Distribution Grid Parameter Variation due to Solar PV Power Integration

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Abstract- Photo-Voltaic (PV) power is rapidly improving at a gross annual rate and is also rapidly becoming a key part of the integrated distribution network. The increasing penetration of solar PV over the distribution grid also presents new challenges for distribution engineers. The conventional distribution system was designed and operated for unidirectional power flow from the utility source to the end-use loads. The intermittent nature of the solar PV output and higher penetration forces the regular tap change of the On-Load tap Change Transformer (OLCT), sudden voltage rise, miscoordination of the relay, significant short-circuit current deviation and increased harmonic distortion. The presented paper analyses the effects of Distributed Generation (DG) penetration on-grid parameters. Modified IEEE 13 node test system has been simulated to tabulate & analyse the change in fault current level, Total Harmonic Distortion (THD) and effect on power quality.

Keywords: Voltage variation, Total Harmonic Distortion (THD), short-circuit current, fault current analysis, power losses, power factor, IEEE 13 node feeder.

1. Introduction

The use of green energy technologies has increased every year over the last decade. The objective of Renewable Power Sources (RPSs) is to achieve an improvised integration of RESs into the technical and economic power system technology while at the same time reducing the need to sustain increased demand in the future and reduce future CO2 emissions. Such innovations, while pollution-free, have a few problems with the integration of RPSs into the power system network. For example, some forms of RPS, such as photovoltaic (PV) and wind generation, may cause the power system to oscillate at voltage and frequency. This is because these kinds of RESs are inherently unpredictable. The electrical system poses new challenges to intermittent sources, particularly photovoltaic ones. Also, the implementation of PVs in electrical power systems causes several problems for electrical engineers, including power efficiency, power imbalance, voltage variance and frequency between generation and load demand [1][2][3][4][5]. Photovoltaics is the third-largest source of renewable energy for globally installed electricity, based on hydro and wind power. These research studies are carried out to study the adverse impacts of high PV penetration on the distribution grid.

This paper examines the extensive implementation of distributed photovoltaic power at the end of the end-user. The individual PV systems are dispersed in and connected to the distribution network in consumer nodes. The study included six different levels of penetration. Bus voltage, system loss, THD compensation, short-circuit level are the main parameters used to estimate the impact of PV on the distribution system.

Power quality is a vital factor in the distribution system, which should remain within bounds. The lousy power quality might lead to below ranked and may affect the lifespan of the system equipment. Extensive penetration of RPS is a bonus for higher power demand but might result in problematic towards power high-quality issues [6][7].

Intermittent nature of PV and integrated inside a circulation network, create wavering of voltage and voltage unbalance of capricious nature. The significant variation between PV output voltage and bus voltage creates the issues of voltage rise, unbalance loading, flicker in the working system and poor power quality. Therefore, Distribution System Operator (DSO), plays a vital role to maintain the grid performance, especially when the massive penetration of solar PV get injected into the system [6][8][9][10][11]. Moreover, the extensive integration of PV generators increases the short circuit capacity of the system and Total Harmonic Distortion (THD). The increase in short circuit current & harmonic variations has a straight impact on coordination of protection devices. PV inverters are the chief culprits for the increase in THD, because of semiconductor devices [12][9]. As per IEEE 519 standards [13] [14], the permissible limit of THD is 20% in the network. If the THD exceeds the permissible value, it can damage the protection device and malfunctioning may occur.

Protection is a vital part of the power system network, which is essential to maintain system healthy, but the rise in short circuit level creates a change in the performance of Directional Overcurrent Relay (DOCR) and leads protection miscoordination [15][16][17]. Many techniques have been developed to bring down the short circuit current level within the proper functioning limit of the protection scheme [18]. FCL technique is one of them which help to reduced short circuit current amount and lifespan of gears is also maintained[19] [20][21].

This paper presents the penetration effect of PV on-grid in terms of voltage variation, power quality and change in short circuit current level. The organization of the paper is as follow, section 1, presents the load flow studies of the IEEE 13 node feeder for PV connected cases. Section 2, presents the impact of solar PV plant on power grid voltage. In section 3, power loss variation concerning the various level of solar PV penetration are depicted. Section 4, presents the impact of solar PV plant on the power factor of the distribution grid. In section 5, variation in THD due to distributed solar PV generation has been discussed. Section 6, presents the impact of distributed solar PV generation on the level of short-circuit current.

