase in PV penetration raise problem in grid but the problems should not limit growth in solar energy production.

Acknowledgments

This work is supported by the Ministry of Education, Malaysia under High Impact Research Grant (HIR-MOHED000004-16001).

References

[1] Renewables Global status report. REN21; 2015.
[2] Omran WA, Kazerani M, Salama M. Investigation of methods for reduction of power fluctuations generated from large grid-connected photovoltaic systems. IEEE Trans. Energy Convers. 2011;26:318–27.
[3] Yadav AK, Chandel S. Solar radiation prediction using Artificial Neural Network techniques: a review. Renew. Sustain. Energy Rev. 2014;33:772–81.
[4] Giraud F, Salameh ZM. Analysis of the effects of a passing cloud on a grid-interactive photovoltaic system with battery storage using neural networks. IEEE Trans. Energy Convers. 1999;14:1572–7.
[5] Lim YS, Tang JH. Experimental study on flicker emissions by photovoltaic systems on highly cloudy region: A case study in Malaysia. Renew. Energy 2014;64:61–70.
[6] Anderson P. The effect of photovoltaic power generator on utility operation. IEEE Trans. Power Appar. Syst. 1985;104:524–30.
[7] Jewell WT, Unruh TD. Limits on cloud-induced fluctuation in photovoltaic generation. IEEE Trans. Energy Convers. 1990;5:8–14.
[8] Jewell W, Ramakumar R. The effects of moving clouds on electric utilities with dispersed photovoltaic generation. IEEE Trans. Energy Convers. 1987:570–6.
[9] Gevorgian V, Booth S. Review of Prepa Technical Requirements for Interconnecting Wind and Solar Generation. Golden, CO, USA: National Renewable Energy Laboratory; 2013.
[10] Karimi M, Mokhlis H, Naidu K, Uddin S, Bakar A. Photovoltaic penetration issues and impacts in distribution network–a review. Renew. Sustain. Energy Rev. 2016;53:594–605.
[11] Ding M, Xu Z, Wang W, Wang X, Song Y, Chen D. A review on China's large-scale PV integration: progress, challenges and recommendations. Renew. Sustain. Energy Rev. 2016;53:639–52.
[12] Shah R, Mithulananthan N, Bansal R, Ramachandaramurthy V. A review of key power system stability challenges for large-scale PV integration. Renew. Sustain. Energy Rev. 2015;41:1423–36.
[13] Marcos J, Marroyo L, Lorenzo E, Alvira D, Izco E. Power output fluctuations in large scale PV plants: one year observations with one second resolution and a derived analytic model. Prog. Photovolt.: Res. Appl. 2011;19:218–27.
[14] Denholm P, Margolis RM. Evaluating the limits of solar photovoltaics (PV) in traditional electric power systems. Energy Policy 2007;35:2852–61.
[15] Eltawil MA, Zhao Z. Grid-connected photovoltaic power systems: Technical and potential problems—a review. Renew. Sustain. Energy Rev. 2010;14:112–29.
[16] Woyte A, Van Thong V, Belmans R, Nijs J. Voltage fluctuations on distribution level introduced by photovoltaic systems. IEEE Trans. Energy Convers. 2006;21:202–9.
[17] Liu Y, Bebic J, Kroposki B, De Bedout J, Ren W. Distribution system voltage performance analysis for high-penetration PV. IEEE Energy Conf. 2008:1–8.
[18] Hara R, Kita H, Tanabe T, Sugihara H, Kuwayama A, Miwa S. Testing the technologies. IEEE. Power Energy Mag. 2009;7:77–85.
[19] Cheng D, Mather BA, Seguin R, Hambrick J, Broadwater RP. Photovoltaic (PV) Impact Assessment for Very High Penetration Levels.
[20] Liu X, Cramer AM, Liao Y. Reactive power control methods for photovoltaic inverters to mitigate short-term voltage magnitude fluctuations. Electr. Power Syst. Res. 2015;127:213–20.
[21] Weckx S, Gonzalez C, Driesen J. Combined central and local active and reactive power control of PV inverters. IEEE Trans. Sustain. Energy 2014;5:776–84.
