21th International Conference on Renewable Energies and Power Quality (ICREPQ'23)
Madrid (Spain), 24th to 26th May 2023
Renewable Energy and Power Quality Journal (RE&PQJ)
ISSN 2172-038 X, Volume No.21, July 2023

Optimal Allocation of Curtailment Level of PV Power Output in Different Regions in Consideration of the Reduction in Aggregated PV Power

N. Harag[1], C. T. Urabe[1], and T. Kato[1]

[1] Department of Electrical Engineering
Nagoya University
Furo-cho, Chikusa-ku, Nagoya, Aichi 464-8601 (Japan)
Phone number: +81527892108, e-mail: harag.noha.mamdouh.ali.hassan.w3@s.mail.nagoya-u.ac.jp, urabe.chiyori.c0@f.mail.nagoya-u.ac.jp, kato.takeyoshi.b5@f.mail.nagoya-u.ac.jp

Due to the extremely high penetration of photovoltaic power generation system (PV), the power output curtailment (Cr) of PV is necessary not only to maintain supply-demand balance but also to preserve enough capacity for the frequency control. Although the Cr level for the aggregated PV in the power system service area is determined in a day-ahead unit commitment (UC) scheduling, the Cr for individual PV with different weather conditions should be allocated so that the fluctuation of aggregated PV power output is minimized. Assuming that the short-term forecasting of individual PV power output fluctuations characteristics is available, the objective of this study is to propose methods for optimal short-term allocation of Cr level among each region. The proposed methods have proven their effectiveness in meeting the predetermined average PV power ouput as well as reducing the fluctuations of the overall system.

Key words Curtailment, Solar Radiation, Optimization, Radiation Fluctuations, and Unit Commitment

1. Introduction

Traditional synchronous generators are being replaced by renewable energy sources gradually. That causes electric power systems to become more susceptible to frequency fluctuations. PV is one of the most promising renewable power generation options. Surge in PV power generation system (PV) installation activity will cause significant voltage increase and frequency variations as a result of the climate-driven variations [1], [2].

Due to the increase of the installed PV capacity, the power utility will start to request additional services like frequency control. To keep the supply-demand balance, several steps have been made to reduce this behaviour associated with high PV penetration. Power curtailment (Cr) and energy storage are among these strategies. It is undeniable that energy storage system implementation costs are high [3] while power Cr is a more feasible method for forcing a planned output reduction in order to balance the supply and demand for electricity [4], [5].

The PV power output that can satisfy the electricity demand for each hour of the following day is determined by power system operators when they schedule the necessary generating resources for UC based on a day-ahead projection of electricity demand [6]. The UC scheduling also determines the total aggregated PV power output regardless of the fluctuating behaviours of each region in the power system. As a result, an additional adjustment to the Cr level will be needed. Also, to mitigate the overall fluctuations of the aggregated PV power output, the level of PV power output Cr can be allocated among each region. This will help to keep the frequency variations within the permitted bounds established by the grid codes.

Therefore, the main aim of this study is to propose the optimal short-term Cr level allocation across each region. It firstly provides the power needed to maintain a balance between supply and demand, i.e., the required amount of PV power at a given point in time, and secondly, helps mitigating the overall fluctuations of PV power output in different regions.

Many studies have been conducted to forecast the daily PV power output from different perspectives [7]-[9]. Short-term forecasting becomes more necessary with higher PV penetration, to ensure the required PV capacity is reached every hour of the operating day. Accurate short-term forecasting can lead to further adjustment of the Cr compared to the pre-determined Cr set by the UC scheduling. At present, short-term average solar irradiance forecasting is feasible [10]. Although predicting short-term fluctuations using various deep learning-based solar short-term forecasting models is studied, it is still a sophisticated approach with a significant amount of error [11].

Therefore, this study addresses this problem through a simpler approach, in which actual observed solar irradiance data is used to develop the relationship between the average solar radiation and Cr, and between the fluctuations and Cr. These statistical relationships will serve as a benchmark for adjusting Cr without knowing the exact time-series of short-term solar radiation data.