2. Load flow analysis

The IEEE 13 node feeder network has been considered for investigation, which operates at 4.16 kV line to line voltage [22]. The total associated operating load in the system is 3.4 MW and the reactive load is 2.1 MVAR. The load flow analysis was performed using the ETAP simulation software. The gauss seidel algorithm was used as a reference to examine the results. Figure 1, shows that the solar PV plant is connected to the IEEE 13 node distribution feeder on nodes 680,675 and 634. The solar PV penetration level on three nodes is assumed to be the total load on the IEEE 13 node feeder in the ratio of 1(680):1(675):2(634). The total energy consumption used by the renewable energy source in the network. The six different levels of power injection considered for analysis are as follows:

Case 1: The contribution from solar PV is zero per cent.

Case 2: The solar PV contribution is 20% of the active load connected to the system.

Case 3: The solar PV contribution is 40% of the active load connected to the system.

Case 4: The solar PV contribution is 60 per cent of the active load connected to the system.

Case 5: The solar PV contribution is 80 per cent of the active load connected to the system.

Case 6: The solar PV contribution is 100 per cent of the active load connected to the system.

Case 1 refers to the base case where the solar power contribution is zero. Load flow calculation has been performed at each penetration level on the ETAP platform and the grid performance was observed. The parameters to be considered are voltage variation, power factor, power loss calculation. Voltage variation in each case is shown in figure 2, and the voltage of each bus is shown to increase with an increase in solar PV penetration [17][6][18].

Table 1, shows the Solar PV-injected power level in all six cases. The total active and reactive load connected to the system is 3466 kW and 2102 kVAR. Table 2 shows the voltage value of each case for solar PV (PV1, PV2, PV3) which is used as "PV1: PV2: PV3: 1:1:2" penetration. 1:1:2 way of penetration is considered here because we want to analyses the realistic conditions for solar PV penetration on distribution gird.

Systems are assumed to be balanced and thus to represent a single line diagram. The solution of load flow needs to build a matrix for admittance (n x n), where n is the system number. the diagonal elements of the admittance matrix or show self-admittance of the bus and the off-diagonal reflect mutual admittance between buses.

$$Y = \begin{bmatrix} Y_{11} \dots \dots \dots . Y_{jk} \\ \dots \dots \dots \dots \dots . \\ \dots \dots \dots \dots \dots \dots \\ Y_{kj} \dots \dots \dots \dots Y_{kk} \end{bmatrix} \tag{1}$$

Actual and reactive power determined by the initial Gauss Sidle and the specified voltage magnitude and angle of the particular bus. This non-linear equation (Gauss Sidle and Newton Raphson) has been solved by iteration methods. The real and reactive power as calculated [23][24] :

$$P_K^{C(x)} = \sum_{j=1}^{n} |V_k| \left|V_j\right| \left|V_{kj}\right| \cos\left(\emptyset_{kj} - \delta_k + \delta_j\right) \tag{2}$$

$$Q_K^{C(x)} = \sum_{j=1}^{n} |V_k| \left|V_j\right| \left|V_{kj}\right| \sin\left(\emptyset_{kj} - \delta_k + \delta_j\right) \tag{3}$$

The iteration will depend on the tolerance of the power mismatch calculated by their formulas:

$$\Delta P_K^x = P_k^{sc} - P_k^{c(x)} \tag{4}$$

$$\Delta Q_K^x = Q_k^{sc} - Q_k^{c(x)} \quad (5)$$

It should be remembered that busses are divided into three types of busses (Slack (V & δ)), Produced Bus (P&V) and Load Bus (P&Q constants). In other words, there are two iterations available to solve this problem. First of all, the measured real-and reactive-value requires internal iteration (eq 2 & 3) if the variables are taken up (at the beginning of the resolution method) and determined (at the beginning of the solution process). Second, external iterations that are necessary to find power inaccuracies intolerance (eq 4 & 5), i.e. increased precision iteration. In this paper, the first iteration is known as calculation iterations, while the second iteration is known as precision iterations.