[22] Whitaker C, Newmiller J, Ropp M, Norris B. Distributed photovoltaic systems design and technology requirements. Sandia/SAND2008-0946 P, Tech Rep. 2008.
[23] Ku Ahmad KNE, Selvaraj J, Rahim NA. A review of the islanding detection methods in grid-connected PV inverters. Renew. Sustain. Energy Rev. 2013;21:756–66.
[24] Senjyu T, Datta M, Yona A, Sekine H, Funabashi T. A coordinated control method for leveling output power fluctuations of multiple PV systems. IEEE Int. Conf. Power Electron. 2007:445–50.
[25] Gansler R, Klein S, Beckman W. Investigation of minute solar radiation data. Solar Energy 1995;55:21–7.
[26] Marcos J, Marroyo L, Lorenzo E, García M. Smoothing of PV power fluctuations by geographical dispersion. Prog. Photovolt.: Res. Appl. 2012;20:226–37.
[27] Woyte A, Belmans R, Nijs J. Fluctuations in instantaneous clearness index: analysis and statistics. Solar Energy 2007;81:195–206.
[28] Jewell W, Ramakumar R, Hill SR. A study of dispersed photovoltaic generation on the PSO system. IEEE Trans. Energy Convers. 1988;3:473–8.
[29] da Silva Fonseca Junior JG, Oozeki T, Ohtake H, Shimose K-i, Takashima T, Ogimoto K. Regional forecasts and smoothing effect of photovoltaic power generation in Japan: an approach with principal component analysis. Renew. Energy 2014;68:403–13.
[30] Asano H, Yajima K, Kaya Y. Influence of photovoltaic power generation on required capacity for load frequency control. IEEE Trans. Energy Convers. 1996;11:188–93.
[31] Wiemken E, Beyer HG, Heydenreich W, Kiefer K. Power characteristics of PV ensembles: experience from the combined power productivity of 100 grid-connected systems distributed over Germany. Solar Energy 2001;70:513–9.
[32] Murata A, Otani K. An analysis of time-dependent spatial distribution of output power from very many PV power systems installed on a nation-wide scale in Japan. Solar Energy Mater. Solar Cells 1997;47:197–202.
[33] Lave M, Kleissl J, Arias-Castro E. High-frequency irradiance fluctuations and geographic smoothing. Solar Energy 2012;86:2190–9.
[34] Hoff TE, Perez R. Quantifying PV power output variability. Solar Energy 2010;84:1782–93.
[35] Hoff TE, Perez R. Modeling PV fleet output variability. Solar Energy 2012;86:2177–89.
[36] Okada N, Takigawa K. A voltage regulation method for dispersed grid-connected PV systems under high-density connection. Solar Energy Mater. Solar Cells 2003;75:637–46.
[37] Mills A. Implications of Wide-area Geographic Diversity for Short-term Variability of Solar Power. United States: Lawrence Berkeley National Laboratory; 2010.
[38] Kuszamaul S, Ellis A, Stein J, Johnson L. Lanai high-density irradiance sensor network for characterizing solar resource variability of MW-scale PV system. 35th IEEE Photovolt. Spec. Conf. (PVSC) 2010:283–8.
[39] Perpinan O, Marcos J, Lorenzo E. Electrical power fluctuations in a network of DC/AC inverters in a large PV plant: relationship between correlation, distance and time scale. Solar Energy 2013;88:227–41.
[40] Rowlands IH, Kemery BP, Beausoleil-Morrison I. Managing solar-PV variability with geographical dispersion: An Ontario (Canada) case-study. Renew. Energy 2014;68:171–80.
[41] Riffonneau Y, Bacha S, Barruel F, Ploix S. Optimal power flow management for grid connected PV systems with batteries. IEEE Trans. Sustain. Energy 2011;2:309–20.
[42] Makarov YV, Lu S, Ma J, Nguyen TB, Commission CE. Assessing the Value of Regulation Resources Based On Their Time Response Characteristics. United States: Pacific Northwest National Laboratory; 2008.
[43] Daud MZ, Mohamed A, Hannan M. An improved control method of battery energy storage system for hourly dispatch of photovoltaic power sources. Energy Convers. Manag. 2013;73:256–70.

