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Performance Enhancement of an Overloaded Distribution Network with the Penetration of Solar PV Distributed Generation

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Abstract: Power losses and voltage drops severely impact the performance of home appliances and distribution transformers. Power loss is minimized to save electricity while the voltage level is maintained in allowable standard limits for the smooth operation of the power system. For this purpose, different techniques are discussed. Instead of utilizing traditional methods power engineers prefer to integrate renewable energy source(s) at optimal sites. In this paper, small scale solar photovoltaic modules are penetrated through the net –metering. The distribution feeder in district Khuzdar of Balochistan is taken as a case study for this research where irrigation loads of some optimal sites are solarized. Due to this integration of solar systems power loss is reduced while the voltage at consumers' ends is improved. This technique not only relieves the grid but also saves a huge amount of revenue. The solar PV systems are installed according to the demand of irrigation load. It is investigated that with the implementation of such small scale and a large number of solar PV units in the distribution scheme has declined the importance of large scale renewable grid integration. Performance analysis of existing and proposed distribution system has been carried out and the results obtained clearly demonstrates the effectiveness of the proposed method. The proposed systems are modelled in MATLAB/SIMULINK tool while the load flow analysis is performed in ETAP Software.

Keywords*:* Power quality, Solar PV system, Power loss, Distributed Generation, Voltage profile.

I. INTRODUCTION

Renewable energies are now widely used for the electrification of remote areas of undeveloped countries. Wind energy is harvested at high rates comparatively. However solar still has the advantage over wind energy due to high reliability and potential in the African and South Asian countries [1]. Such renewable sources are also integrated with the grid system to enhance not only the power quality of the system but also to utilize the surplus energy generated from these sources [2]. In Pakistan, the rural feeders are below standard due to its length, unbalanced loads, overloaded distribution transformer and illegal connections [3]. A huge amount of electric power is wasted, and voltage is dropped declining the transformer' terminal voltages at the side consumer [4].

Traditionally to avoid such type of issues junctions are made at different locations and the load is supplied power from the grid for different durations. Similarly, a bifurcation of the distribution network is performed in which a part of the existing feeder is shifted to a separated radial distribution line.

The latest researches prefer the implementation of Distributed Generation (DG) for the reduction of power loss and to enhance the voltage profile according to the IEEE acceptable limits [5]. Research in the paper [6] proposed an Implementation of Distributed Generation (IDG) Algorithm for the performance enhancement of high losses distribution network under extreme load growth. The technique reduced the power loss and improved voltage effectively, but the main issue with this work is that two DGs are proposed with capacities about 61% of the demand on the distribution network. Most of the algorithms developed are basically proposed for the optimal placement and sizing of these DG [7]. Y.M. Atwa et.al developed a technique of mixed integer non-linear programming for the optimal allocation of various renewable DG sources in the distribution scheme to reduce the active power loss and operating lesser dependent on the grid. A probabilistic generation-load model was presented combined all possible operation of DG units [8]. An optimal DG placement method (ODGP) was proposed in [9-10] to obtain several significant benefits. Particle Swarm Optimization (PSO) algorithm is applied for the installation of DGs at optimal sites. The significant drawback of this technique is that DGs were integrated with the system while considering the unvarying load and unity power factor. The paper [11] improved the power quality of the radial IEEE test feeders of 33 and 69 nodes with optimal allocation of multi DG units. This technique is applied for any type of DGs with several assumptions. The simulation results obtained will deviate from the standards when the power factor is changed, load became unbalanced and solar PV modules are penetrated at high rates.

In this paper instead of implementing large size DGs, a large number of small scale solar photovoltaic modules as DG are installed to solarize the irrigation load. The technique is effective as not only the tube wells are detached from the utility grid and are converted on solar power, but also the surplus energy will be sold out to power Distribution Company through the net-metering system. Since the irrigation load is operated for a few hours, hence the power from the solar system can easily be integrated with the power system. The system power loss and voltage drop with the penetration of these DGs are evaluated and compared with the outcomes of existing system under overload condition. The implementation of DGs effectively reduced voltage drop along feeder and power loss is also minimized.

