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Impact of Photovoltaic Penetration on Distribution Systems

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Abstract

Photovoltaic (PV) systems are now increasingly being connected to our distribution networks as a cleaner alternative to fossil fuels and they can be placed very near to actual loads. Varying penetration levels of PV power in the distribution system and its strategic location impacts voltage profile of that area. This paper gives analysis of the impacts of PV penetration levels on distribution system in terms of feeder voltage profile and associated losses, load allocation, load growth and harmonics. The analysis is carried out using CYME 7.1 software on a distribution feeder and its results are present in this paper. Load allocation and load growth which are a part of distribution system analysis can be used to identify under voltage area which helps us to locate Solar PV in that area to improve voltage profile.

Keywords: PV, distribution system, load growth, load allocation, voltage profile, harmonics, CYME

I. INTRODUCTION

In the last decade, PV energy has shown huge potential during which the amount of installed PV has almost doubled. Increase of this amount of energy in the system can triggered various alarms in current scenario or near future. It is therefore essential to study impact of PV penetration levels in the existing system and design the system so as to sustain the load growth without disturbing the stability of the system. Voltage profile improvement and reduction of losses are key areas to look for when designing the system [1-6].

The use of solar PV in distribution system has been studied and how it effects on voltage profile, line losses, was determined in different networks by different researchers [7-9]. The impact of penetration of renewable energy which are connected along distribution system have been evaluated in whereas other studies focus more on regular networks [8-15] which highlight the problems which may occur in the system however different feeders has dissimilar characteristics so the problems cannot be generalized.

Further, Solar PV integrations degrade the supply quality progressively in different aspects. The key issues imposed by solar PV pertaining to power quality can be identified as an increased level of harmonics, voltage unbalance, deterioration of power factor and voltage regulation in the distribution networks. Power electronic techniques used in solar PV in DC to AC inversion cause the harmonic distortion which is difficult to restrict. Moreover, harmonic issue is worsen by the presence of non-linear loads at the vicinity of solar installations [16]. Therefore, a comprehensive study of harmonic penetration is required [17-18].

This paper provides a study of impact of PV penetration on a real distribution feeder. The load flow study is carried out using simulations and by constructing various scenarios in the system. The abnormalities on the system like under voltage conditions and over voltage conditions and violation of permissible harmonics levels are identified considering load growth of 3% per annum and load allocation of 80%, 110% and 150%. Also, best possible scenario is identified from the results.

This paper is organized as follows: Introduction is followed by Mathematical Modelling of PV systems in Section II. Impacts on Distribution Network are discussed on Section III while Section IV concludes the paper.

II. MATHEMATICAL MODELLING OF PV SYSTEM

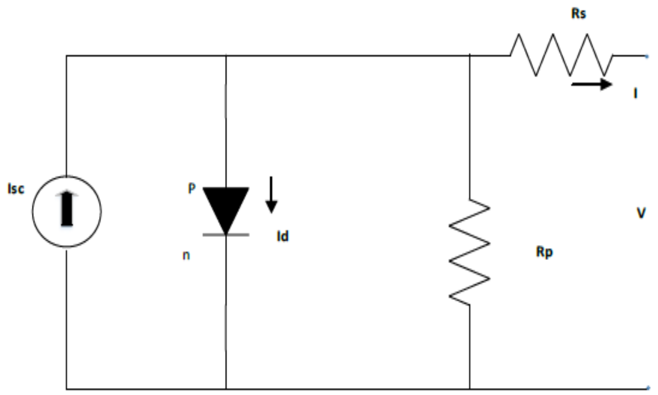

Fig. 1. PV cell equivalent circuit

Fig. 1. shows the equivalent circuit diagram of a single PV cell. Photocurrent is represented by I_{ph} which intrinsic values of series and shunt resistances are represented by R_s and R_{sh} respectively. R_{sh} has a very large value while R_s has a very small value so it is neglected for circuit analysis. PV cells are combined to form modules by series parallel combinations and many modules combined to form arrays which are used for generating electricity. The equivalent circuit for PV array is shown in Fig. 2.