2. Cr Level Adjustment Methods

This study utilizes the time-series data of observed solar radiation in the central region of Japan. This data is utilized to develop a model that allocates the PV power output Cr in different regions. Since the capacity of the PV is known and constant, solar radiation data is used directly instead of the PV power output data. In this paper, solar radiation data of three regions are used to demonstrate the importance of the proposed methods. Also, the time horizon under investigation is one hour from 12:00 to 13:00 when the Cr usually applied during the day.

A. Proposed Method: Short term Adjustment of Cr based on short-term forecasting of average output only (Method-1)

The main purpose of this Method-1 is to obtain a resultant aggregated average solar radiation equal to the requested average solar radiation by the system operator in the short-term. In Method-1, in short-term such as few hours ahead, forecasting of PV power output in each region takes place. Hence, the adjusted Cr is allocated to each region distinctively based on the relation between Cr and the corresponding hourly average curtailed PV power output (Avg-Cr) modes as shown in Fig. 1.

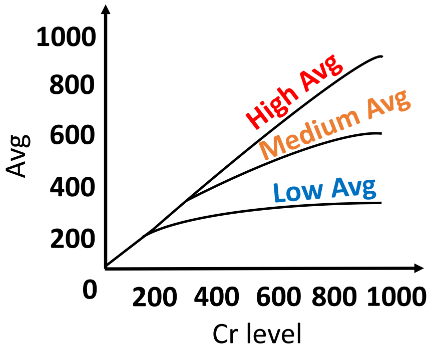

Fig. 1. Avg-Cr modes.

The Avg-Cr modes are prepared based on the analysis of the observed PV power output in the past. The three modes of Avg-Cr can be expressed to range from high Avg to low Avg modes. Thus, instead of exact Avg forecasting, the forecasting of the mode to which the value can be categorized is enough for the proposed method. By predicting Avg mode, Cr is adjusted and becomes more accurate compared to that determined a day-ahead. The Cr adjustment procedures of Method-1 are composed of two main steps: preparation of Avg-Cr patterns and the utilization of these patterns to apply Cr level adjustment methods on the day of operation.

B. Proposed Method: Short term Adjustment of Cr based on short-term forecasting of average output and fluctuations (Method-2)

The main purpose of Method-2 is to minimize the total fluctuations of the resultant aggregated solar radiation as long as the predetermined average solar radiation is met. Cr adjustment in this method undergoes a more advanced approach than Method-1 by considering the solar radiation fluctuations directly. Despite the fact that the forecasting of actual fluctuations is challenging, the forecasting of typical fluctuation patterns can be available. The relations between Cr level and the corresponding hourly maximum fluctuations (MF-Cr) shown in Fig. 2 are also prepared for typical four PV power output conditions based on the analysis of the observed PV power output in the past.

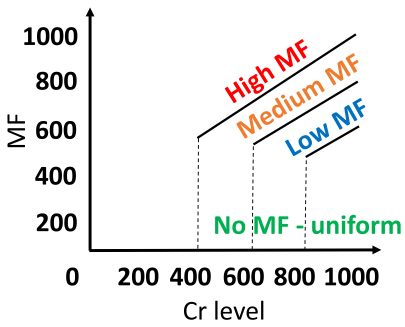

Fig. 2. MF-Cr modes.

The four patterns of MF-Cr can be expressed to range from high MF to no MF (i.e. uniform output) modes. Thus, instead of exact MF and Avg forecasting, the forecasting of the mode to which the values can be categorized is needed. By predicting both the MF and Avg modes, Cr is adjusted and becomes more accurate compared to that determined a day-ahead and Method-1. The two main steps of preparation of Avg-Cr and MF-Cr, and the utilization of both Avg-Cr and MF-Cr patterns to apply the Cr adjustment methods on the day of operation.

C. Same Cr for all regions (Method-3)

When the Cr is requested by the UC scheduling a day-ahead, the same Cr is equally applied to all the regions in the power system regardless of each region's PV power output. Consequently, this might lead to unsatisfying the the PV power output scheduled by the UC to meet the demand.