Power loss and voltage drop in the distribution system severely influence the power quality and performances of home appliances [12]. Pakistan is facing a shortage of electric power and the power waste in such scenario will overburden the power generator. Distribution feeders are of the redial type which is lengthy, overloaded and provides unreliable supply to the consumers due to the high rate of power interruptions. In this study a 101 km Peer Umar eleven kilovolt feeder located in district Khuzdar comes under the jurisdiction of Quetta Electric Supply Company is taken as a case study. The technical data including consumer profile, load demand and transformers' capacities, obtained from the grid station and field survey is presented in Table 1.

Table 1. Technical data of 11KV Peer Umar Feeder

No of Consumers	$1-\varphi$	2110
	3-φ	450
Total No of Transformers	25 KVA	115
	50 KVA	56
	100 KVA	9
	400 KVA	1
Power factor	0.9	
Bus voltage	10.8 kV	
Load Current	360 A	
Demand for load	6734.21 kVA	
Length of feeder	101 km	
Consumer class	Domestic	2452
	Industrial	8
	Irrigation	100
Type of conductor	HT-Side	Dog/Rabbit

The main aim of this work is to solarize these irrigation load and to attain the high voltage profile and minimizing power loss by reducing the demand on the utility grid. Performance analysis of this existing system is carried out before the integration of solar photovoltaic systems at the locations discussed earlier.

A. Voltage Drop in the Feeder

The feeder modelled in figure 1, consists of 181 distribution transformers out of which 100 are installed for the tube wells. Since the feeder has high resistance and impedance, the voltage is dropped along the feeder. The voltage drop is evaluated according to the given expressions (1~2), [12].

$$Vt = \sum_{i=1}^{N} Vd(i, i+1). \quad (1)$$

$$V(g)drop = \sum_{j=1}^{M} \sum_{i=1}^{N} [Vd(i, i+1)]. \quad (2)$$

B. Power Loss in Distribution System

Due to the line resistance when the load current is drawn, active power is lost loss along the feeder.

It is simply evaluated using the expression (3).

II. PERFORMANCE ANALYSIS OF PROPOSED DISTRIBUTION NETWORK

$$Pt = \sum_{i=1}^{N} Pl(i, i+1). \quad (3)$$

The change in power loss from segment to segment is separately evaluated and is integrated as shown in the expression (4) to attain the overall power loss [12].

$$\Delta Pl = \int_{x=n0}^{n+1} [\frac{\mathrm{d}I2}{\mathrm{d}s} \emptyset(n+1) \times R(n, n+1)\, dx]. \quad (4)$$

Table 2. Power Loss and Voltage Drop of Existing Line

Segment No	Segment Current (A)	Line losses (KW)	Voltage Drops (KV)
1	360	313.945	1.185
2	107.67	4.0626	0.0414
3	82.7	4.6221	0.061443378
4	73.55	8.0769	0.120726688
5	64.53	1.2172	0.02073679
6	51.61	3.141	0.066907582
7	44	1.3665	0.034142728
8	35.59	0.6283	0.01940798
9	23.35	0.2518	0.011855233
10	10.62	0.0118	0.001221515
11	252.33	94.5477	0.509186268
12	221.73	39.6108	0.242763706
13	199.31	55.841	0.380731404
14	189.87	38.02	0.272113673
15	176.95	36.731	0.282082918
16	172.22	22.3521	0.176371882
17	167.49	26.9647	0.218776824
18	161.46	0.2258	0.001900438
19	139.83	31.514	0.247767553
20	129.88	12.666	0.107210782
21	112.36	0.1033	0.001010718
22	96.73	3.2558	0.037003073
23	93.63	6.612	0.077635272
24	88.73	0.091025	0.001127798
25	86.93	1.4236	0.018003608
26	83.91	0.8308	0.01088489
27	80.88	0.4214	0.00572789
28	70.08	0.1776	0.002786058
29	66.58	0.1603	0.00264686
30	64.9	0.1596	0.002703519
31	62.1	0.0468	0.000828506
32	44.6	0.02945	0.000725925
33	39.24	0.00506	0.000141763
34	18.44	0.008329	0.000496562
35	10.9	0.002091	0.000210896
	Total	709.123455	4.163836364