The voltage-current characteristic equation of a solar cell is given as:

$I_{ph} = [I_{sc} + K_i \ (T - 298)\ ] \times Ir / 1000$ (equation 1)

Iph is photo-current in A

Is is short circuit current in A

T is operating temperature in K

Ir is solar irradiation (W/m^2)

Ki is short-circuit current of cell at 25^{o}C temperature and 1000 W/m^2 irradiation.

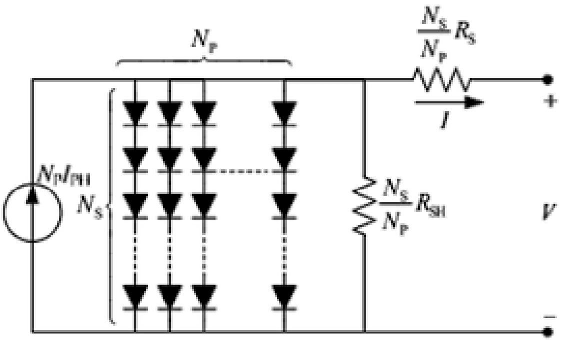

Fig. 2. Equivalent circuit of solar array

Module reverse saturation current I_{rs} is given by

$I_{rs} = [I_{sc} / \exp(q\, V_{oc} / N_s\, k_n T) - 1]$ (equation 2)

Where,

V_{oc} is open circuit voltage in V.

k is Boltzmann's constant and the value is1.3805 x 10^{-23} J/K

q is electron charge and the value is1.6× 10^{-19}Columbs

Ns is the number of cells series connected.

n is the ideality factor of the diode

III. IMPACT ANALYSIS OF PV ON DISTRIBUTION NETWORK

For determining the impacts on voltage profile, losses and Harmonics, CYMDIST software is used. With help of CYMDIST, network modelling and analysis, various simulation types can be performed for planning of distribution system. Distribution models can be designed in meshed, looped or radial by using this software. The version used in this analysis is CMYE 7.1 which is used for distribution system analysis. By using this software load flow analysis, load growth analysis, harmonics analysis, fault analysis, Arc flash hazard analysis can be performed.

The steps followed for design and analysis are shown using flowchart in Fig. 3. The method starts with collection of data from a real substation, in this case Pawarwadi Substation (Nashik). Then two types of simulation cases are designed, one without PV and one with PV for load flow analysis. In PV case, various scenarios are constructed by varying PV penetration levels in the system and best possible scenario is identified in terms of improvement in voltage profile and reduction of losses in the system. These results are compared with the results obtained from without PV system and validated.

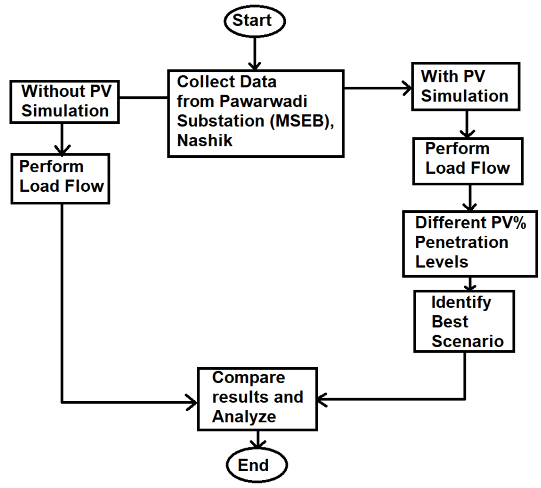

Fig. 3. Flowchart for Feeder Load Flow Analysis under the presence of PV systems

The feeder of Pawarwadi Substation in Nashik is designed in CYMDIST 7.1 software for analysis and is shown in Fig. 4. It is a 10.18 km 3-ph 33/11kV substation.

Fig. 4. Feeder Network Modelling Using CYMDIST 7.1

As seen from the flowchart, it is necessary to conduct load flow studies for analysis of the system. The devices connected in the system are tabulated in Table I which gives the total count of devices connected to the system such as breakers, transformers, fuse, cables, switch, spot loads etc.