D. Short term Adjustment of Cr based on perfect forecasting of average and fluctuations (Method-4)

In Method-2, short-term forecasting of Avg modes and MF modes are addressing a simple categorization of the regions. In Method-4, it is assumed that the perfect short-term forecasting of the time-series of solar radiation in each region is available. This kind of zero-error forecasting is challenging and nearly impossible. Therefore, Method-4 is assumed to be an ideal situation

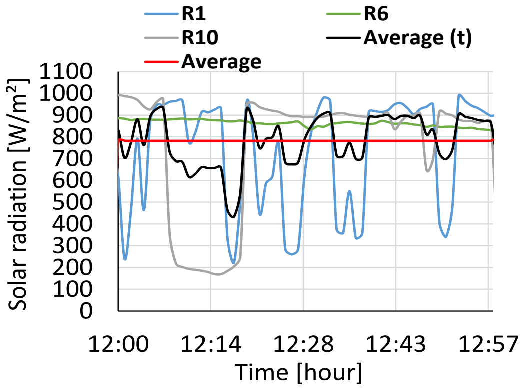

Fig. 3. Solar radiation data of the three regions; R1, R6 and R11.

and merely used for comparison with the proposed methods.

3. Data Preparation for the Proposed Methods (Method-1 and Method-2)

The data preparation procedure of the proposed methods includes forming the representative patterns for one hour from 12:00 to 13:00 in September. Three regions are used to demonstrate the concept and calculation output in each step. Fig. 3 shows the raw time-series solar radiation data of the three regions on 1st September and the average solar radiation. Their different solar radiation behaviors are identified as the following:

- Region (R) 1 has a high Avg and moderate fluctuations.
- R11 has a high Avg and no fluctuations, i.e. uniform solar radiation.
- R29 has a high Avg and low fluctuations.

A. Method-1

1) Application of different Cr levels

Different Cr levels are applied on the observed solar radiation data ranging from 0 to 1000 W/m^2. No Cr is applied at 1000 W/m^2 level and 100% of Cr is applied at 0 W/m^2 level. In Fig. 4, Cr levels ranging from 100 W/m^2 to 1000 W/m^2 are applied to R1 as an example. Then the average solar radiation (Avg) of every curtailed data will be plotted against each Cr level as in Fig.6.

2) Computation of Avg at every Cr level for all the regions

In Fig. 6, the actual Avg-Cr patterns of the three regions are shown. Then, similarly the Avg-Cr patterns for all the regions in the central region of Japan at one hour (here, 12:00-13:00) for the entire month of September are calculated.

3) Formation of the representative patterns of Avg-Cr

The Avg-Cr patterns of the all the regions of central Japan for 30 days for one hour are stacked (over than 1500 patterns). Then, this stack is divided into three modes; mode 1 is low radiation average, mode 2 is moderate radiation average and mode 3 is high radiation average. We average the patterns that lies in each mode to get a single representative Avg-Cr pattern for each mode as

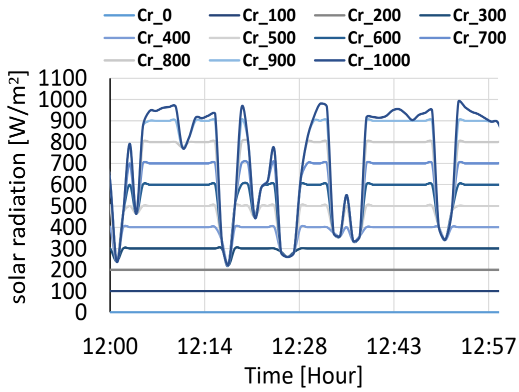

Fig. 4. The curtailed data of R1.

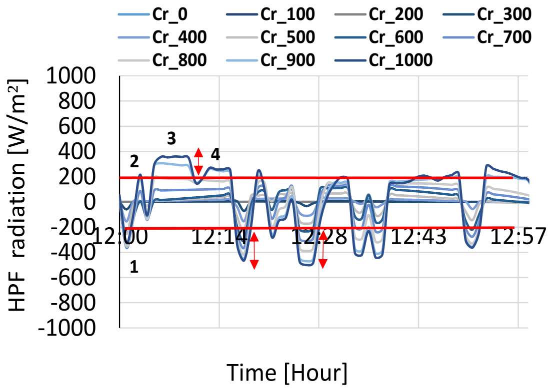

Fig. 5. The HPF data of R1.

shown in Fig. 8. Since predicting the actual pattern of average solar radiation for the next hours can be challenging, then by just forecasting the mode of the average radiation for the next hour, the representative pattern of Fig. 8 can be used instead of the actual pattern in Fig. 6. Then optimization will be operated using these representative patterns.

