Maximum Allowable PV Penetration by Feeder Reconfiguration Considering Harmonic Distortion Limits

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Abstract *- In recent days the renewable energy sources are having important role in power system area because the availability of conventional sources are decreasing exponentially and also due to global warming and cost of conventional sources. More consumers are opting for Solar PV as an alternative source for energy due to many attractive schemes. The Solar PV system will inject the current harmonics because the PV plants having power electronic devices like inverters. Individual current harmonic can be neglected but cumulative impact of current harmonics can elevate voltage harmonic distortion. So many regulations are there to limit the transformer wise and feeder wise net PV penetration to avoid harmonic distortion. Because of these reasons any new PV addition can be approved, if and only if harmonic distortion remains in acceptable limit. Harmonic distortion varies in feeder with PV penetration at different zones, like: near to substation, mid-section of feeder, or tail end of feeder. More PV can be allocated to substation end as compared to tail end; based on the network impedance seen from tail end will be more. A harmonic distortion limits also one of main constraint to add the new solar PV systems with existing power system. This paper presents the methodologies to reconfigure the loads between two parallel moving radial feeders optimally to find the maximum PV capacity that can be allocate in a distribution feeder without violating the harmonic distortion limits specified by IEEE-519 standard. MATLAB-2015b is used for programming and the network modelling and analysis and results are verified by using MiPower.9.1.*

Keywords - *Feeder reconfiguration, PV penetration, Equivalent network, Network driving point impedance, Harmonic distortion.*

I. Introduction

More number of end users is choosing the PV source as alternative energy source. The Solar PV is clean & green energy source hence many new research areas are evolving day by day to improve the power quality reliability, flexibility. The Solar PV sources will use nonlinear devices like power electronic converter to step up/step down the energy. These nonlinear devices will inject harmonics in to the system. The constraints like harmonic distortion, equipment overloading will limit the maximum PV penetration. The overloading can be minimized by using feeder reconfiguration. Feeder reconfiguration is defined as the modification of the radial structure of the feeders to transfer the load from one distribution feeder to another feeder by changing the state of the switches (either switches are open or close). With the reconfiguration of feeders it is possible to transfer the loads from heavily loaded feeders to lightly loaded feeders. Minimization of losses and voltage profile improvement can be achieved by feeder reconfiguration.

II. Problem Description

Power distribution companies are following so many guidelines to approve new PV penetration based upon customer category. The PV systems are installed after doing so many studies related to the transformer and harmonic distortions, etc. Penetration of PV can inject the harmonics in to the system. A Practical challenge came related to determine the maximum PV capacity that can be allocated to the network without violating the harmonic limits specified by IEEE standards [1]. This can be done by shifting the nonlinear loads from one feeder to another feeder and this procedure is known as feeder reconfiguration. By shifting the nonlinear loads the total harmonic content injection to the feeder from net amount of the nonlinear loads (i.e., PV systems) will be decreased. And voltage profile also increase due to this reconfiguration. An approach to decide the maximum PV capacity penetration without violating the harmonic distortion limits has been analysed in [4], and this approach is limited to few distribution patterns like PV sources are allocated in equal distribution(i.e., uniformly increasing or uniformly decreasing)manner across the feeder. The harmonic distortion levels can be obtained with the help of power system simulation tools at specific PV injection points. An algorithm was proposed in [8] on the feeder configuration technique to reduce the losses in network. These voltage harmonic distortions depend upon the driving point harmonic impedance of the network. The voltage harmonic distortion limits are specified for systems having different voltage ratings in [1]. By taking the network driving point impedance and voltage harmonic distortions. A methodology is proposed to penetrate the maximum PV capacity to the system with different configurations of the existed network using switching operation.

III. PROBLEM FORMULATION

A Distribution feeder can get PV penetration at anywhere in the system near substation or middle or tail end of the feeder. The harmonic distortions will vary with the network impedance, while the network impedance depends on the length of the feeder. The maximum harmonic current and maximum PV capacities are depend on the network impedance. This network impedance can be change by re-configuring the feeders in various ways. The most optimised feeder reconfiguration procedure to cater maximum PV capacity penetrations is explained in this section using a typical distribution feeder network represented in Fig.1.