[44] Li L, Ding Q, Li H, Dan M. Optimal dispatching method for smoothing power fluctuations of the wind-photovoltaic-battery hybrid generation system. IEEE Conf. Innov. Smart Grid Technol.-Asia (ISGT Asia) 2012:1–6.
[45] Teleke S, Baran ME, Bhattacharya S, Huang AQ. Rule-based control of battery energy storage for dispatching intermittent renewable sources. IEEE Trans. Sustain. Energy 2010;1:117–24.
[46] Ceraolo M. New dynamical models of lead-acid batteries. IEEE Trans. Power Syst. 2000;15:1184–90.
[47] Koohi-Kamali S, Rahim N, Mokhlis H. Smart power management algorithm in microgrid consisting of photovoltaic, diesel, and battery storage plants considering variations in sunlight, temperature, and load. Energy Convers. Manag. 2014;84:562–82.
[48] Hill CA, Such MC, Chen D, Gonzalez J, Grady WM. Battery energy storage for enabling integration of distributed solar power generation. IEEE Trans. Smart Grid 2012;3:850–7.
[49] Daud MZ, Mohamed A, Che Wanik MZ, Hannan MA. Performance evaluation of grid-connected photovoltaic system with battery energy storage. IEEE Int. Conf. Power Energy (PECon) 2012:337–42.
[50] Teng J-H, Luan S-W, Lee D-J, Huang Y-Q. Optimal charging/discharging scheduling of battery storage systems for distribution systems interconnected with sizeable PV generation systems. IEEE Trans. Power Syst. 2013;28:1425–33.
[51] Akatsuka M, Hara R, Kita H, Ito T, Ueda Y, Saito Y. Estimation of battery capacity for suppression of a PV power plant output fluctuation. 35th IEEE Photovolt. Spec. Conf. (PVSC) 2010:540–3.
[52] Daud MZ, Mohamed A, Ibrahim AA, Hannan M. Heuristic optimization of state-of-charge feedback controller parameters for output power dispatch of hybrid photovoltaic/battery energy storage system. Measurement 2014;49:15–25.
[53] Li X, Li Y, Han X, Hui D. Application of fuzzy wavelet transform to smooth wind/PV hybrid power system output with battery energy storage system. Energy Proc. 2011;12:994–1001.
[54] Datta M, Senjyu T, Yona A, Funabashi T, Kim C-H. Photovoltaic output power fluctuations smoothing methods for single and multiple PV generators. Curr. Appl. Phys. 2010;10:S265–70.
[55] Li X, Hui D, Lai X. Battery energy storage station (BESS)-based smoothing control of photovoltaic (PV) and wind power generation fluctuations. IEEE Trans. Sustain. Energy 2013;4:464–73.
[56] Bridier L, David M, Lauret P. Optimal design of a storage system coupled with intermittent renewables. Renew. Energy 2014;67:2–9.
[57] Hund TD, Gonzalez S, Barrett K. Grid-Tied PV system energy smoothing. 35th IEEE Photovolt. Spec. Conf. (PVSC) 2010:2762–6.
[58] Ellis A, Schoenwald D, Hawkins J, Willard S, Arellano B. PV output smoothing with energy storage. 38th IEEE Photovolt. Spec. Conf. (PVSC) 2012:1523–8.
[59] Johnson J, Ellis A, Denda A, Morino K, Shinji T, Ogata T, et al. PV Output Smoothing using a Battery and Natural Gas Engine-Generator. SAND2013. Albuquerque, NM (United States): Sandia National Laboratories (SNL-NM); 2013.
[60] Traube J, Lu F, Maksimovic D, Mossoba J, Kromer M, Faill P, et al. Mitigation of solar irradiance intermittency in photovoltaic power systems with integrated electric-vehicle charging functionality. IEEE Trans. Power Electron. 2013;28:3058–67.
[61] Wang T, Kamath H, Willard S. Control and optimization of grid-tied photovoltaic storage systems using model predictive control. IEEE Trans. Smart Grid 2014;5:1010–7.