B. Method-2

1) Application of different Cr levels

Same as Method-1

2) Application of high-pass filter (HPF) on every curtailed data

Using the curtailed data, HPF function is applied with a cut-off frequency of 32 minutes. This is implemented to highlight the fluctuations. Fig. 5 shows an example of the HPF data applied on the curtailed data of R1.

3) Computation of maximum fluctuation (MF) using the HPF data based on few parameters.

The MF is the difference between the maximum and minimum point of fluctuations calculated in 20 minute-moving-window and this parameter represents the short-cycle fluctuation in the time-series data. To consider whether a region's solar radiation behaviour is fluctuating or not, this study sets some parameters to distinguish the fluctuating behaviour such as threshold, count and range. Firstly, the threshold is an initially assumed value of solar radiation. When the fluctuations cross this value (here, 200 W/m^2) for number of times

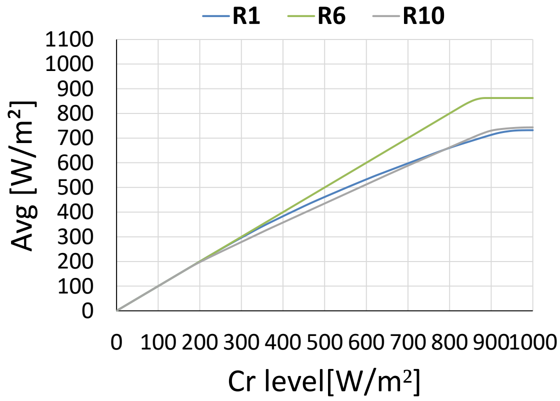

Fig. 6. The actual Avg-Cr modes of R1, R6 and R10.

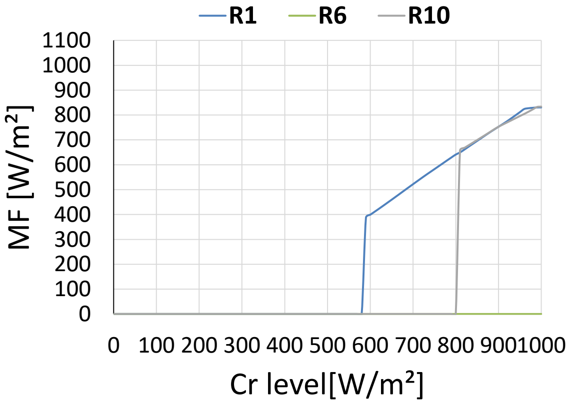

Fig. 7. The actual MF-Cr modes of R1, R6 and R10.

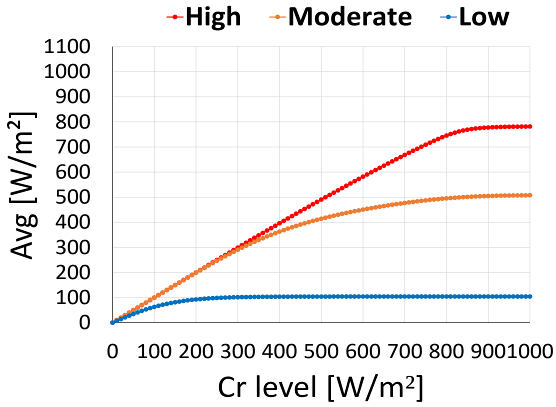

Fig. 8. The representative Avg-Cr modes.

