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Investigating the Voltage Fluctuation Caused by Solar PV Generation Variability in Distribution Grids

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SUMMARY

Renewable energy resources, particularly solar generation, are experiencing a rapid proliferation in power systems, thus forcing system operators to look at various solutions in order to integrate these resources. This proliferation, however, poses a set of new challenges in power grid operation and planning, mainly due to the inherent variability and uncertainty characteristics associated with certain generation technologies. The generation variability of solar photovoltaic (PV) is caused by changing cloud cover and is mainly seen as large ramp rates, i.e., the rate at which a generation output of a unit changes. The ramp rate limit in this paper is set to be 10%/min of the rated capacity. The solar generation variability can potentially cause voltage variations in the distribution grid. This paper investigates the effect of the solar PV large ramp rate in the operation of the IEEE 33-bus test system. A one-hour time horizon with a resolution of 1 minute of solar PV output has been used to investigate the possible voltage fluctuations caused by the solar generation ramp rate. The simulation results show that mitigation of the ramp rate can reduce the standard deviation in daily voltage values by almost 23% compared to the case when the ramp rates are not mitigated.

KEYWORDS

Solar photovoltaic, ramp rate, global horizontal irradiance (GHI).

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1. INTRODUCTION

The environmental concerns associated with the fossil fuels, have contributed to rapid deployment of renewable generation resources, solar PV in particular, in recent years. The declining cost of the solar PV, on the other hand, has accelerated a widespread deployment of this technology. In the first quarter of 2017, a total of 2 GW of solar PV was installed in the U.S., following exceptional capacity growth of more than 15 GW in 2016. Figure 1 depicts the quarterly installed solar PV in the U.S. form 2012 to 2017. In 2016, solar generation was ranked as number one newly-added generation, representing 39% of the new capacity [1]. Utility solar PV is considered a major growth driver. In the first quarter of 2017, more than half of the newly-added capacity came from the utility solar PV, reaching a total capacity of 1.1 GW. It is further estimated that solar energy will provide 28% of all global energy used in 2040, making it the most significant energy source by then [2].

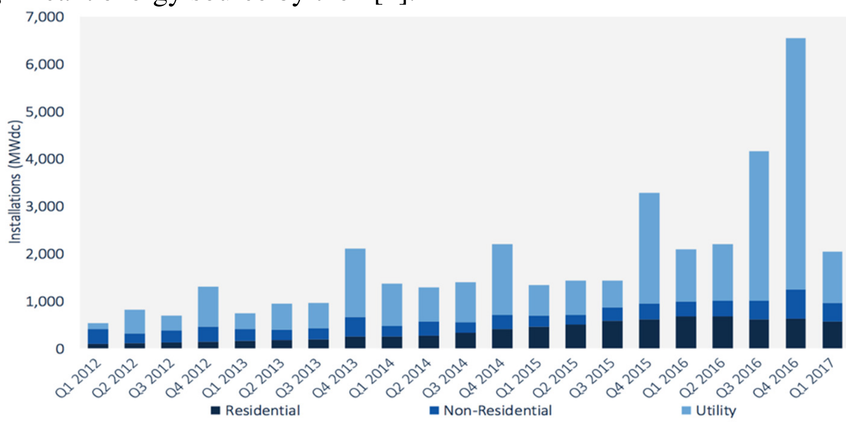

Fig. 1 Quarterly solar PV installation in the U.S. [1]

The installation of solar PV at both distribution and transmission levels has been streamlined due to considerable enhancements in power electronics. However, at high penetration levels the market value of this resource drops as discussed in [3]. The paper reveals that the value of solar can decline up to 50-80% at 15% penetration. It further discusses various integration options in order to mitigate the drop in the variable generation value. Three factors that negatively impact solar, especially at high penetration levels, are listed in [4] as the low capacity credit, the reduction in utilizing dispatchable resources, and the over generation produced by variable generation.

The negative impacts of solar generation in transmission and distribution result from two key characteristics: the variability and uncertainty of solar generation. The first characteristic is the intermittent supply in solar generation due to solar irradiance variations and other metrological factors such as the movement of the clouds. The second one is the difficulty to predict in advance the time, the duration, and the magnitude of this variability [5]. These two characteristics must be managed by the power system operator to maintain the system adequacy and reliability, while minimizing the curtailment from solar generation. In [6], a study presents the value of solar PV with the use of energy storage to ensure the availability of the solar power throughout the day and to reduce the variability to allow solar generation to be integrated into the grid with less curtailment.