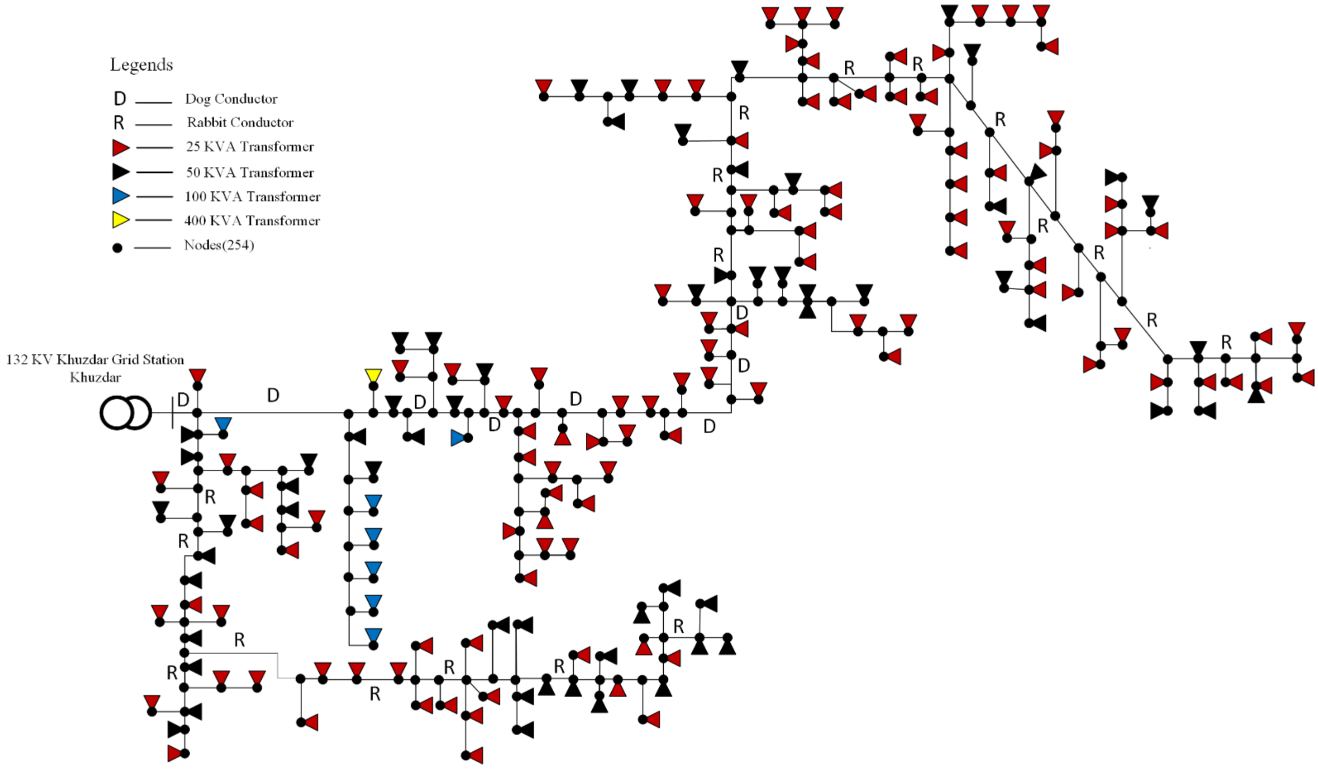

Fig. 1 Single line model of proposed eleven kV Peer Umar distribution network

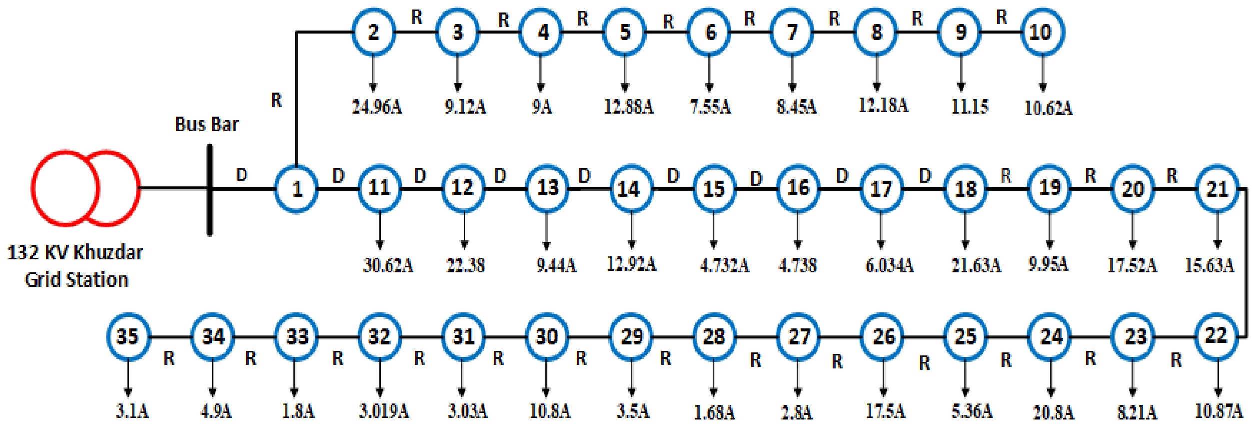

Fig. 2 Simplified model of the distribution system

Table 1 demonstrates the voltage drop and power loss in each segment. The overall active power loss and voltage drop are beyond the standards of IEEE of permissible limits. In order to make the calculation easy and to analyze the system more conveniently when DG is integrated, the existing feeder (as shown in Fig. 1) with 268 number of nodes, is simplified to only 35 nodes presented in figure 2, having same parameters, line loss and voltage drop. All parameters values involved in the system were calculated according to the provide information and data gathered during the field visit as listed in table A-1. The current in every section (segment) is obtained. The total feeder load calculated during the field visit is 6734.21 KVA.

As discussed earlier the feeder basically consists of unbalanced loads. For such feeder, various simulation techniques can be applied. In this research, the analysis is based on the analytical technique as well as simulations. The analysis carried out is modelled in SIMULINK tool in order to verify the design proposed for the DG(s) integration with utility feeder at optimal sites. Table 3 illustrates the parameters resistance, inductance, inductive reactance, impedance of the line and it is investigated that since the first segment is about 5 km long hence most of the power is lost in this section. Load current of 360 A is drawn from the grid during peak hours and most of the demand is shared by the agricultural consumer.