Table I: Feeder Specifications

Breaker	48
Cable	47
Fuse	188
Spot Load	642
Switch	48
Transformer	47

The ratings of the devices are:

- Breaker-800A, 300A, 200A (Rated current)
- Overhead line (Aluminium conductor steel reinforced) DOG
- Transformer - 150 KVA 11/0.4 (40 nos.),
  200KVA 11/0.4 (6 nos.),
  250KVA 11/0.4 (1 nos.).

The analysis conducted on the system is discussed in following sections.

A. Load Flow Analysis without PV

Table II: Load Flow Analysis Without PV

Total Summary	kW	kVar	kVA
Sources (Swing)	4150.63	889.65	4244.91
Total Generation	4150.63	889.65	4244.91
Total Loads	4090.83	718.76	4153.49
Line Losses	30.40	76.16	82.00
Cable Losses	0.06	0.21	0.22
Transformer Load Losses	16.62	96.44	97.86
Transformer No-Load Losses	12.72	0.00	12.72
Total Losses	59.8	172.81	182.86

The load flow analysis without PV connection to the distribution feeder is tabulated in Table II.

B. Load Growth

Load growth analysis is an important aspect in distribution system. As per MSEB record from past 30 years load growth is approximately 3% for that area. Load growth from 2019 to 2034 is analyzed taking 3% per year growth. The feeder size and pattern after 15 years is shown in Fig. 5. After load growth analysis, 219 overload cases (signified by yellow colour), and 231 under voltage (signified by red colour) cases arises. Predicted Output after load flow analysis in 2034 is given in Table III.

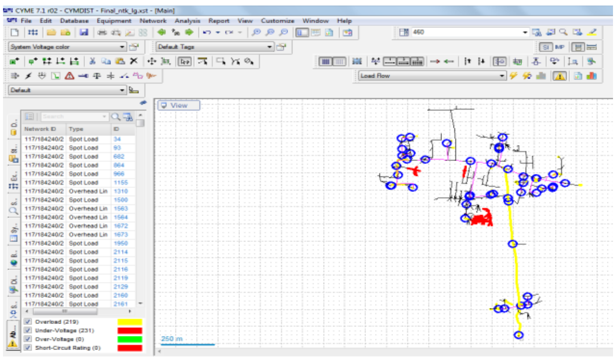

Fig. 5. Load Growth at year 2034

Table III: Load Flow for feeder considering load growth

Total Summary	kW	kVar	kVA
Sources (Swing)	6503.33	1548.08	6685.05
Total Generation	6503.33	1548.08	6685.05
Total Loads	6373.38	1119.80	6471.00
Line Losses	75.72	189.74	204.29
Cable Losses	0.15	0.63	0.65
Transformer Load Losses	41.47	239.81	243.37
Transformer No-Load Losses	12.61	0.00	12.61
Total Losses	129.96	430.18	449.38

Based on simulations conducted, after resolving the abnormalities by changing the conductor and adding two new transformers of 150kVA load growth can be resolved till 2034.

C. Load Allocation

Load allocation is useful for designing a load model which is accurate. This is done by allocating KW-KVAR and Ampere-Power factor per phase according to the demand of feeder throughout the network by using data such as connected capacity of transformer, data from load, billing and consumption data.