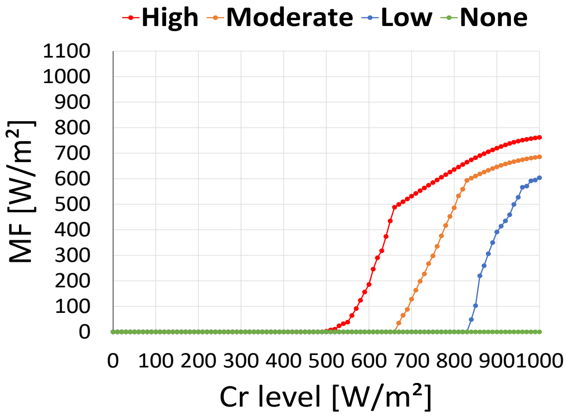

Fig. 9. The representative MF-Cr modes.

(Count) shown in Fig. 5, they get recorded. In addition, the range which is the sum of the heights of crossing fluctuations, crossings can be frequent and very short in terms of radiation changes, therefore, recording the sum of radiation changes when fluctuations cross the threshold is essential.

When the solar radiation changes comply with the pre-set number of count and range, it is characterized as fluctuating. Consequently, MF is calculated against each corresponding Cr level. As the threshold is 200 W/m^2, Count is 3 and Range is 200 W/m^2, the MF for the three regions at every Cr level is plotted in Fig. 7.

4) Formation of representative patterns of MF-Cr

The MF-Cr patterns of the all regions in central Japan for 30 days for one hour (over 1500 patterns) are stacked. Then, this stack is divided into four modes; mode 0 is zero fluctuations (uniform output), mode 1 is low fluctuations, mode 2 is moderate fluctuations and mode 3 is high fluctuations. We average the patterns that lies in each mode to get a single representative MF-Cr pattern for each mode as shown in Fig. 9.

Since predicting the actual pattern of fluctuation for the next hours can be challenging, then by just acknowledging the modes of fluctuations for the next hour, the representative pattern of Fig. 9 can be used instead of the actual pattern in Fig. 7. Then optimization will be operated using these representative patterns.

4. Application of the Cr Adjustment Methods on the Day of Operation and its results.

The time horizon under investigation on the day of operation is 1 hour from 12:00 to 13:00 on the 1st of September 2010 when is Cr is applied on the three regions R1, R6 and R10. The assumed predetermined average solar radiation is 700 W/m^2.

A. Method-1

At the actual operation, the short-term forecast of average solar radiation will provide information such as R1. R6 and R10 have high Avg, they will be given the representative Avg-Cr that were prepared previously and their patterns are shown in Fig. 8. Using these distinctive patterns for each region, Cr levels will be optimized among each region to minimize the gap between the predetermined aggregated average and the resultant aggregated average based on the different possibilities of allocated Cr levels.

As a result of the optimization, Fig. 10 shows the Cr levels allocated on the three regions where R11 and R61 of the high Avg and relatively lower MF than R1 did not experience Cr. While R1 of high Avg and high MF

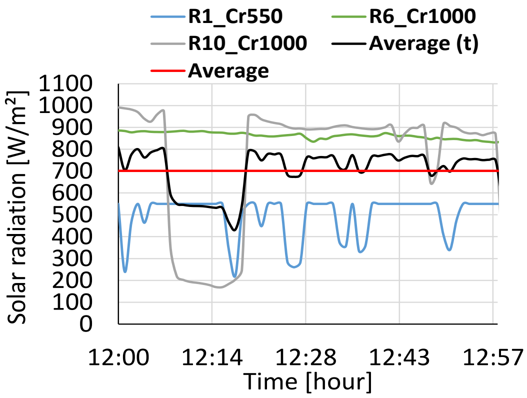

Fig. 10. Cr adjustment based on Method-1.

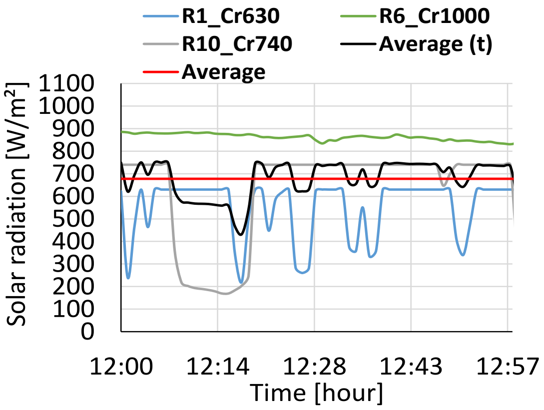

Fig. 11. Cr adjustment based on Method-2.