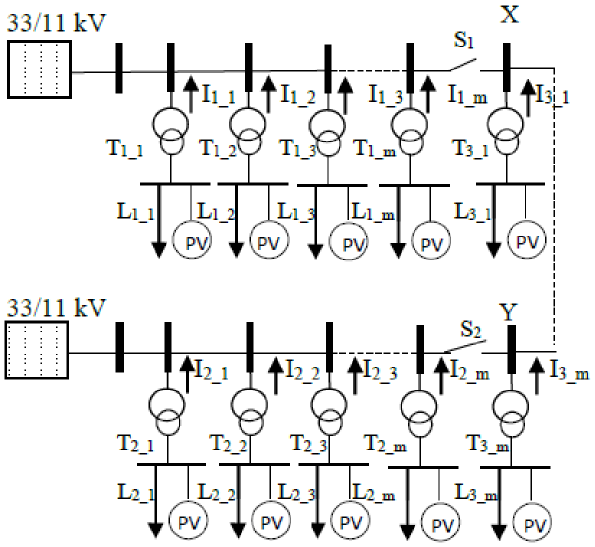

Fig 1 Typical Distribution Network Consisting Two Radial Feeders

The above network can be configured in two ways by operating the switches S_1, S_2.In configuration 1 switch S_1 is closed, and switch S_2 is open. The section from X to Y marked as a dotted line in Fig.1 is added to feeder-1. In configuration 2 switches S_1 is open, switch S_2 is closed. The section from Y to X marked as a dotted line in Fig.1 is added to feeder-2.

A. Methodology

Maximum harmonic currents that can be injected by PV into the system by maintaining the total voltage harmonic distortion must be within the limit as specified in [1] can be obtained by maximizing the V_THD function with the individual and total voltage harmonic distortions limits as a constraints. The hth harmonic voltage (V_h) is

$$V_h = I_h * Z_h \qquad \dots (1)$$

Individual voltage harmonic distortion factor (V_HDF_h) is defined as

$$V\_HDF_h = \frac{V_h}{V_1} \qquad \dots (2)$$

And total voltage harmonic distortion (V_THD) is defined as

$$\mathrm{V\_THD} = \sqrt{\frac{\sum_{h=2,3,\dots}^{n} V_h^2}{V_1^2}} \qquad \dots (3)$$

The representation of V_THD as a function of harmonic currents as variables is defined as

$$f(I_h) = \sqrt{\frac{\sum_{h=2,3,\dots}^{n} I_h^2 Z_h^2}{V_1^2}} \qquad \dots (4)$$

The V_HDF_h for less than 69kV system should be less than or equal to the 3% as specified in [1], hence

$$\frac{V_h}{V_1} \leq 0.03 \qquad \dots (5)$$

From (1) and (5)

$$\frac{I_h \cdot Z_h}{V_1} \leq 0.03 \qquad \dots (6)$$

$$\Rightarrow I_h \leq \frac{0.03 * V_1}{Z_h} \qquad \dots (7)$$

The relationship between harmonic current and fundamental current is formed as (8) by assuming hth harmonic current is a_h percentage of fundamental current,

$$\frac{100 * I_2}{a_1} = \frac{100 * I_3}{a_2} = \dots\dots\dots\dots\dots = \frac{100 * I_n}{a_n} = I_1 \qquad \dots (8)$$

Assuming fundamental harmonic current should be less than or equal the x_h percentage of the total load capacity the relationship is formed as (9)

$$I_1 \leq \frac{load * x_h}{100 * V_1 * \sqrt{3}} \qquad \dots (9)$$

By comparing (8) and (9) the obtained inequality constraints are

$$I_h \leq \frac{a_h}{100} * \frac{load * x_h}{100 * V_1 * \sqrt{3}} \qquad \dots (10)$$

And also the V-THD for less than 69kV system should be less than or equal to the 5% as specified in [1], hence

$$\sqrt{\frac{\sum_{h=2,3,\dots}^{n} I_h^2 Z_h^2}{V_1^2}} \leq 0.05 \qquad \dots (11)$$

Finally the problem is formulated to find the maximum harmonic current injected by the PV system by setting the limit on the voltage harmonic distortions caused by the harmonic currents. So the objective function is to maximize the V-THD function formulated in (4) subjected to the constraints formulated in (7), (8), (10), and (11). A maximization program has been created using