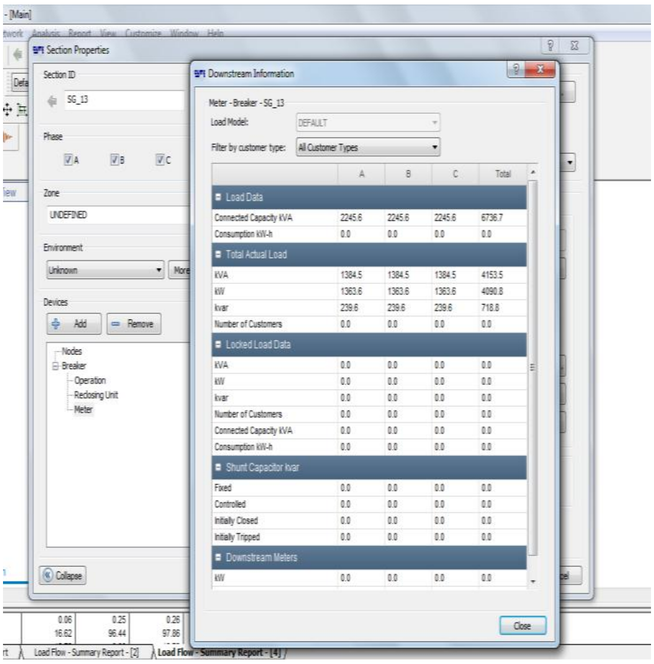

Fig. 6. Data in CYME showing Load Allocation for the feeder

The load flow studies were carried out for various scenarios of load allocation and its data was tabulated in Tables IV and V for 80% and 150% load allocation respectively.

Table IV: Load flow of the feeder considering 80% loading

Total Summary	kW	kVar	kVA	PF %
Total Generation	3323.12	761.93	3409.35	97.47
Total Loads	3275.23	602.51	3330.19	98.35
Line Losses	20.02	50.08	53.93	37.11
Cable Losses	0.04	0.14	0.14	27.47
Transformer Load Losses	15.18	111.13	112.16	13.54
Transformer No-Load Losses	12.65	0.00	12.65	100.00
Total Losses	47.89	161.35	168.30	28.45

It was observed that for 80% loading, the feeder voltage levels were normal and that there were no abnormalities found in the feeder to raise any alarm triggers.

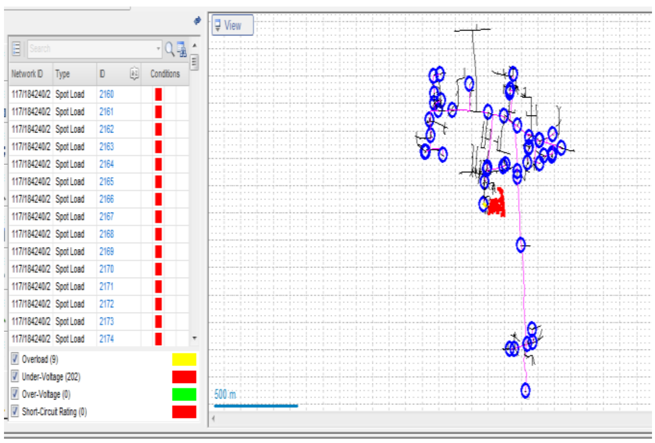

Fig. 7. Load Allocation Considering 110% Overload Condition

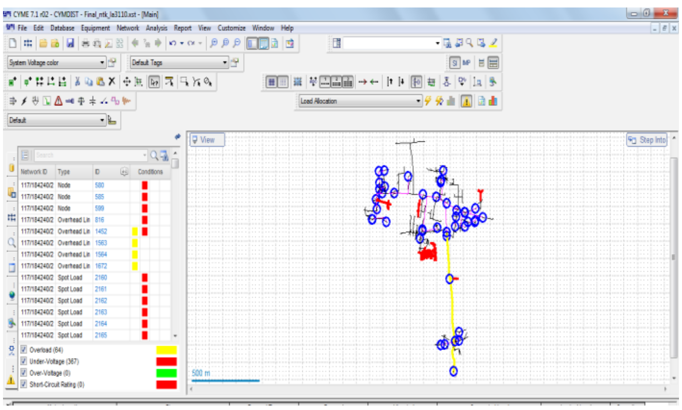

Fig. 8. Load Allocation Considering 150% Overload Condition

Table V: Load Flow Considering 150% Load Allocated

Total Summary	kW	KVAR	kVA	PF %
Sources (Swing)	6235.53	1509.79	6415.71	97.19
Total Generation	6235.53	1509.79	6415.71	97.19
Total Loads	6097.39	938.16	6169.14	98.84
Line Losses	71.36	178.54	192.27	37.11
Cable Losses	0.14	0.49	0.51	27.47
Transformer Load Losses	54.22	394.50	398.21	13.61
Transformer No-Load Losses	12.43	0.00	12.43	100.00
Total Losses	138.14	573.53	589.93	23.42

It was observed that total over-voltage nodes were 9 and 64 while those with under voltage were 202 and 367 with 110% and 150% loading respectively. As we go on increasing the load on the feeder, under voltage cases increase in the system.