Solar PV is considered a non-dispatchable energy source due to its output variability. Therefore, large-scale solar PV integration may cause instability and power quality issues in power systems due to fluctuations in generation output. Power system operators should be ready to clear any imbalances in the power system caused by under/over generation from solar PV by dispatching other dispatchable resources, utilizing demand response, and/or curtailing the PV generation. These solutions commonly result in a higher operational cost. Solar forecasting is considered a solution for predicting solar generation variability; however, it greatly depends on the forecasting accuracy, especially at high resolutions. The energy storage system is also proposed as a solution to capture solar PV fluctuations. In [7], the author studies the solar PV fluctuation and determines the sizing requirements for an energy storage unit to mitigate its fluctuation. A 1.2 MW PV in Hawaii is studied in [8] to investigate the effect of the unmitigated ramp rate. The study has revealed that the ramp rate could reach up to 63%/minute of the rated capacity. The integration of the electric vehicle chargers can improve the solar PV integration into the grid by reducing the solar PV output ramp rate as explained in [9]. Hundreds of distributed batteries are used in a control algorithm that was designed in [10] to smooth the PV generation. The trade-off between the smoothing and the size of the energy storage is also discussed. The Puerto Rico Electric Power Authority (PREPA) has included a ramp rate limit of 10%/min of the rated capacity for both wind and solar generation. Likewise, the Germany transmission and distribution operator has imposed the same ramp rate limit [11].

This paper investigates the impact of solar ramp rate on the IEEE 33-bus test system by integrating a 1.04 MW solar PV system. The paper exhibits the changes in the voltage when the ramp rate limitation has been applied to solar output. The ramp rate limitation is 10%/minute of the installed capacity. The system is studied for one selected hour, representing the highest ramps. The rest of the paper is organized as follows: Section 2 presents the data analyses for solar PV generation and ramps. Section 3 exhibits the numerical simulation; and section 4 concludes the paper.

2. DATA ANALYSES

The solar irradiance and generation with different ramp rates of one cloudy day is shown in Figure 2(a). It is clear from the figure that ramps are small in morning and evening hours due to clear weather conditions. However, ramp rate in the middle of the day is high due to solar irradiance variability. Passing clouds can cause ramp rates to reach up to 500 kW/min as shown in Figure 2(b). Ramp rate can be calculated under different time scales using (1). The ramp rate should be curtailed at a maximum of 10% of the installed capacity in this work.

$$RR = \left| \frac{P(t) - P(t + \Delta t)}{\Delta t} \right| \tag{1}$$

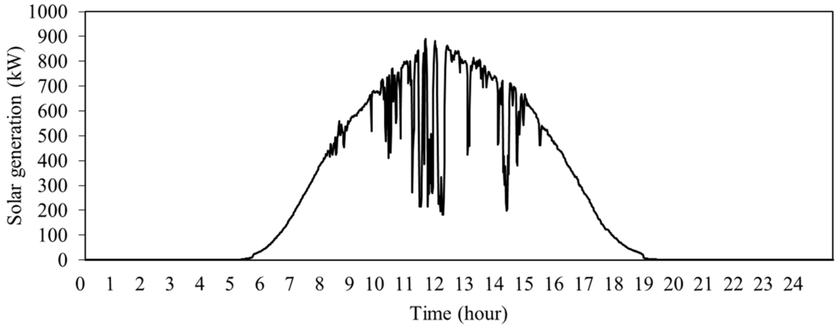

Fig.2 (a) One-minute resolution solar generation.

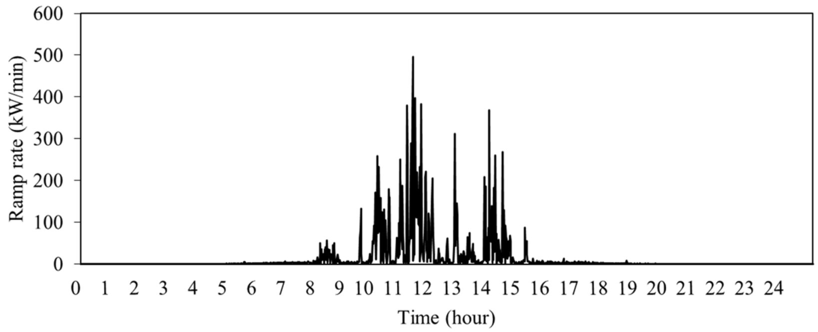

Fig. 2(b). One-minute resolution solar generation ramp rate.

3. CASE STUDY

Figure 3 depicts the total number of the ramps that exceeded the ramp rate limit. A total of 49 ramps is experienced when the ramp rate limit is set to 10%/min of the installed capacity where 37% of these ramps have occurred between 11:30 AM and 12:30 PM. If the ramp rate limit is set to 20%/min of the total installed capacity, the total number of ramps is reduced to 20. After 40%/min ramp rate limit, the number of violations is zero. Figure 4 exhibits actual solar generation and ramp rate along with the mitigated solar generation and ramp rate for the time between 11:30 and 12:30.