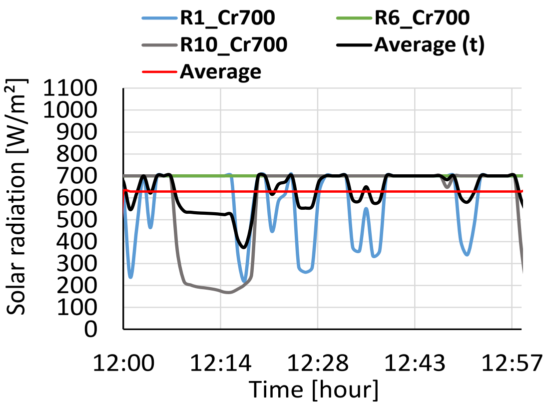

Fig. 12. Cr adjustment based on Method-3.

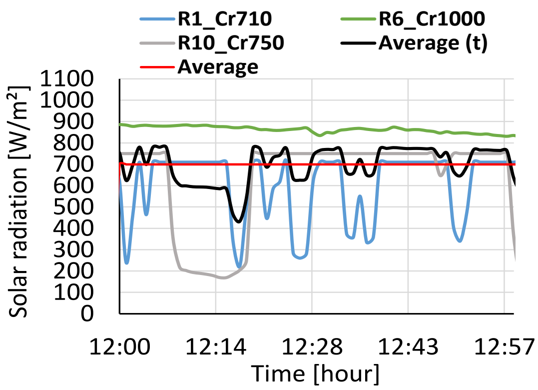

Fig. 13. Cr adjustment based on Method-4.

experienced Cr. This is because this Method indirectly suppress MF even if all the Avg modes are the same.

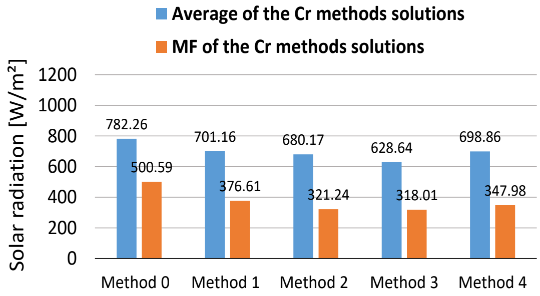

Fig. 14. Average and MF of all the Methods' Cr solutions.

B. Method-2

At the actual operation, the short-term forecast of fluctuations will provide the information that R1 has high fluctuations, R6 has no fluctuations, and R10 has moderate fluctuations, they will be given the representative MF-Cr that were prepared previously and their patterns are shown in Fig. 9. Using both the distinctive patterns of MF-Cr and Avg-Cr for each region, the Cr levels will be optimized among each region. The optimization objective is to minimize the total fluctuations of the aggregated PV based on the different possibilities of allocated Cr levels as long as the predetermined average is achieved.

As a result of the optimization, Fig. 11 shows the Cr levels allocated on the three regions where R1 of the high MF experienced the most Cr (i.e. the lowest Cr level) while R6 of moderate MF experienced Cr and R6 of zero fluctuations (i.e. uniform solar radiation) was not curtailed.

C. Method-3

In this method the same Cr is applied to all regions as it was predetermined a day-ahead by UC scheduling neglecting the behaviour of the solar radiation data. In Fig. 12, it shown that the three regions have the same Cr level.

D. Method-4

As a result of the optimization on the actual operation day, Fig. 13 shows the results of Cr level when perfectly forecasting their solar radiation of the three regions. R1 is the most curtailed, followed by R10 then R6 that was not curtailed. Comparing the proposed method-2 and method-4, the Cr levels are nearly the same which validates that the proposed method that follows a simple approach has nearly the same influence on the adjustment of Cr level as the ideal method-4.