D. Feeder Voltage Profile and losses

The losses in the feeder were computed using the CYME software for scenarios considering without PV and with increasing PV penetration levels in Table VI and Table VII respectively. It was observed that for 45% PV penetration, the losses were optimized and very minimum as compared to all other scenarios.

Table VI: Losses according to various PV penetration levels for Pawarwadi feeder

Penetration Level		Impact on Losses				
		Line	Load	No-Load	Cable	Total
Scenario 1	10% (426.53 kW)	36.03	14.6	12.74	0.06	68.83
Scenario 2	15% (659.85 kW)	25.42	13.96	12.75	0.06	52.19
Scenario 3	20% (853.06 kW)	24.82	16.2	12.76	0.06	53.84
Scenario 4	25% (1086.38 kW)	26.95	15.39	12.76	0.05	55.15
Scenario 5	30% (1319.7 kW)	21	11.79	12.77	0.04	45.6
Scenario 6	35% (1512.91kW)	27.38	13.3	12.78	0.05	53.51
Scenario 7	45% (1882 kW)	15.21	11.68	12.79	0.04	39.72
Scenario 8	50% (2132.65 kW)	19	11.99	12.8	0.04	43.83
Scenario 9	55% (2318 kW)	23.55	13.71	12.8	0.06	50.12
Scenario 10	60% (2559.18kW)	26.47	14.78	12.81	0.06	54.12

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Table VII: Losses in the System for with and without PV

Impact on losses	PV Penetration	Line Losses	Transformer Load Losses	Transformer No Load Losses
Load flow analysis Result Scenario 7	45% (1882 kW)	15.21	11.68	12.79
Load flow analysis Result without PV	0	30.04	16.62	12.72

It can be observed from Table VII that losses were minimized by half with inclusion PV penetration of 45% in the present feeder situation as per scenario 7 of table VI. Therefore, this penetration level is considered as optimal value of penetration for the system.

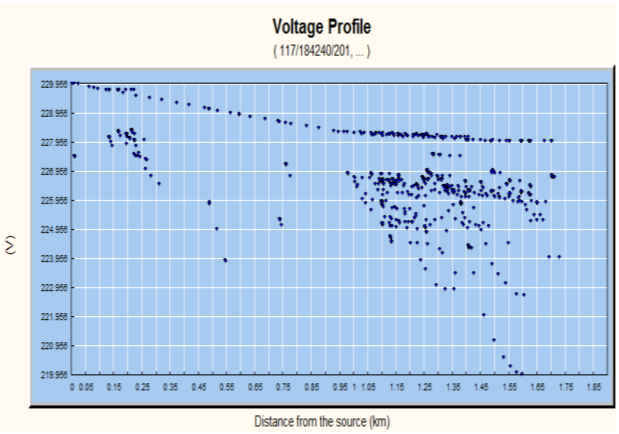

Fig. 9. Feeder Voltage Profile Without PV

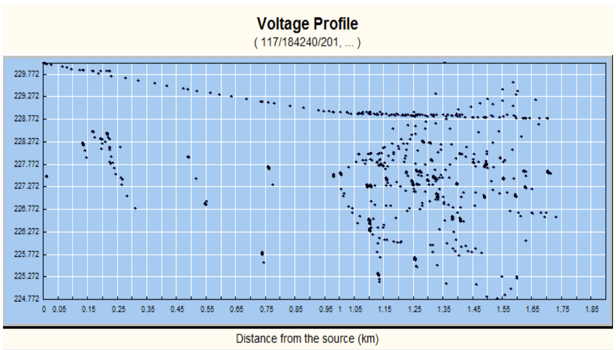

Fig. 10. Feeder Voltage Profile with PV

Figs. 9 and 10 show feeder voltage profiles with and without PV in the system. It was observed that including the PV in the system improved the voltage profile on the system by 3% and thus feeder network is voltage regulated.

E. Harmonics

The harmonics pattern of voltage in the feeder is shown in Fig. 11 and its THD graph is shown in Fig. 12. It is clear from the Figs that as PV is connected in the system, harmonics get injected in the system through them. It has to be seen that total THD doesn't rise above permissible limit while designing the system.