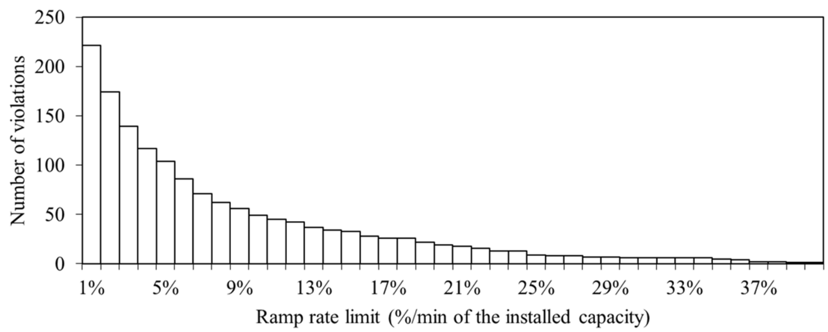

Fig. 3 The number of ramp rate volitions as ramp rate limit increases.

In order to investigate the impact of solar power ramp rate mitigation, the IEEE 33-bus test system shown in Figure 5 is used to run the power flow for a selected hour (11:30am to 12:30pm) and calculate the voltage changes at each bus. A 1.04 MW solar PV is connected to bus 18. The load is considered to be constant at this hour, with a value of 5.6 MW. It is assumed that solar has no voltage control. The following cases are studied:

Case 1: Voltage deviation at each bus without solar generation ramp rate mitigation.

Case 2: Voltage deviation at each bus with solar generation ramp rate mitigation.

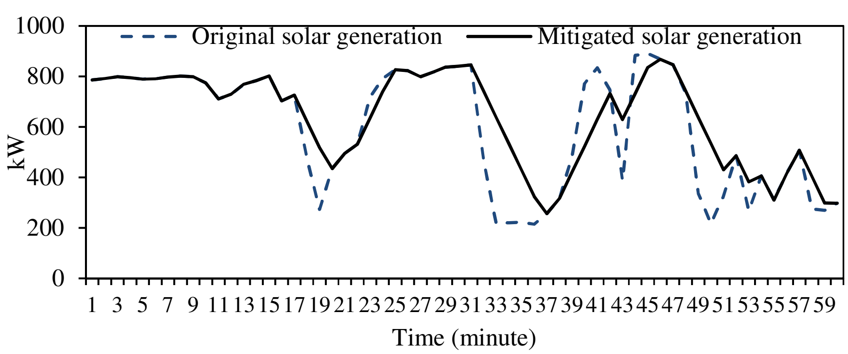

Fig. 4(a) Original solar generation vs. mitigated solar generation

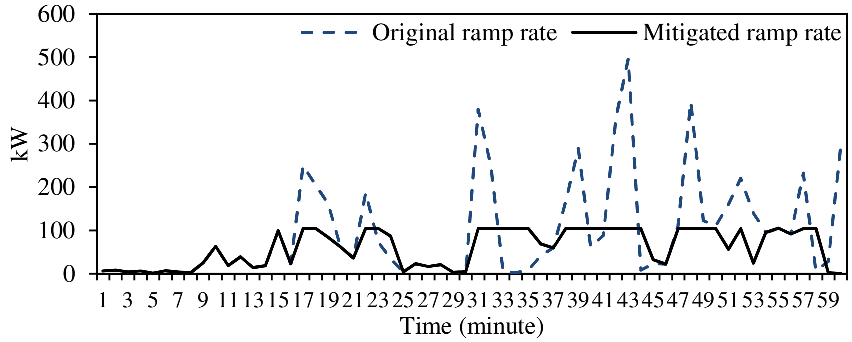

Fig. 4(b) Ramp rate vs. mitigated ramp rate

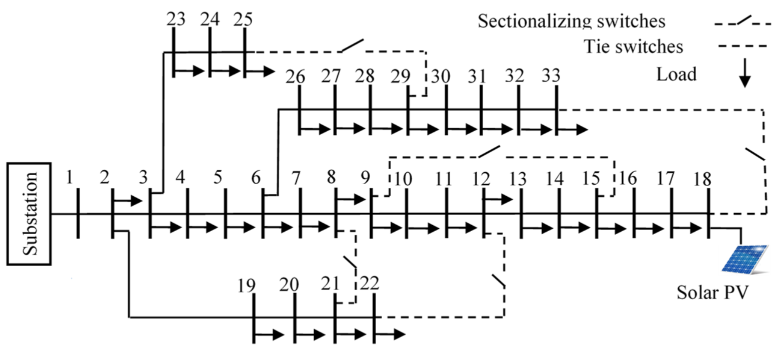

Fig. 5 IEEE 33-bus test system with PV connected to bus 18

The solar generation is adjusted as in Figure 4(a) to mitigate the solar generation ramp rate. It is assumed that ramp rate, with negative and positive slopes, is corrected by charging and discharging the energy storage to reduce the ramp rate to a maximum of 104 kW/min. The energy storage sizing requirement is ignored in this paper assuming that the existing energy storage is optimally sized and placed to limit and capture the solar ramp rate of larger than 104 kW/min. In [12] the solar gneration ramp rate is mitigated by controling the voltage using a capcitor. Other techinques can be used to mitigate the solar generation ramp rate, which are not discussed in this paper.