[62] Alam M, Muttaqi K, Sutanto D. A novel approach for ramp-rate control of solar pv using energy storage to mitigate output fluctuations caused by cloud passing. IEEE Trans. Energy Convers. 2014;29:507–18.
[63] Liu X, Aichhorn A, Liu L, Li H. Coordinated control of distributed energy storage system with tap changer transformers for voltage rise mitigation under high photovoltaic penetration. IEEE Trans. Smart Grid 2012;3:897–906.
[64] Alam M, Muttaqi K, Sutanto D. Mitigation of rooftop solar PV impacts and evening peak support by managing available capacity of distributed energy storage systems. IEEE Trans. Power Syst. 2013;28:3874–84.
[65] Kakimoto N, Satoh H, Takayama S, Nakamura K. Ramp-rate control of photovoltaic generator with electric double-layer capacitor. IEEE Trans. Energy Convers. 2009;24:465–73.
[66] Kakimoto N, Takayama S, Satoh H, Nakamura K. Power modulation of photovoltaic generator for frequency control of power system. IEEE Trans. Energy Convers. 2009;24:943–9.
[67] Yan R, Marais B, Saha TK. Impacts of residential photovoltaic power fluctuation on on-load tap changer operation and a soluation using DSTATCOM. Electr. Power Syst. Res. 2014;111:185–93.
[68] Monai T, Takano I, Nishikawa H, Sawada Y. A collaborative operation method between new energy-type dispersed power supply and EDLC. IEEE Trans. Energy Convers. 2004;19:590–8.
[69] Woyte A, Bodach M, Belmans R, Nijs J. Power fluctuations in micro-grids introduced by photovoltaics: analysis and solutions. In: Proceedings of the Second European PV-Hybrid and Mini-Grid Conference. Kassel, Germany,; 2003: p. 449–54.
[70] Jung H-Y, Kim A-R, Kim J-H, Park M, Yu I-K, Kim S-H, et al. A study on the operating characteristics of SMES for the dispersed power generation system. IEEE Trans. Appl. Supercond. 2009;19:2028–31.
[71] Tam K-S, Kumar P, Foreman M. Enhancing the utilization of photovoltaic power generation by superconductive magnetic energy storage. IEEE Trans. Energy Convers. 1989;4:314–21.
[72] Kinjo T, Senjyu T, Urasaki N, Fujita H. Output levelling of renewable energy by electric double-layer capacitor applied for energy storage system. IEEE Trans. Energy Convers. 2006;21:221–7.
[73] Zhou H, Bhattacharya T, Tran D, Siew TST, Khambadkone AM. Composite energy storage system involving battery and ultracapacitor with dynamic energy management in microgrid applications. IEEE Trans. Power Electron. 2011;26:923–30.
[74] Jamehbozorg A, Keshmiri SN, Radman G. PV Output Power Smoothing Using Energy Capacitor System. Proc. IEEE Southeastcon 2011:164–8.
[75] Sugihara H, Yokoyama K, Saeki O, Tsuji K, Funaki T. Economic and efficient voltage management using customer-owned energy storage systems in a distribution network with high penetration of photovoltaic systems. IEEE Trans. Power Syst. 2013;28:102–11.
[76] Rahman S, Tam KS. A feasibility study of photovoltaic-fuel cell hybrid energy system. IEEE Trans. Energy Convers. 1988;3:50–5.
[77] Datta M, Senjyu T, Yona A, Funabashi T, Kim CH. A frequency-control approach by photovoltaic generator in a PV–diesel hybrid power system. IEEE Trans. Energy Convers. 2011;26:559–71.
[78] Senjyu T, Datta M, Yona A, Sekine H, Funabashi T. A new method for smoothing output power fluctuations of PV system connected to small power utility. In: Proceedings of the 7th IEEE Internatonal Conference on Power Electronics; 2007: p. 829–34.
[79] Park J-S, Katagi T, Yamamoto S, Hashimoto T. Operation control of photovoltaic/diesel hybrid generating system considering fluctuation of solar radiation. Solar Energy Mater. Solar Cells 2001;67:535–42.