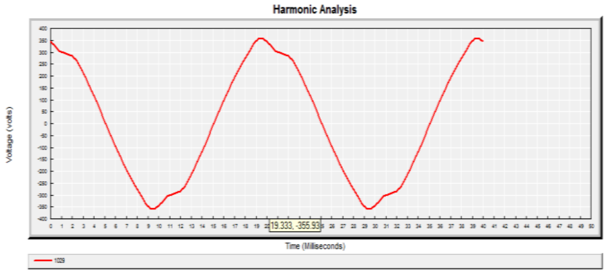

Fig. 11. Voltage after inclusion of PV in the distribution network

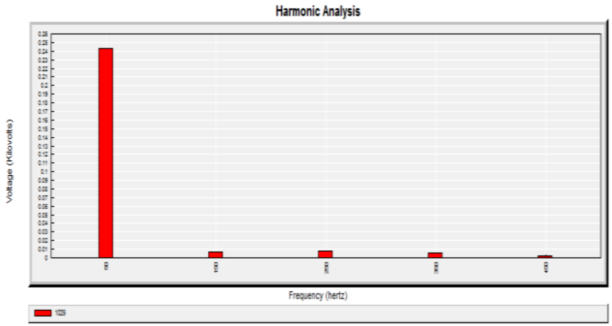

Fig. 12. THD of the voltage in the Distribution Network

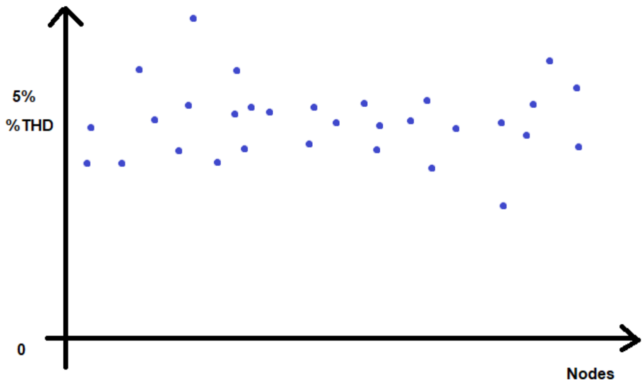

Fig. 13. THD at various nodes in the distribution network considering solar PV

Fig. 13 shows the THD in the system and that it is violating the permissible limit of 5% in the system at its various nodes.

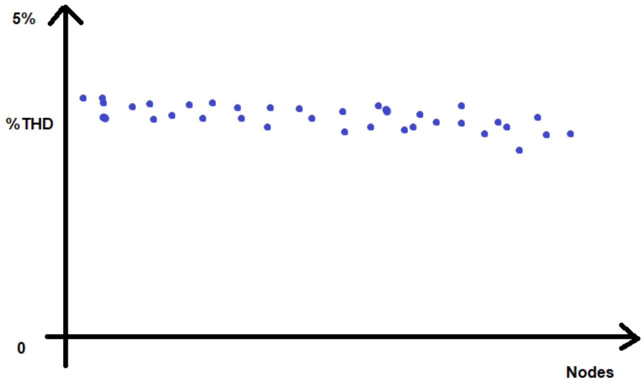

Fig. 14. THD at various nodes in the distribution network by removal of two PV installations in the system

The PV arrays were then optimally placed in the system and by removing two solar PV arrays from the system; it was observed that the feeder is not violating IEEE 519-1992 standard voltage harmonic level in the system as seen in Fig. 14. The PV penetration level for acceptable harmonic limit is 1582.07kW which is 38.2% of the system.

IV. CONCLUSION

In this paper, impacts of PV penetration on various aspects of distribution system were presented. A distribution feeder was designed and simulated using CYME 7.1 software. Simulations for various scenarios were constructed and its load flow analysis was presented in the paper. It was seen that for 45% PV penetration voltage profile of the system improved. Losses were calculated for this penetration level and were found significantly lower than system without PV installation. Further, after harmonic analysis it is concluded that it can host 38.2% PV penetration. The harmonics were seen to be within standard limit of 5% for the same.

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