Table 3. Line parameters of the selected 11KV distribution system

Segment No	Length (Km)	Resistance (Ohm)	Inductance (H)	Inductive Reactance (Ohm)	Impedance (Ohm)
1	5.9155	2.4224	0.0071	2.2290	3.2919
2	0.4248	0.3504	0.0005	0.1601	0.3853
3	0.8192	0.6758	0.0010	0.3087	0.7430
4	1.8098	1.4931	0.0022	0.6819	1.6414
5	0.3543	0.2923	0.0004	0.1335	0.3214
6	1.4294	1.1792	0.0017	0.5386	1.2964
7	0.8556	0.7058	0.0010	0.3224	0.7760
8	0.6013	0.4960	0.0007	0.2266	0.5453
9	0.5598	0.4618	0.0007	0.2109	0.5077
10	0.1268	0.1046	0.0002	0.0478	0.1150
11	3.6263	1.4850	0.0044	1.3664	2.0179
12	1.9675	0.8057	0.0024	0.7413	1.0949
13	3.4327	1.4057	0.0041	1.2935	1.9102
14	2.5754	1.0546	0.0031	0.9704	1.4332
15	2.8647	1.1731	0.0034	1.0794	1.5941
16	1.8403	0.7536	0.0022	0.6934	1.0241
17	2.3473	0.9612	0.0028	0.8845	1.3062
18	0.0212	0.0087	0.0000	0.0080	0.0118
19	1.9537	1.6118	0.0023	0.7361	1.7719
20	0.9101	0.7509	0.0011	0.3429	0.8255
21	0.0099	0.0082	0.0000	0.0037	0.0090
22	0.4218	0.3480	0.0005	0.1589	0.3825
23	0.9142	0.7542	0.0011	0.3445	0.8292
24	0.0140	0.0116	0.0000	0.0053	0.0127
25	0.2283	0.1884	0.0003	0.0860	0.2071
26	0.1430	0.1180	0.0002	0.0539	0.1297
27	0.0781	0.0644	0.0001	0.0294	0.0708
28	0.0438	0.0362	0.0001	0.0165	0.0398
29	0.0438	0.0362	0.0001	0.0165	0.0398
30	0.0459	0.0379	0.0001	0.0173	0.0417
31	0.0147	0.0121	0.0000	0.0055	0.0133
32	0.0179	0.0148	0.0000	0.0068	0.0163
33	0.0040	0.0033	0.0000	0.0015	0.0036
34	0.0297	0.0245	0.0000	0.0112	0.0269
35	0.0213	0.0176	0.0000	0.0080	0.0193
Total	36.4661	19.8671	0.0438	13.7404	24.4549