E. Discussion

The purpose of Fig. 14 is give an overview on the average and MF of all the methods solutions using the three regions. The comparison between the methods shows that:

- Method-0 is the solar radiation data with no Cr and it has the highest average that is the most deviated the predetermined average solar radiation and the highest MF.
- Method-1 has the closest average to the predetermined value of 700 W/m^2 and lower MF compared to Method-0 because the priority of this method is not meet the predetermined average.
- Method-2 has close average to the predetermined and very low MF since the purpose of this method is to meet the predetermined average as well as reducing the fluctuations.
- Method-3 has furthest resultant average from the predetermined average and the lowest MF due to the severity of Cr applied.
- Method-4 has close average to the predetermined average and low MF because of the perfect forecasting of solar radiation. It is noted that this method is used for the purpose of comparison only.

5. Conclusion

PV power output Cr is determined a day-ahead by UC scheduling in the current power system. In order to advance the Cr adjustment and allocation in each region, the proposed methods use the past data of solar radiation to form Avg-Cr and MF-Cr functions. Hence, knowing the modes of Avg and MF of each region, Cr levels can be allocated to meet the aggregated power requirement and mitigate the total fluctuations of the regions in the power system. Although forecasting regions characteristics such as fluctuation level can be challenging, the accuracy of a few hours ahead forecasting will be improved for the future by using the multi-points observations, satellite image, etc.

References

[1] Rajiv K. Varma, “Impacts of high penetration of solar PV systems and smart inverter developments”, in Smart Solar PV Inverters with Advanced Grid Support Functionalities, IEEE, (2022), pp.1–34, doi: 10.1002/9781119214236.ch1.

[2] T. Aziz and N. Ketjoy, “PV Penetration limits in low voltage networks and voltage variations”, IEEE Access, (2017), pp. 16784–16792, doi: 10.1109/ACCESS.2017.2747086.

[3] D. Kim, H. Kim and D. Won, “Operation strategy of shared ESS based on power sensitivity analysis to minimize PV curtailment and maximize profit”, IEEE Access, (2020), pp. 197097–197110, doi: 10.1109/ACCESS.2020.3034339.

[4] J. M. Riquelme-Dominguez and S. Martinez, “A photovoltaic power curtailment method for operation on both sides of the power-voltage curve”, Energies, (2020), p. 3906, doi: 10.3390/en13153906.

[5] S. Ghosh, S. Rahman and M. Pipattanasomporn, “Distribution voltage regulation through active power curtailment with PV inverters and solar generation forecasts”, IEEE Transactions on Sustainable Energy, (2017), pp. 13–22, doi: 10.1109/TSTE.2016.2577559.

[6] L. Montero, A. Bello, and J. Reneses, “A Review on the unit commitment problem: approaches, techniques, and resolution methods”, Energies, (2022), p. 1296, doi: 10.3390/en15041296.

[7] H. Sangrody, N. Zhou and Z. Zhang, “Similarity-Based Models for Day-Ahead Solar PV Generation Forecasting”, IEEE Access, (2020), pp. 104469-104478, doi: 10.1109/ACCESS.2020.2999903.

[8] T. Masuta et al., “Evaluation of unit commitment based on intraday few-hours-ahead photovoltaic generation forecasts to reduce the supply-demand imbalance,” Proceedings of the 8th International Renewable Energy Congress (IREC), (2017), pp. 1–5, doi: 10.1109/IREC.2017.7926001.

[9] L. Gigoni et al., “Day-ahead hourly forecasting of power generation from photovoltaic plants”, IEEE Transactions on Sustainable Energy, (2018), pp. 831–842, doi: 10.1109/TSTE.2017.2762435.

[10] W. Hu, X. Zhang, L. Zhu and Z. Li, “Short-term photovoltaic power prediction based on similar days and improved SOA-DBN model”, IEEE Access, (2021), pp. 1958–1971, doi: 10.1109/ACCESS.2020.3046754.

[11] C. -J. Huang and P. -H. Kuo, “Multiple-input deep convolutional neural network model for short-term photovoltaic power forecasting”, IEEE Access, (2019), pp. 74822–74834, doi: 10.1109/ACCESS.2019.2921238.