Table 1. Level of solar PV penetration data

	PV Penetration Level in % & values (All value in kW)					
	Total active power load: 3466 kW Total reactive power load: 2102 kVAR					
Cases	**1**	**2**	**3**	**4**	**5**	**6**
Penetration in %	**0%**	**20%**	**40%**	**60%**	**80%**	**100%**
Total PV Power	0	693.20	1386.4	2079.60	2772.80	3466.00
PV 1	0	173.30	346.60	519.90	693.20	866.50
PV 2	0	173.30	346.60	519.90	693.20	866.50
PV 3	0	346.60	693.20	1039.80	1386.40	1733.00

Table 2. Solar PV panel parameters data

Solar PV Parameters	**Values**
Module short-circuit current (Isc)	5.96 A
Module open-circuit voltage (Voc)	64.2 V
Module voltage and current at maximum power (Vmp , Imp)	54.7 V, 5.58 A
sun irradiance (MAX)	1000 W/m^2

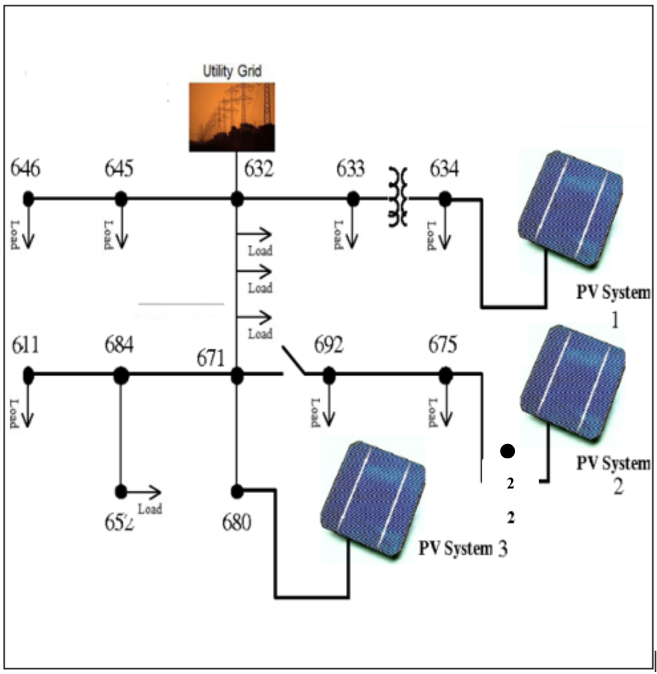

Fig 1. Integration of solar PV at node 675,680,634 in IEEE 13 node feeder

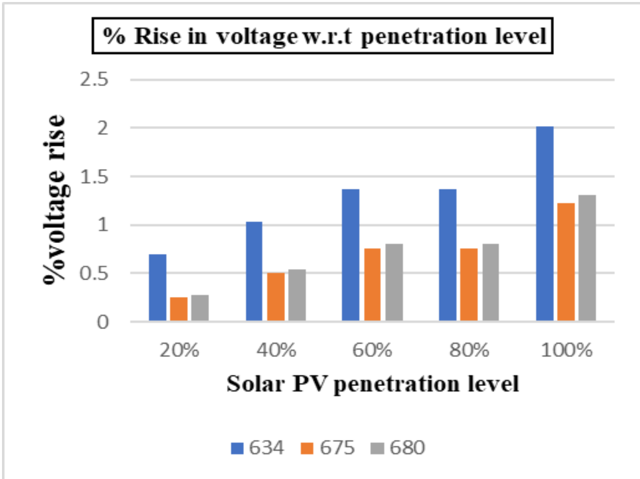

Fig 2. Percentage bus voltage rise at bus 634,675,680 when solar PV integrated with the network

3. Impact of solar PV on voltage variation

The evaluation was carried out in six different cases including solar photovoltaics, for solar penetration inserted at bus 680, 675, 634. The voltage was measured on each bus. For all six cases shows in Table 1, the solar photovoltaic penetration range is between 0 and 3.4 MW.