Table 3.2. Which presented the detailed analytical results of the real information in reference to the existing section voltage drops, nodes voltage and power loss under the loaded situation. The result shows the high voltage drop 32% and power loss of 21.7%. Respectively the power loss and voltage drop curves are shown in the above figures. The curves in the figure show the keen and unbalanced changed in the node voltages of the feeder. There are a lot of debates for this unbalanced node voltage variation, the unbalanced distribution of the load is one of the main reason. Experimenting the existing situation of the feeder, it is noticed that the voltage of any one node is not in permissible limits. Experimenting with the voltage profile of the existing network, the serious nature of the power tendency issue can be argued. Under such serious conditions, the reliability and efficiency of the distribution network are seriously influenced. The power loss curve of figure 3.9. Indicates that there is expressive power loss at node 1, 11 and 13. The keen deviation in power loss are noted are up to node number 23. Accordingly, the power loss decreases almost to zero up to node number 35. In the start of the feeder, the huge current flow in the system, which causes the power loss in segments of the network. The expressive contraction in the power loss has been noticed at the end of the feeder. Comparatively, both the curves of figure 3.8 and figure 3.9 describes the huge voltage drops and power loss in the starting nodes of the system.

III. PERFORMANCE ENHANCEMENT OF SYSTEM

A. Enhancement with DG

To provide the voltage with in permitted limits to the end users, DGs are usually installed in the distribution system. The DG lesson the current along the feeder section, while it produces the real and reactive power to the load. The decrease in the current, effect the voltage raises up in an amount at the receiver end. To measure the profit of voltage profile advancement a voltage profile progress index has been presented which is usually the difference of voltage at various nodes, when DG is linked to the system at the various node and when DG is not an appliance to the system underneath same circumstances.

After DG integration the current through the distribution system decreases to very low as compared to the existing system. This decreasing in the current sets the voltage profile with in permissible to great extend except the very tail nodes. The voltage drop is reduced from 4.164 to 1.895 KV after DG integration. The voltage profile has been improved by 19% as comparatively. The voltage profile is improved by a remarkable magnitude as shown in Table 5. A noteworthy voltage drop diminution in the system is shown in figure 5 ~ 6, presenting the voltage profile curve.