Matlab-2015b for the above described problem. The harmonic current quantities are obtained at HV side of the transformer for any PV plant connected to HV line. By using transformation ratio LV side currents are calculated. These currents are used to calculate the maximum PV penetration capacity. As HT consumer with PV plant are connected to HT line, distortion limit also to be checked at HT side only. So network impedance and harmonic current has been considered at HV side. The complexity for conducting the analysis on the whole feeder can be minimised by converting the whole network to its equivalent network, which is explained in next section 3.2

B. Network Equivalence

The procedure for obtaining an equivalent network comprising a single equivalent transformer, equivalent load, equivalent transmission line and equivalent PV source as described below to form the equivalent network for the feeder -1(with S_1 open) from Fig.1.

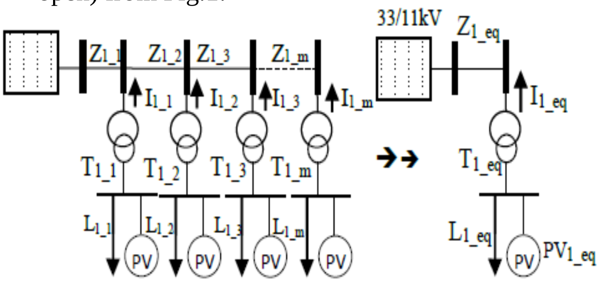

Fig 2 Feeder-1 and its equivalent network

From fig.2. Loss in line 1 =

$$(I_{1\_m}+..+I_{1\_3}+I_{1\_2}+I_{1\_1})^2 Z_{1\_1} l_{1\_1} \quad \dots (12)$$

Loss in line 2 =

$$(I_{1\_m}+..+I_{1\_3}+I_{1\_2})^2 Z_{1\_2} l_{1\_2} \quad \dots (13)$$

Loss in line 3 = $(I_{1\_m}+..+I_{1\_3})^2 Z_{1\_3} l_{1\_3}$ ... (14)

Loss in line m = $I_{1\_m}^2 Z_{1\_m} l_{1\_m}$ ... (15)

Total transmission line loss in feeder-1 is as in (16)

Loss=

$$(I_{1\_m}+..+I_{1\_3}+I_{1\_2}+I_{1\_1})^2 Z_{1\_1} l_{1\_1} + (I_{1\_m}+..+I_{1\_3}+I_{1\_2})^2 Z_{1\_2} l_{1\_2} + (I_{1\_m}+..+I_{1\_3})^2 Z_{1\_3} l_{1\_3} + \dots\dots\dots + I_{1\_m}^2 Z_{1\_m} l_{1\_m}$$

... (16)

Where $I_{1\_1}, I_{1\_2}, I_{1\_3}, \dots\dots I_{1\_m}$ are the harmonic currents injected from renewable energy sources. $Z_{1\_1}, Z_{1\_2}, Z_{1\_3}, \dots\dots Z_{1\_m}$ are the impedances and $l_{1\_1}, l_{1\_2}, l_{1\_3}, \dots\dots l_{1\_m}$ are the lengths of the transmission lines from 1 to m in feeder 1

From equivalent network of feeder-1

Total transmission loss=$I_{1\_eq}^2 Z_{1\_eq}$ ... (17)

$$Z_{1\_eq} = \frac{total\ transmission\ loss}{I_{1\_eq}^2} \quad \dots (18)$$

In radial system the equivalent current is equal to the total current drawn by the total load. Hence the equivalent current in the equivalent network can be written as in (19)

$$I_{1\_eq} = I_{1\_1} \quad \dots (19)$$

The equivalent impedance (Z_{1_eq}) of equivalent transmission line of feeder-1 can be rewritten as in (20)

$$Z_{1\_eq} = \frac{total\ transmission\ loss}{I_{1\_1}^2} \quad \dots (20)$$

In this case all distribution transformers HT, LT side voltages are equal and all transformers are connected in parallel. Then the equivalent transformer impedance ($Z_{1\_T\_eq}$) will be defined as in (21)

$$Z_{1\_T\_eq} = \frac{\text{sum of impedance of transfomers connecected feeder} - 1}{\text{total no. of. transfomers connecected to feeder} - 1} \quad \dots (21)$$

The equivalent load of the feeder-1 (L_{1_eq}) will be defined as in (22)

L_{1_eq}=Sum of the loads connected to feeder-1 ... (22)

The equivalent PV system of the feeder-1 (PV_{1_eq}) will be defined as in (23)

PV_{1_eq}=Sum of the PV's connected to feeder-1 ... (23)

The equivalent networks representation of the feeder-1 and feeder-2 of the Fig.1. is showed in Fig.3.