The variation in voltage at each solar penetration level is shown in figure 2. It is evident that bus voltage varies with increased penetration of the PV and the highest voltage variance at 100% solar penetration level [25].

4 Impact of solar PV plant on distribution grid power losses.

In PV penetration analysis, it is found that power loss decreases with the increase of PV penetration this is shown in figure 3. The active power losses decreased by around 32% according to the study for case 2 (20% penetration), and by just about 40% for case 3 (40% penetration). In case 4 (60% penetration), losses of the operating system decreased by approximately 67%. The losses of the operating system have reduced by about 70% for Case 5 (80 % penetration) & 6 (100 % penetration). In the reactive loss of power, i.e. the MVAR, a similar trend occurs.

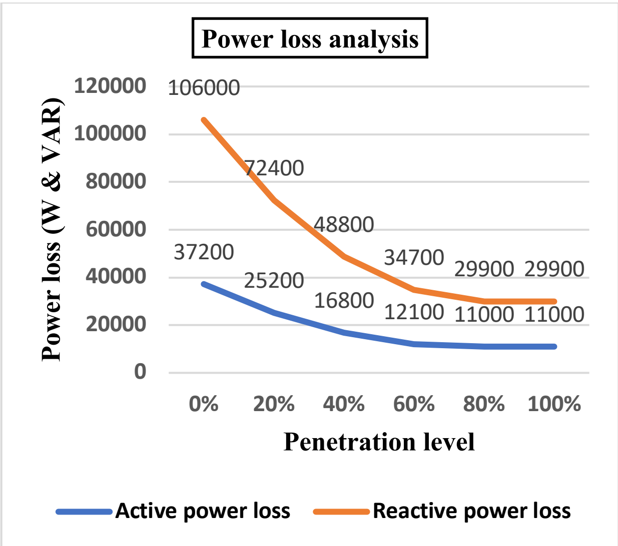

Fig 3. Active & reactive power losses for each case of solar PV penetration**.**

5 Impact on power factor concerning with solar PV.

Most of the PV inverters connected to the grid can only inject power at unit power factor, thereby generating active power only [18][19]. The power factor and power efficiency of the grid can be influenced by providing only active grid power through solar PV. In the study of these cases in Figure 4, the power factor changes as the rate of solar photovoltaic penetration increases (671-632,675-692). In these situations, many power factors in the figure are negative because of the flow of power is the opposite direction.

4 THD (Total harmonic distortion) analysis

Power quality is always important for the customer because of these harmonics can affect the electrical equipment and unwanted tripping of relays. When harmonic distortion reaches the system, the capacity of the power system to operate at the optimal level is compromised. This causes inefficiency during the operations of power consumption. Some precaution is considered by the power grid service providers that are considering the tolerance level for maintaining power quality and preventing power supply interruptions.

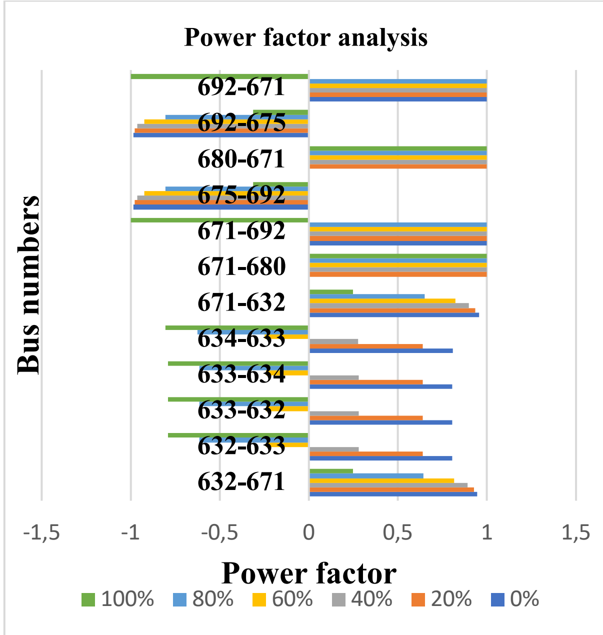

Fig 4. Power factor variation for each case of solar PV.