[80] Datta M, Senjyu T, Yona A, Funabashi T, Kim CH. A coordinated control method for leveling PV output power fluctuations of PV–diesel hybrid systems connected to isolated power utility. IEEE Trans. Energy Convers. 2009;24:153–62.
[81] Canever D, Dudgeon G, Massucco S, McDonald J, Silvestro F. Model validation and coordinated operation of a photovoltaic array and a diesel power plant for distributed generation. IEEE Power Eng. Soc. Summer Meet. 2001:626–31.
[82] Darras C, Muselli M, Poggi P, Voyant C, Hoguet J-C, Montignac F. PV output power fluctuations smoothing: the MYRTE platform experience. Int. J. Hydrog. Energy 2012;37:14015–25.
[83] Tesfahunegn SG, Ulleberg Ø, Vie PJ, Undeland TM. PV Fluctuation Balancing Using Hydrogen Storage–a Smoothing Method for Integration of PV Generation into the Utility Grid. Energy Proc. 2011;12:1015–22.
[84] Li X, Song Y-J, Han S-B. Frequency control in micro-grid power system combined with electrolyzer system and fuzzy PI controller. J. Power Sour. 2008;180:468–75.
[85] Li X, Song Y-J, Han S-B. Study on power quality control in multiple renewable energy hybrid microgrid system. IEEE Lausanne Power Tech 2007:2000–5.
[86] Wang C, Nehrir MH. Power management of a stand-alone wind/photovoltaic/fuel cell energy system. IEEE Trans. Energy Convers. 2008;23:957–67.
[87] Ina N, Yanagawa S, Kato T, Suzuoki Y, Smoothing PV. System's output by tuning MPPT control. IEEJ Trans. Power Energy 2004;124:455–61.
[88] Zarina P, Mishra S, Sekhar P. Exploring frequency control capability of a PV system in a hybrid PV-rotating machine-without storage system. Int. J. Electr. Power Energy Syst. 2014;60:258–67.
[89] Shafiu A, Bopp T, Chilvers I, Strbac G. Active management and protection of distribution networks with distributed generation. IEEE Power Eng. Soc. Gen. Meet. 2004:1098–103.
[90] Tonkoski R, Lopes L, Turcotte D. Active power curtailment of PV inverters in diesel hybrid mini-grids. IEEE Electr. Power Energy Conf. (EPEC) 2009:1–6.
[91] Tonkoski R, Lopes LA, El Fouly TH. Coordinated active power curtailment of grid connected PV inverters for overvoltage prevention. IEEE Trans. Sustain. Energy 2011;2:139–47.
[92] Lee YS, Wang WY, Kuo TY. Soft computing for battery state-of-charge (BSOC) estimation in battery string systems. IEEE Trans. Ind. Electron. 2008;55:229–39.
[93] Luan S-W, Teng J-H, Lee D-J, Huang Y-Q, Sung C-L. Charging/discharging monitoring and simulation platform for li-ion batteries. IEEE Region 10 Conference TENCON 2011: 868–72.
[94] Kim I-S. Nonlinear state of charge estimator for hybrid electric vehicle battery. IEEE Trans. Power Electron. 2008;23:2027–34.
[95] Coleman M, Lee CK, Zhu C, Hurley WG. State-of-charge determination from EMF voltage estimation: using impedance, terminal voltage, and current for lead-acid and lithium-ion batteries. IEEE Trans. Ind. Electron. 2007;54:2550–7.
[96] Kow KW, Wong YW, Rajkumar RK, Rajkumar RK. A review on performance of artificial intelligence and conventional method in mitigating PV grid-tied related power quality events. Renew. Sustain. Energy Rev. 2016;56:334–46.
[97] de la Parra I, Marcos J, García M, Marroyo L. Control strategies to use the minimum energy storage requirement for PV power ramp-rate control. Solar Energy 2015;111:332–43.
[98] Arabkoohsar A, Machado L, Farzaneh-Gord M, Koury R. The first and second law analysis of a grid connected photovoltaic plant equipped with a compressed air energy storage unit. Energy 2015;87:520–39.
[99] van Haaren R, Morjaria M, Fthenakis V. An energy storage algorithm for ramp rate control of utility scale PV (photovoltaics) plants. Energy 2015;91:894–902.