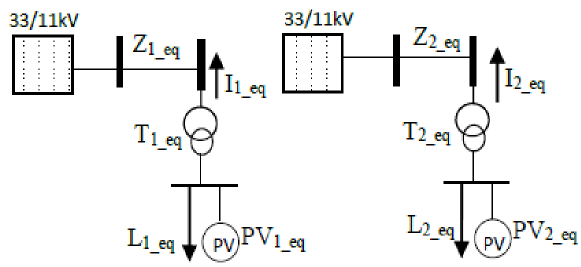

Fig 3 Equivalent networks for two feeders

The equivalent driving point impedance calculated at HV side of the transformer if the HT loads are considered and the equivalent driving point impedance is calculated till tail end of the transformer(i.e., LV side) if the LT loads are considered. In this present work the driving point impedance is calculated at the HV side of the transformer to find the maximum harmonic currents and maximum PV penetration and the currents and PV capacities transformed by using transformer transformation ratio.

C. Calculation of PV Capacity

The Maximum PV penetration for respective feeders can be calculated by finding the maximum currents by solving the optimization function subjected to the constraints as described in section III. After getting the maximum harmonic currents the PV capacity will calculate by following equations. If at HV side of transformer allowable current calculated found to be I_1. At LV side of the transformer allowable current calculated found to be I_2 as in (24).

$$I_2 = \frac{V_1}{V_2} * I_1 \qquad \dots (24)$$

Hence at LV side of the transformer the allowable PV capacity as in (25)

$$\text{PV capacity} = 1.732 * V_2 * I_2 \qquad \dots (25)$$

Where V_1 is the voltage at HV side and V_2 is the voltage at LV side

The entire approach discussed in section III-A,B and C to determine optimal switching operation with respect to maximum PV is explained in step by step process as follows:

Step 1 Model radial distribution network with transmission lines, distribution transformers, loads using any power system simulation tool.

Step 2 Connect the network as per Configuration 1

Step 3 Compute the driving point impedance of network as described in section III.B

Step 4 Calculate the maximum PV penetration capacity by maximizing the THD function which is explained in section III.C

Step 5 Note the PV capacities obtained for the two feeders and find the sum of the PV capacities of both feeders

Step 6 Connect the network as per Configuration 2

Step 7 Repeat the procedure from step 3 to step 5

Step 8 Compare total PV capacities of two configurations

Step 8 Choose the solution which gives maximum PV penetration.

Step 9 Operate the network in obtained configuration

Step 10 Analyse the network in different aspects with finalised PV penetration.

IV. CASE STUDY

The proposed methodology has been tested on a typical distribution system having two parallel radial feeders are represented in Fig.4. This test system is consisting of 22 step down (11kV/0.415kV) distribution transformers of each rating is 0.2 MVA at the tail end of the transformers 22 lumped linear loads having unity power factor are connected. Weasel type conductor transmission line having thermal rating 2.4316 MVA is taken for the both feeders. The test system data is specified in appendix. The radial distribution system has two switches S_1 and S_2. The Switch S_1 is located between the buses 1_9 and 1_10 and the switch S_2 is located between the buses 2_9 and 2_10. By operating the two switches (open/close) two configurations are possible. In this work if S_1 is closed and S_2 is open that configuration is named as Configuration-1and if S_2 is closed and S_1 is open that configuration is named as Configuration-2.The network is operated in these two configurations and simulation results are specified in section V.