Power electronic devices used as power converters create a problem of power quality such as the distortion of harmonics. The power output of the PV system depended solely on the use of inverters, solar irradiation and temperature that could influence electricity production, voltage and current profile. The PV system must be incorporated into the grid in compliance with the required requirements of the utility company. The standards IEEE 1547, IEC 61727 & ENC 61000-3-2 and IEEE Standard 519-1992 forms define for the power quality. Which Indicates voltage deformity at the Common Coupling Point (PCC) in IEEE Standard 519-1992, THD voltage for each harmonic content is limited to 3 per cent and for circuits with an electrically rated 2.3 to 69 kV only 5 per cent THD is permissible. The point of common coupling (PCC) is known as the main point where PV is integrated into the system. It is recommended before a distributed resource such as PV is connected to the network, the system voltage distortion should be below 2.5 per cent and current distortion should below 20 per cent. The maximum amount of current injected into the grid is monitored under the standards IEEE 1547 & IEC 61727.

Figure 5, shows distortion not available in case 1 because the contribution of solar PV is zero. Figure 6, depicts the distortion of the sign waveform due to harmonics injected due to solar PV. For the study of the harmonics grid parameter, the ratio of the RMS value of the harmonic components to the RMS basic values, is expressed in per cent, needs to be measured, called Total Harmonic Distortion (THD). This index is used to calculate variations in standard waveforms that contain harmonics [26][27][28]. THD calculation on different penetration level has been shown in table 3,4.

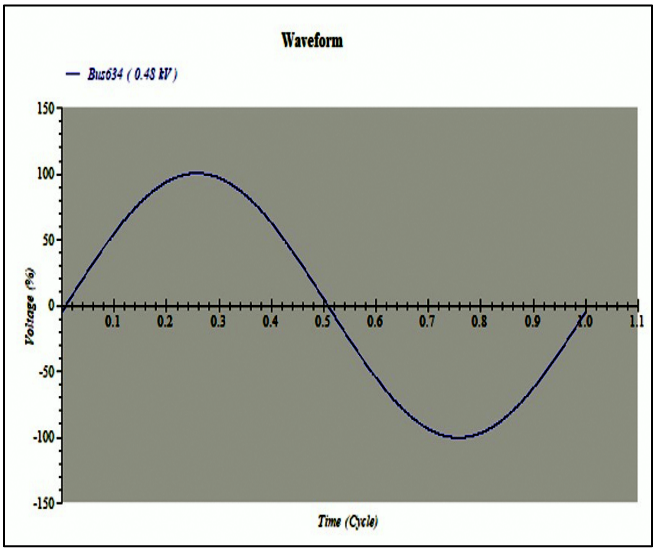

Fig 5. Voltage waveform for bus 634 when solar PV contribution is 0%

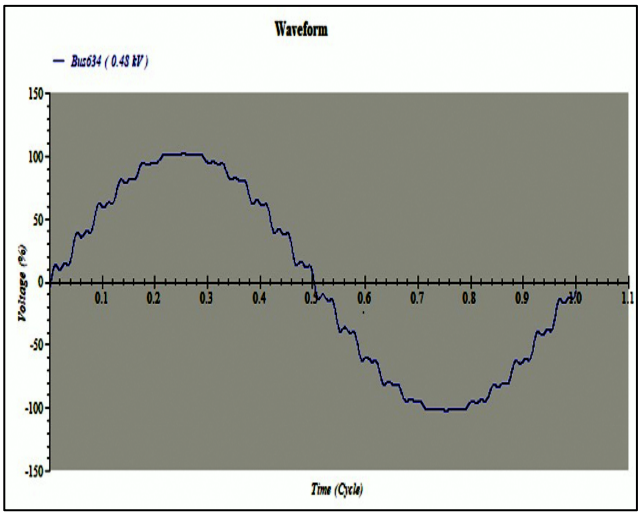

Fig 6. Voltage waveform for bus 634 when solar PV contribution is 80%

Table 3. Total voltage harmonic distortion (THD) for each level of penetration

Voltage harmonic distortion						
	Cases					
	C1	C2	C3	C4	C5	C6
Bus	0%	20%	40%	60%	80%	100%
632	0	0.02	0.08	0.10	0.14	0.18
633	0	0.07	0.12	0.19	0.25	0.31
634	0	1.26	2.50	3.72	4.92	6.10
671	0	0.09	0.19	0.28	0.37	0.46
675	0	0.20	0.40	0.60	0.79	0.98
680	0	0.24	0.48	0.72	0.95	1.18
692	0	0.09	0.19	0.28	0.37	0.46