After the DG-integration, the functioning of the distribution feeder has been enhanced. This is done by integrating 97 small scale DGs having the total size of 3 MVA. Which is about 44.55 % of the of the main source capacity. To rectify the voltage profile of the distribution feeder both the reactive and active power loss must be reduced [24]. By integrating the DGs in the distribution system at the position of tub wells can rectify the voltage profile which in terms enhance the distribution feeder efficiency. After DGs integration, the voltage drops and power losses are minimized, and the overall operation of the system is increased. These are evaluated using the expressions (5 ~ 7).

$$VP(i) = \frac{(Vi-Vnom)x(Vmax-Vi)}{(Vnom-Vmin)x(Vmax-Vnom)}, \quad (5)$$

$$VPI = \frac{1}{n}\sum_{i=0}^{n} VP(i), \quad (6)$$

$$\Delta Ploss = \int_{x=n0}^{n+1}\left[\frac{\Delta I2}{\Delta s} \times \emptyset(n+1) \times R(n, n+1)\, dx\right] \quad (7)$$

When the solar PV renewable Distributed Generation units of proposed sizes were integrated as illustrated in figure 3, the current reduced from 360 A to 181 Amp. Due to the decrease in the load current drawn from the grid, the net voltage drop and power loss will obviously be decreased.

B. Enhancement through bifurcation

Bifurcation technique is used to enhance the quality of voltage profile by reducing line losses and voltage drop which helps you to achieve your objectives. It is a traditional method Longley used for quality impartments. Here, it is introduced for comparison purpose with modern DG integration techniques. Through bifurcation, the existing distributed system is divided into three different sections. After analyzing each of the section and estimating the losses, their results are compared with the existing feeder analyzed data. The existing feeder is very lengthy and wide-spread, therefore causing high line losses and severe voltage drop. This poor voltage in distribution feeder is not enough efficient to be utilized by the consumers at the far end of the network. The technique well reduces these losses and hence improving the voltage quality without any additional plantation or power magnitude improvement.

The data calculated after bifurcation of the existing feeder is given in Table 4 below.

Table 4. Segment current, line loss and voltage drop along feeder length.

Segment No	Length (Km)	Segment Current (A)	Line losses (KV)	Voltage Drops (KV)
1	5.915543647	360	313.945	1.185074551
2	0.424776703	107.67	4.0626	0.041481133
3	0.819170624	82.7	4.6221	0.061443378
4	1.809778411	73.55	8.0769	0.120726688
5	0.354311024	64.53	1.2172	0.02073679
6	1.429375289	51.61	3.141	0.066907582
7	0.85555973	44	1.3665	0.034142728
8	0.601252832	35.59	0.6283	0.01940798
9	0.559793701	23.35	0.2518	0.011855233
10	0.126817453	10.62	0.0118	0.001221515

In the same way, bifurcation 2 is performed to further make improvements in the power quality to even better results. Voltage profile improvement after analyzing all sections are expressed in the Fig.3 given below.

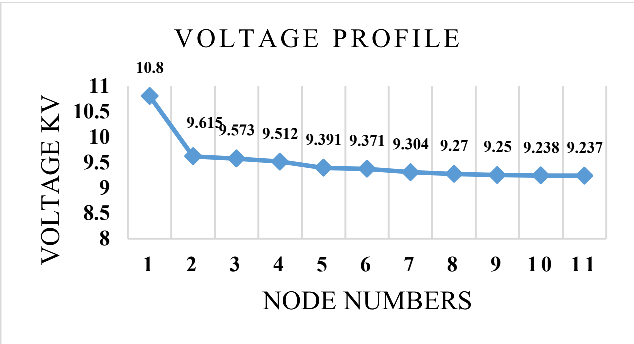

Fig. 3 Voltage profile graph

IV. RESULTS AND DISCUSSIONS

Line losses have been improved by 555.2264 KW. The reduction comparison is shown below in fig 6. The feeder performance has been enhanced by integrating 97 small scale DGs having the total size of 3 MVA. Which is only 44.55 % of the of the main source capacity. In the same way, the voltage drops are reduced from 1185 V in segment

1, 509.2 V in segment 2 and 380 V in segment 3 to 598.5 V, 2210.9 V and 155 V respectively.