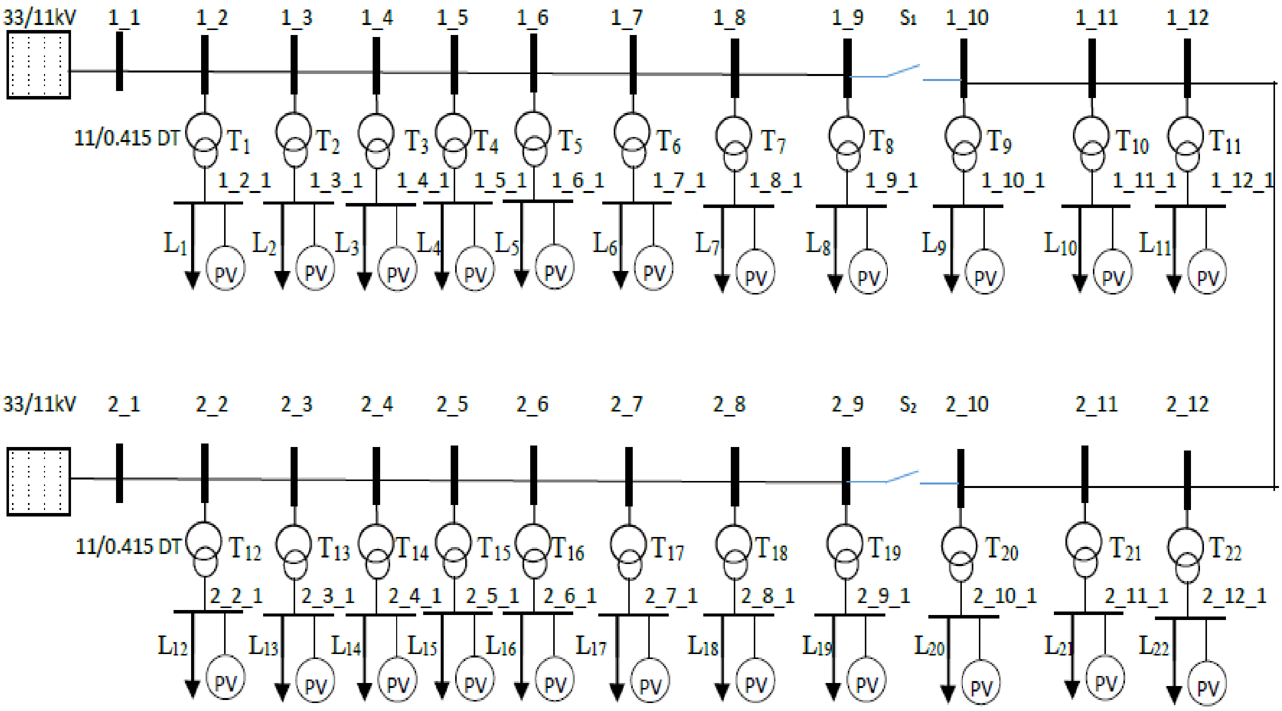

Fig 4 Case Study for the Optimum Network Reconfiguration

V. Results & Discussion

For the network shown in Fig.4, the network impedance and total load connected to the respective feeders for different configurations are tabulated in Table .I and Table. II

Configuration-1: S_1 is closed and S_2 is open

Table. I. Input parameters for Configuration-1

Parameter	feeder-1	feeder-2
Load(kw)	860	240
Network impedance at HV side(Ohm)	14.806	10.254

Configuration-2: S_1 is open and S_2 is closed

Table. II. Input parameters for Configuration-2

Parameter	feeder-1	feeder-2
Load(kW)	560	540
Network impedance at HV side(Ohm)	8.232	17.083

Table. III. Maximum fundamental harmonic current with different configurations

PV capacity in % of load capacity	Maximum Fundamental harmonic current at LV side (Amp)			
	Configuration-1		Configuration-2	
	feeder-1	feeder-2	feeder-1	feeder-2
100	301.47	333.88	514.28	263.69
90	301.47	300.49	514.28	263.69
80	301.47	267.09	514.28	263.69
70	301.47	233.7	514.28	263.69
60	301.47	200.32	467.43	263.69
50	301.47	166.93	389.52	263.69

Table. IV. Maximum PV capacity with different configurations

PV capacity in % of load capacity	Maximum PV capacity at LV side (kW)			
	Configuration-1		Configuration-2	
	feeder-1	feeder-2	feeder-1	feeder-2
100	216.7	239.99	369.67	189.54
90	216.7	215.99	369.67	189.54
80	216.7	191.99	369.67	189.54
70	216.7	167.98	369.67	189.54
60	216.7	143.99	335.99	189.54
50	216.7	119.9	279.99	189.54

The maximum allowable PV capacities at LV sides of the two feeders with different configurations at different loading conditions are tabulated in Table.3 and Table.4. The Individual maximum PV capacities that can be penetrate at LV side of the feeders without violating the voltage harmonic distortions at HV side by taking constraint that PV capacity is equal to the 100% of the load capacity is tabulated in Table. V.