Table 4. Total current harmonic distortion (THD) for each level of penetration

Current harmonic distortion (All values in percentage)							
Bus numbers		**Cases**					
		C1	**C2**	**C3**	**C4**	**C5**	**C6**
From bus	To bus	**0%**	**20%**	**40%**	**60%**	**80%**	**100%**
632	671	0	0.17	0.41	0.79	1.41	2.23
	633	0	1.10	2.74	4.14	4.45	4.25
633	632	0	1.10	2.74	4.14	4.45	4.25
	634	0	1.10	2.74	4.14	4.45	4.25
634	633	0	1.10	2.74	4.14	4.45	4.25
671	632	0	0.17	0.41	0.79	1.41	2.23
	680	0	5.66	5.66	5.66	5.66	5.66
	692	0	2.52	6.16	11.93	22.45	47.73
675	692	0	3.03	7.76	16.03	32.71	64.49
680	671	0	5.66	5.66	5.66	5.66	5.66
692	675	0	3.03	7.76	16.03	32.71	64.49
	671	0	2.52	6.16	11.93	22.45	47.73

It is clear from table 3 and 4 found the THD is higher than the allowable limits by the standard system IEEE 159. In case 5 & 6 prescribed THD limits are 20% of the current harmonic distortion and 2.5% for harmonic distortion of voltage.

The current THD on bus 671,675 & 692 was found to be higher than the THD threshold value for case 5 & 6. In the THD voltage analysis in bus 634, THD for case 4 was found to be 3.72% which higher than that of a threshold value, but also below the rated value of connected devices. The THD value of case 5 & 6 is 4.92% & 6.10% respectively, which is greater than that of connected rated devices, meaning that it is a warning to the service provider. All the THD analysis found that the maximum bearing capacity of PV on the grid in a 60% penetration level. More than 60% penetration PV connection possible only with the implementation of PV along with the harmonic filters.

The harmonic filter was used mainly for case number as 5,6 to minimize the harmonic percentage. Electrical transient analysis software tool was used for filter analysis. The 0.2 Mvar rated harmonic filter was used at bus 634 for reducing the voltage THD. After the use of filter implementation voltage, THD was found 0.9% for case 5 and 1.15% for case 6. After filter implementation current THD for bus 671,675 & 692 was reported as 6.55%, 6.91% & 4.91%.

The analysis of the THD spectrum is shown for both cases with filter and without the filter. Figure 7 show results without filter case while fig 8 show with filter case. The THD amplitude was found higher for the Case no. 5 this is shown in Figure 7. Voltage THD Amplitude with filter shown in Figure 8.

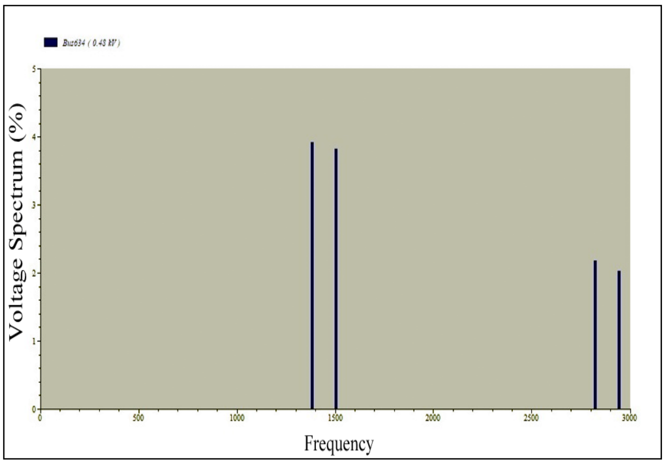

Fig 7. Voltage spectrum showing harmonics at a different frequency for bus 634 without using the filter

The graphical THD variance analysis is shown in figures 9 and 10. The maximum harmonic variation in voltage is observed for bus 634, and for bus 671-692, 675-692 maximum harmonic current variation is observed. The analysis shows that when PV penetration increases more by 60 per cent, maximum harmonics occur, which is not permissible in compliance with IEEE and IEC Guidelines.