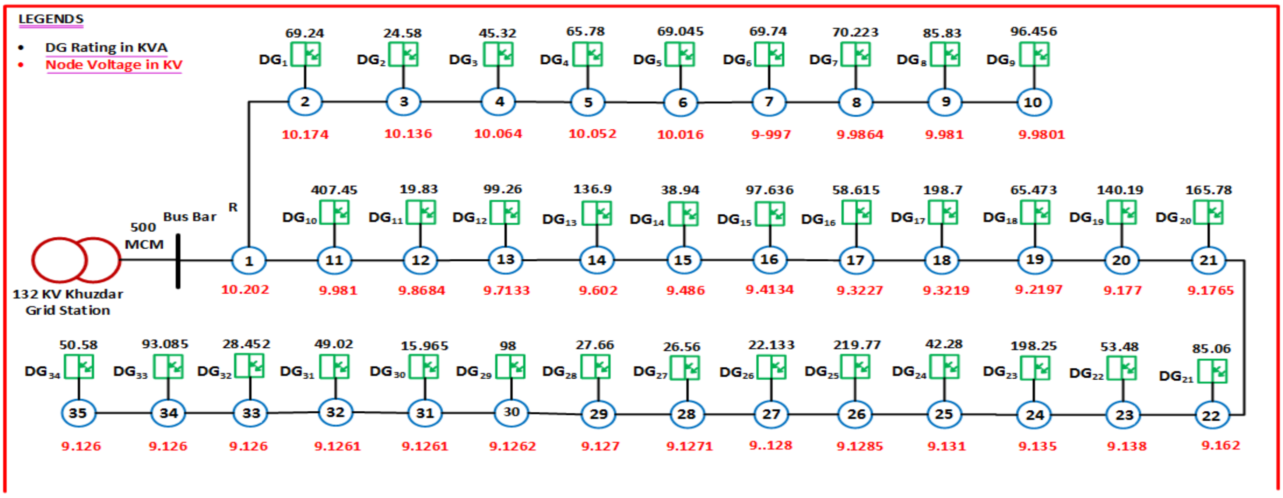

Figure.4. Integration of Solar PV Distributed Units at proposed sites of the distribution network

Table 5. Performance key indicators of the feeder with DG integration

Segment No	Segment Current (A)	Line losses (KW)	Voltage Drops (KV)
1	181.81	80.07263177	0.598495567
2	72.335	1.833629594	0.027867909
3	51.305	1.7788843	0.038117927
4	43.585	2.836308408	0.071541437
5	37.185	0.40417941	0.011949443
6	27.915	0.9189153	0.036189211
7	24.345	0.418334653	0.018891016
8	19.345	0.185630165	0.010549238
9	11.225	0.058190844	0.005699143
10	5.04	0.002657627	0.000579702
11	109.475	17.79684839	0.220913751
12	102.425	8.452333899	0.112141219
13	81.205	9.269590527	0.155121638
14	77.665	6.361361922	0.111306201
15	72.969	6.246092439	0.116322738
16	70.61	3.757366725	0.072312267
17	69.414	4.63139658	0.090669141
18	67.009	0.038892003	0.000788718
19	57.684	5.363071065	0.102211425
20	51.834	2.017364492	0.042786908
21	43.134	0.015223564	0.000388005
22	37.934	0.50071733	0.014511264
23	32.494	0.796359473	0.02694308
24	27.764	0.008912177	0.000352893
25	19.494	0.0715897	0.004037298
26	16.934	0.033836712	0.002196696
27	13.334	0.011453366	0.000944309
28	11.934	0.005150233	0.000474441
29	11.934	0.005150128	0.000474431
30	10.184	0.003929889	0.000424232
31	5.584	0.000378402	7.44988E-05
32	3.564	0.000188058	5.80089E-05
33	1.5	7.39392E-06	5.41907E-06
34	1.5	5.51129E-05	4.03928E-05
35	0	0	0
Total	-	153.896632	1.89537957

Ninety-seven DGs are integrated with the system. The elaborated study of the outcomes presents remarkable diminution in the voltage drops and power loss as listed in table 6. It is noticed from the figure 7, that, the power loss of 313.95 KW at node number 1, 95 KW at node number 2 and 55 KW at node number 2 are reduced to 80.073 KW, 17.80 KW and 9.2 KW respectively as ascertained in the power loss comparison curve. In the same way, the voltage drop is reduced from 1185 V in segment 1, 509.2 V in segment 2 and 380 V in the segment 3 to 598.5 V, 2210.9 V and 155 V respectively