TABLE. V .INDIVIDUAL MAXIMUM PV CAPACITIES IN KW AT LV SIDE FOR DIFFERENT CONFIGURATIONS (kW)

Bus Name	Configuartion-1	Configuration-2
1_2_1	18.21545	46.20875
1_3_1	18.21545	46.20875
1_4_1	18.21545	46.20875
1_5_1	18.21545	46.20875
1_6_1	18.21545	46.20875
1_7_1	18.21545	46.20875
1_8_1	18.21545	46.20875
1_9_1	18.21545	46.20875
1_10_1	18.21545	9.671235
1_11_1	18.21545	9.671235
1_12_1	18.21545	9.671235
2_2_1	7.807673	29.0137
2_3_1	7.807673	29.0137
2_4_1	7.807673	29.0137
2_5_1	7.807673	29.0137
2_6_1	7.807673	29.0137
2_7_1	7.807673	29.0137
2_8_1	7.807673	29.0137
2_9_1	7.807673	29.0137
2_10_1	29.99875	29.0137
2_11_1	29.99875	29.0137
2_12_1	29.99875	29.0137

The maximum fundamental harmonic currents injected by the individual PV systems those which are penetrated at LV side of the feeders without violating the voltage harmonic distortions at HV side by taking constraint that PV capacity is equal to the 100% of the load capacity is tabulated in Table.VI.

TABLE. VI. INDIVIDUAL FUNDAMENTAL HARMONIC CURRENT IN AMPS AT LV SIDE FOR DIFFERENT CONFIGURATIONS (Amps)

Bus Name	Configuartion-1	Configuration-2
1_2_1	25.34488	64.285
1_3_1	25.34488	64.285
1_4_1	25.34488	64.285
1_5_1	25.34488	64.285
1_6_1	25.34488	64.285
1_7_1	25.34488	64.285
1_8_1	25.34488	64.285
1_9_1	25.34488	64.285
1_10_1	25.34488	13.45469
1_11_1	25.34488	13.45469
1_12_1	25.34488	13.45469
2_2_1	10.86209	40.36407
2_3_1	10.86209	40.36407
2_4_1	10.86209	40.36407
2_5_1	10.86209	40.36407
2_6_1	10.86209	40.36407
2_7_1	10.86209	40.36407
2_8_1	10.86209	40.36407
2_9_1	10.86209	40.36407
2_10_1	41.735	40.36407
2_11_1	41.735	40.36407
2_12_1	41.735	40.36407

The individual voltage harmonic distortions and V_THD are given below which are obtained for HV side of the two feeders for the different configurations is tabulated in Table.VII, VIII, IX, and Table.X.

TABLE. VII. % VOLTAGE HARMONIC DISTORTIONS ON FEEDER-2 HV SIDE IN CONFIGURATION-1

Bus Name	THD	7^{th} order	11^{th} order	13^{th} order
2_1	0.5037	0.2228	0.2918	0.3449
2_2	1.0139	0.4537	0.5865	0.6915
2_3	1.4823	0.6686	0.8566	1.0081
2_4	1.9032	0.8623	1.0993	1.2923
2_5	2.2756	1.0339	1.314	1.5437
2_6	2.5993	1.1832	1.55	1.7621
2_7	2.8741	1.3099	1.6589	1.9475
2_8	3.0999	1.414	1.789	2.0999
2_9	3.2767	1.4956	1.899	2.2191
2_10	3.4045	1.5545	1.9645	2.3053
2_11	3.5194	1.6076	2.038	2.3829
2_12	3.6216	1.6547	2.0897	2.4518
1_12	3.6932	1.6877	2.139	2.5001
1_11	3.7409	1.7097	2.1584	2.5323
1_10	3.7647	1.7207	2.1721	2.5484

TABLE. VIII. % VOLTAGE HARMONIC DISTORTIONS ON FEEDER-1 HV SIDE IN CONFIGURATION-1

Bus Name	THD	7^{th} order	11^{th} order	13^{th} order
1_1	0.2307	0.1021	0.1337	0.158
1_2	0.4173	0.1863	0.2414	0.2848
1_3	0.5827	0.2621	0.3369	0.3967
1_4	0.7251	0.3275	0.419	0.4929
1_5	0.8439	0.3822	0.4875	0.5731
1_6	0.939	0.426	0.5423	0.6373
1_7	1.0104	0.4589	0.5834	0.6855
1_8	1.058	0.4809	0.619	0.7176
1_9	1.0818	0.4919	0.6246	0.7337