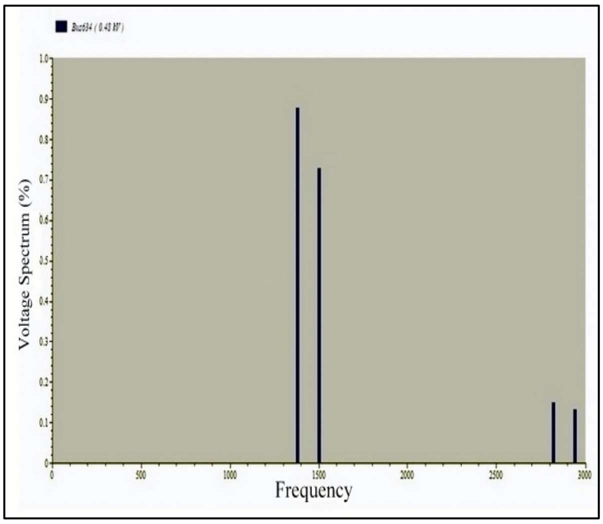

Fig 8. Voltage spectrum after using the filter at bus 634

5 Solar PV impact on short circuit current

The big challenge for power distribution is the short circuit (SC) current variability. The security systems are not able to fulfil obligations on time because of SC variation. The three phases short circuit current study is carried out for all penetration situations. The result of this current analysis is given in Table 5.

In the study, found to increase in the fault currents when the solar penetration level increases. For the highest level of penetration, the maximum fault current observed was 5.77 kA and the lowest fault current. In IEEE 13 node standard system both line single-phase and three-phase line present. For the single-phase line consider the line to ground fault and for the two-phase line to line fault was consider for the SC current analysis. For the IEEE 13 node network, the Bus 645,646,611,684,652 contains one phase and two-phase lines. In the present study for these busses, faults that taken into account are ground fault and line to line faults.