Case 1: Voltage deviation at each bus without solar generation ramp rate mitigation

Figure 2(b) depicts the ramp rate for a selected day. The highest ramp rate occurs between 11:30am and 12:30pm where the ramp rate has reached 496 kW/min. To run the simulation, the solar generation data for the hour in Figure 4(a) is selected as solar generation connected to bus 18. The solar generation is considered in this study with unity power factor so no reactive power is generated by the solar PV. In this hour, 18 violations to ramp rate limit, which is 104 kW/min, have been recorded. The power flow is simulated under this case without mitigating the ramp rate. Table 1 depicts the standard deviation for each bus over the hour and the highest deviation is on bus 18 where the PV is connected. In the simulation, bus one is considered an infinite bus with the bus voltage fixed to 1 pu. All the buses are still within the voltage limits used in the power flow. Figure 6 illustrates the changes in the voltage at bus 18 for each minute. It is clear that the trend for changes in voltage at bus 18 follows the ramp rate trend.

Table 1: Standard Deviation for the voltage at each bus – Case 1

Bus#	Standard deviation	Bus#	Standard deviation	Bus#	Standard deviation	Bus#	Standard deviation
2	0.000159	10	0.008644	18	0.018148	26	0.003724
3	0.001008	11	0.008964	19	0.000159	27	0.003738
4	0.001635	12	0.009573	20	0.000160	28	0.003800
5	0.002286	13	0.011965	21	0.000160	29	0.003846
6	0.003713	14	0.012846	22	0.000160	30	0.003865
7	0.004048	15	0.013790	23	0.001013	31	0.003888
8	0.005222	16	0.014973	24	0.001023	32	0.003893
9	0.006924	17	0.017006	25	0.001027	33	0.003895

Case 2: Voltage deviation at each bus with solar generation ramp rate mitigation
Under this case, the solar generation ramp rate is mitigated as shown in Figure 4(b) and limited to 104 kW/min. The ramp rate mitigation reduces the standard deviation in the voltage at each bus compared to case 1. Bus 18 still has the highest standard deviation, but it is reduced by almost 23% compared to Case 1. The buses closest to PV have experienced a bigger reduction in the standard deviation compared to the ones that are further from PV. Results further indicate that standard deviation increases gradually as buses get closer to bus 18.

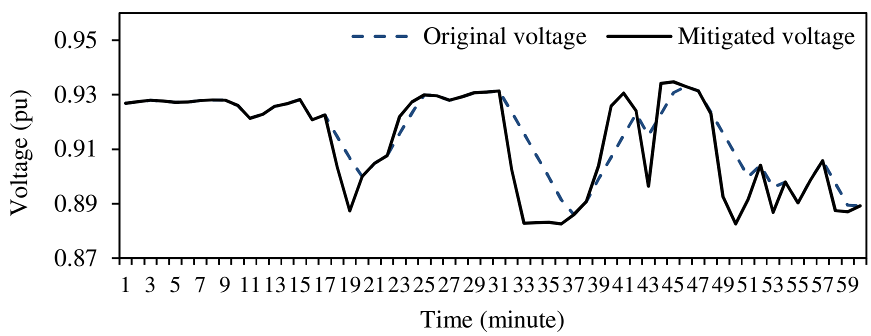

Fig. 6 Voltage at bus 18 with/without ramp rate mitigation.

4. CONCLUSION

In this paper, the effect of the solar generation ramp rate was investigated in the IEEE 33-bus test system. The power flow was simulated under two different cases. In the first case, the solar ramp rate was not mitigated while in the second case the solar generation ramp rate was mitigated to limit the ramp rate<10%/min of the installed capacity. The solar generation between 11:30am and 12:30pm had the highest ramp rate. A total of 18 violations to ramp rate limit have occurred at this hour. The ramp rate mitigation reduced the standard deviation for bus 18 where the PV is connected by almost 23%. In the case of higher solar penetration, the solar ramp rate may cause a negative impact on the system voltage. The literature presented different studies to mitigate the solar generation ramp rate, thus reducing any deviation caused in the system voltage, especially at the bus where the PV is connected.

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