TABLE. XI. VOLTAGE HARMONIC DISTORTIONS ON FEEDER-1 HV SIDE IN CONFIGURATION-2

Bus Name	THD	7th order	11th order	13th order
1_1	0.5852	0.2588	0.339	0.4007
1_2	1.0583	0.4725	0.6124	0.7223
1_3	1.478	0.6647	0.8545	1.0062
1_4	1.8391	0.8307	1.0627	1.2501
1_5	2.1405	0.9694	1.2364	1.4536
1_6	2.3817	1.0806	1.3755	1.6165
1_7	2.5628	1.1641	1.4798	1.7387
1_8	2.6835	1.2197	1.5494	1.8201
1_9	2.7439	1.2475	1.5842	1.8609
1_10	3.5338	1.6127	2.0393	2.3934
1_11	3.5212	1.6069	2.032	2.3849
1_12	3.4959	1.5952	2.0174	2.3678
2_12	3.4579	1.5777	1.9955	2.3421
2_11	3.3819	1.5427	1.9518	2.2909
2_10	3.268	1.4901	1.8861	2.2141

TABLE. X. % VOLTAGE HARMONIC DISTORTIONS ON FEEDER-2 HV SIDE IN CONFIGURATION-2

Bus Name	THD	7th order	11th order	13th order
2_1	0.5514	0.2438	0.3194	0.3775
2_2	0.9971	0.4451	0.577	0.6806
2_3	1.4113	0.6348	0.8159	0.9608
2_4	1.7894	0.8087	1.0339	1.2162
2_5	2.1302	0.9656	1.2304	1.4463
2_6	2.4334	1.1053	1.4051	1.6509
2_7	2.6989	1.2277	1.5581	1.8301
2_8	2.9265	1.3326	1.6893	1.9836
2_9	3.1162	1.4201	1.7987	2.1116

From the above tabular forms the individual V_HDF and V_THD for two feeders with different configurations are within the specified limits as specified in [1].

TABLE. X1. TOTAL MAXIMUM PV PENETRATION WITH DIFFERENT CONFIGURATIONS

PV capacity in % of load capacity	Maximum PV capacity (kW)	
	Configuration-1	Configuration-2
100	456.69	559.21
90	432.69	559.21
80	408.69	559.21
70	384.68	559.21
60	360.69	525.53
50	336.6	469.53

From Table. XI the total maximum PV capacities obtained with the configuration-1 are lower than the total maximum PV capacities obtained with the configuration-2 at every loading condition. The distortion limits at HV side of the transformer are also within the limits specified by IEEE standards [1] for both the configurations. Hence for the given radial distribution feeder network configuration-2 is the optimal configuration.

VI. CONCLUSION

The proposed methodologies help in determining the feasible way to reconfigure feeders by operating the switches. Case study results are also found to be convincing in order to compute maximum allowable PV capacity in feeder restricting harmonic distortions below acceptable limit. Same approach was also tested with the different loading conditions and results obtained regarding maximum allowable PV capacity with respect to optimal switching operation found to be very much acceptable. The harmonic distortion results are verified by using the power system simulation tool MiPower.9.1. The voltage harmonic distortion limits are under the IEEE-519 limits at all HV side (i.e., 11kV) buses of the both feeders after penetration of maximum PV capacity to the respective feeders.