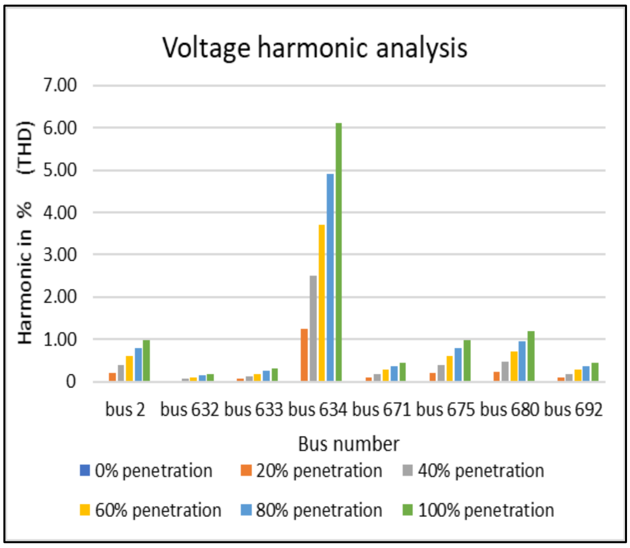

Fig 9. Graphical analysis of voltage THD at every penetration level

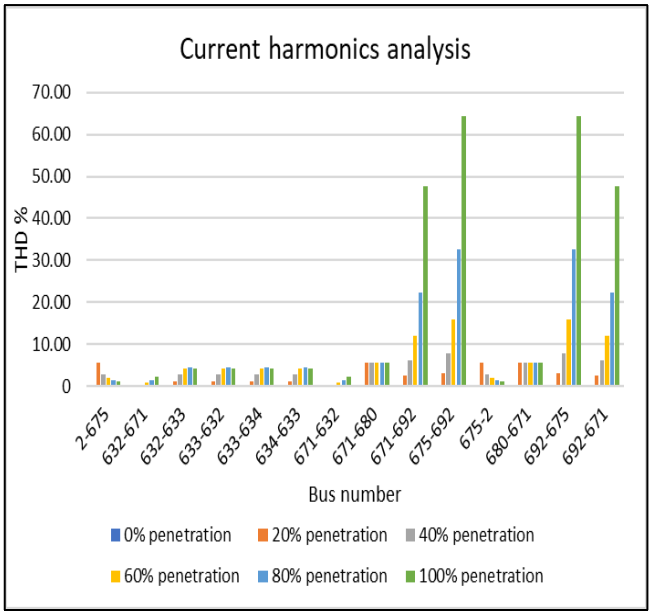

Fig 10. Graphical analysis of current THD at every penetration level

Table 5. Analysis of **f**ault current for each solar PV penetration case.

FAULT CURRENT (KA)						
BUS NO.	**CASE 1 (0%)**	**CASE 2 (20%)**	**CASE 3 (40%)**	**CASE 4 (60%)**	**CASE 5 (80%)**	**CASE 6 (100%)**
646	1.551	1.557	1.566	1.578	1.595	1.614
645	1.67	1.68	1.693	1.71	1.73	1.75
632	0.139	0.217	0.341	0.467	0.613	0.75
611	1.59	1.611	1.631	1.659	1.693	1.73
684	1.99	2.004	2.023	2.049	2.079	2.113
671	0.137	0.215	0.338	0.473	0.61	0.784
633	0.138	0.216	0.339	0.471	0.606	0.74
634	1.148	1.773	2.753	3.782	4.796	5.77
692	0.137	0.215	0.338	0.473	0.61	0.748
675	0.137	0.214	0.337	0.469	0.605	0.741
680	0.136	0.213	0.336	0.469	0.606	0.743
652	1.354	1.35	1.354	1.363	1.377	1.394

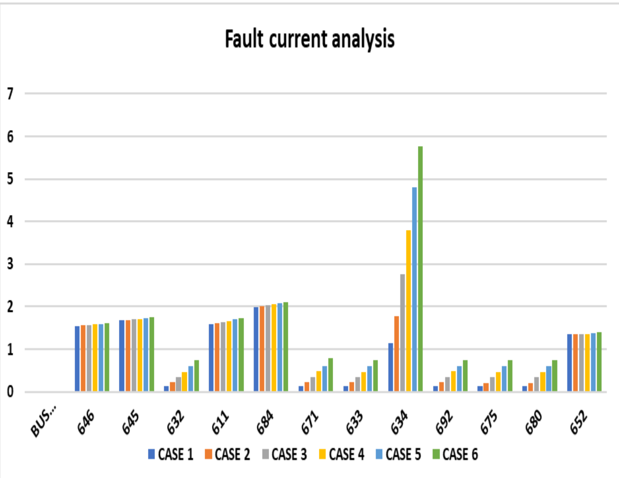

Fig 11. Fault current analysis for IEEE 13 node distribution feeder

6 Conclusion

The present research study focuses on the penetration impact of solar PV system on distribution grids. This study examined the detailed effect of solar PV on voltage profiles, voltage imbalances, network stability and the effect of harmonics on grid operation. It is evident from the conducted study that distribution feeders are starting to experience voltage flickers between 40 to 60 per cent penetration & also witness the maximum THD level after reaching 60% penetration. There is no specific way to estimate the safe degree of solar penetration for distribution systems, so for this reason individual systems must be studied. Safe penetration rates depend on feeder topology, load profile, solar light / cloud patterns, and number of harmonics.

The maximum solar share allowed is the point at which voltage increases and/or flicker problems begin, and the harmonic value exceeds the standard maximum limit (IEEE 519). The study also reveals that increase solar penetration reduces the power losses of the system which is helpful to cater more consumer demand.

Albeit, increased penetration reduces the power losses but it has been observed that shot circuit current level increases, which creates the issue of relay maloperation. However, the increase THD and short circuit current effects, can be mitigate through implementation of adaptive & non adaptive protection techniques.

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