Table 6. Results with solar PV (DG) integration

	Without DG	With DG	improvement
voltage profile	7.12	9.162	2.04
power loss	709.1235	153.732	555.8
voltage drop	3680.2	1674	2006.2

It is noticed from the figure 7, that, the power loss of 313.95 KW at node number 1, 95 KW at node number 2 and 55 KW at node number 2 are reduced to 80.073 KW, 17.80 KW and 9.2 KW respectively as ascertained in the power loss comparison curve. In the same way, the voltage drops are reduced from 1185 V in segment 1, 509.2 V in segment 2 and 380 V in the segment 3 to 598.5 V, 2210.9 V and 155 V respectively.

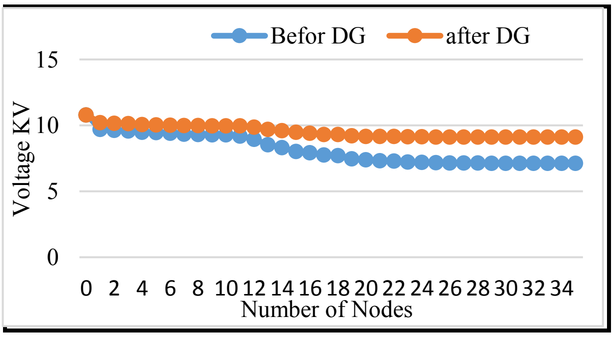

Figure 5. Voltage profile improvement with DG

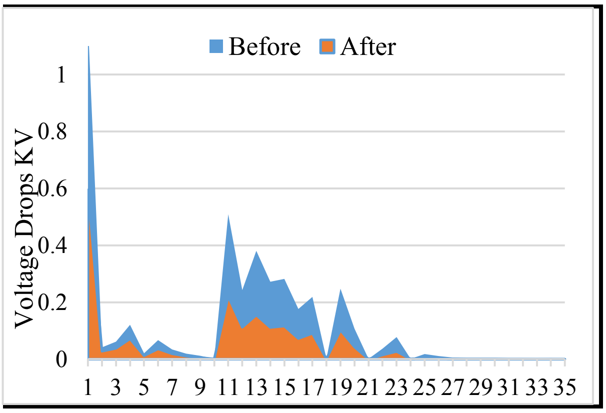

Figure 6. Voltage drop reduction with DG

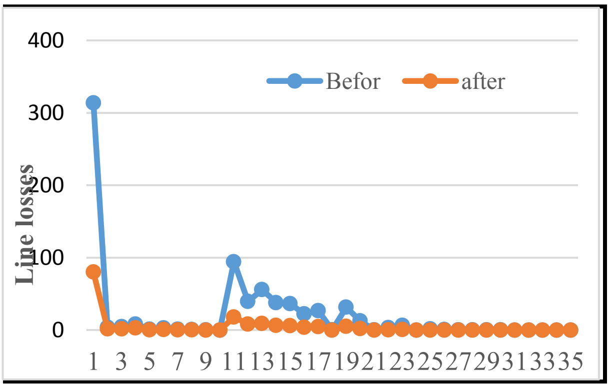

Figure 7. Power loss minimization with DG integration

V. CONCLUSION

Before the implementation of renewable solar PV distributed generation at optimal sites the voltage drop was about 3680 volts (34.07% of the bus nominal voltage). But with DG the drop is reduced to only 1674 volts with the same load connected. The voltage profile is improved by 18.57%. Similarly, before the DG integration at optimal sites, the active power loss was 0.71MW which is controlled to a limit of only0.154 MW with a total saving of 555 kW power. The capacities of DGs were selected in such a way that they will not only improve the power quality but will be more economical as compared to the other proposed techniques, considering multi DG units of large size. The total capacity of DG proposed in this work is about 60% of the total distribution system power capacity. In some researches even, the DG sizes crossed the maximum allowable DG size of 75% of the system rating.

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