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APPENDIX

TABLE. A1. GENERATOR DATA

Bus	Rating (MVA)	Voltage (kV)	Real Power (Mw)
1_1	100	11	100
2_1	100	11	100

TABLE. A2 .BUS AND LOAD DATA

S.no	Bus Name	Bus Voltage(kV)	Real Power Demand(kW)
1	1_1	11	--
2	1_2	11	--
3	1_3	11	--
4	1_4	11	--
5	1_5	11	--
6	1_6	11	--
7	1_7	11	--
8	1_8	11	--
9	1_9	11	--
10	1_10	11	--
11	1_11	11	--
12	1_12	11	--
S.no	**Bus Name**	**Bus Voltage(kV)**	**Real Power Demand(kW)**
13	1_2_1	0.415	70
14	1_3_1	0.415	70
15	1_4_1	0.415	70
16	1_5_1	0.415	70
17	1_6_1	0.415	70
18	1_7_1	0.415	70
19	1_8_1	0.415	70
20	1_9_1	0.415	70
21	1_10_1	0.415	70
22	1_11_1	0.415	70
23	1_12_1	0.415	70
24	2_1	11	--
25	2_2	11	--
26	2_3	11	--
27	2_4	11	--
28	2_5	11	--
29	2_6	11	--
30	2_7	11	--
31	2_8	11	--
32	2_9	11	--
33	2_10	11	--
34	2_11	11	--
35	2_12	11	--
36	2_2_1	0.415	30
37	2_3_1	0.415	30
38	2_4_1	0.415	30
39	2_5_1	0.415	30
40	2_6_1	0.415	30
41	2_7_1	0.415	30
42	2_8_1	0.415	30
43	2_9_1	0.415	30
44	2_10_1	0.415	30
45	2_11_1	0.415	30
46	2_12_1	0.415	30

TABLE. A3.TRANSFORMER DATA

S.no	From Bus	To Bus	Name	%Z	$\frac{X}{R}$ ratio
1	1_2	1_2_1	T1	0.05	20
2	1_3	1_3_1	T2	0.05	20
3	1_4	1_4_1	T3	0.05	20
4	1_5	1_5_1	T4	0.05	20
5	1_6	1_6_1	T5	0.05	20
6	1_7	1_7_1	T6	0.05	20
7	1_8	1_8_1	T7	0.05	20
8	1_9	1_9_1	T8	0.05	20
9	1_10	1_10_1	T9	0.05	20
10	1_11	1_11_1	T10	0.05	20
11	1_12	1_12_1	T11	0.05	20
12	2_2	2_2_1	T12	0.05	20
13	2_3	2_3_1	T13	0.05	20
14	2_4	2_4_1	T14	0.05	20
15	2_5	2_5_1	T15	0.05	20
S.no	**From Bus**	**To Bus**	**Name**	**%Z**	$\frac{X}{R}$ **ratio**
16	2_6	2_6_1	T16	0.05	20
17	2_7	2_7_1	T17	0.05	20
18	2_8	2_8_1	T18	0.05	20
19	2_9	2_9_1	T19	0.05	20
20	2_10	2_10_1	T20	0.05	20
21	2_11	2_11_1	T21	0.05	20
22	2_12	2_12_1	T22	0.05	20

TABLE. A4. TRANSMISSION LINE DATA

S.no	From Bus	To Bus	R1	X1	R0	length (km)
			(Ohm/km/ckt)			
1	1_1	1_2	1.2	0.4	0.416	0.8
2	1_2	1_3	1.2	0.4	0.416	0.8
3	1_3	1_4	1.2	0.4	0.416	0.8
4	1_4	1_5	1.2	0.4	0.416	0.8
5	1_5	1_6	1.2	0.4	0.416	0.8
6	1_6	1_7	1.2	0.4	0.416	0.8
7	1_7	1_8	1.2	0.4	0.416	0.8
8	1_8	1_9	1.2	0.4	0.416	0.8
9	1_9	1_10	1.2	0.4	0.416	0.8
10	1_10	1_11	1.2	0.4	0.416	0.8
11	1_11	1_12	1.2	0.4	0.416	0.8
12	2_1	2_2	1.2	0.4	0.416	1
13	2_2	2_3	1.2	0.4	0.416	1
14	2_3	2_4	1.2	0.4	0.416	1
15	2_4	2_5	1.2	0.4	0.416	1
16	2_5	2_6	1.2	0.4	0.416	1
17	2_6	2_7	1.2	0.4	0.416	1
18	2_7	2_8	1.2	0.4	0.416	1
19	2_8	2_9	1.2	0.4	0.416	1
20	2_9	2_10	1.2	0.4	0.416	1
21	2_10	2_11	1.2	0.4	0.416	1
22	2_11	2_12	1.2	0.4	0.416	1
23	1_12	2_12	1.2	0.4	0.416	0.8

TABLE. A5. HARMONIC DATA

Harmonic order	% in fundamental harmonic current
7	30
11	25
13	25