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Loading Capability Enhancement of Existing Unbalanced Distribution System with Distributed Generation

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Abstract: The distribution system supplies power to the consumers of the different nature that may be residential, commercial, and industrial. It is very difficult to have perfect balance in all the phases due the stochastic nature of the load and the switching behavior of the consumers. It is thus important to study the impact of unbalances on the loadability of the network and the impact of the presence of distributed generation. This paper proposed a method for finding the economic size of Distributed generation (DG) and its optimal location in unbalanced radial distribution system (URDS). The main contributions of the paper are: (i) Determination of economic rating of DG based on variational algorithm subjected to minimize the total cost, (ii) Examine the comparative impact of DG power factor in reduction of losses, improvement in voltage profile and cost saving (iii) Estimation of total released feeder capacity after DG placement, (iv) Analysis of P-V, Q-V curve for finding the improvement of loading capability. The results have been determined for IEEE 25 bus unbalanced radial distribution system.

Keywords: Distributed generation; Unbalanced distribution system; DNO; Loss reduction; Loading capability

1. INTRODUCTION

Distribution system is the back-bone of the power system network which is responsible for the connection between high voltage transmission system and low-voltage consumers. The distribution system, which was earlier passive in nature is now operating with the integration of the distributed generation and has changed its operation to an active network. This will be important for the distribution network operator (DNO) to know the impact of the distributed generation and their sizes for meeting the requirement of the loads under the unbalances.

The Distribution network operator (DNO) has the responsibility of effective operation of the network in the presence of the renewable energy sources as the distributed generation (DG). There are various operational and economic advantages of distributed generation integration in the distribution system as explained in [1-3]. The various types of DGs, their definition, application and the sizes based on the definition are well defined in a paper by the authors in [4]. The various issues of interconnection of DGs in distribution system are well explored in [5-6]. The placement of DGs is an important problem, which requires the optimal power flow to analyze the multi objective problem to obtain the benefits and the effective utilization of DGs in the distribution system. The DG integration benefits for DNO as well as DG developers and its impacts on existing system were explained in [7]. The various set of laws for DNO ownership of DG and its impact on existing system were described in [8]. The economic profit of DG incorporation for DNO arising from loss reduction and network reinforcement deferral in deregulated environment was well explored in [9].

DNOs have the responsibility to develop the techniques to find best possible location as well as optimal rating of DGs for obtaining the benefits of DGs in distribution system. Various researchers suggested a variety of method for finding best location as well as optimal size of DGs that can deployed in DS. A hybrid combination of genetic algorithms (GA) and optimal power flow (OPF) technique was proposed for finding best position as well as most appropriate size of DG by DNOs in [10]. Hybrid immune-GA scheme was proposed for profit maximization of DNOs and DG owners by finding best position and optimal size of DGs in a restructured environment in [11]. Expansion planning of DG based on dynamic fuzzy interactive approach with network reinforcement was well explained in [12], which optimized total cost, emission cost and voltage profile of the network by determining the best possible design of

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timing, rating and placement of DG. Investigation of DNO profit and selection of optimal DG size options for various loading conditions were proposed in [13].

The impact of wind based DG allocation in DS using combined Monte Carlo simulation and market-based OPF for deregulated environment was presented with Lawmaking framework for the DNO in terms of DG integration in [14]. The Particle swarm optimization (PSO) and an analytical approach was used for finding best location and rating of DG units with load variations for long term scheduling in [15]. Reduction in line losses (RLL) and voltage profile improvement (VPI) are the two technical benefits among several technical benefits of DG placement as reported in [16, 17]. Reduction in losses provides direct technical as well as economical benefits for the DNOs [18]. With the increased integration of DG, distribution networks have number of technical challenges to DNOs. The key challenges faced by DNOs are to identify the prominent network place and DG capacity for optimum exploitation of distribution system [19]. The strategic benefits of DG planning for the growth of the distribution system and its benefits for DG ownership are explained in [20].

Various researchers show the technique of optimal placement of DG with an objective of VPI and RLL. A comparison of techniques proposed by various authors for DG placement, sizing and its modeling in power distribution networks with future prospective was well explained and reported in [21]. Chance-constrained programming based theory for optimal placement of PV based DG with an objective of VPI and RLL was proposed in [22]. Teaching Learning Based Optimization, ant colony optimization (ACO), hybrid ACO, genetic algorithm, particle swarm optimization (PSO), binary PSO, improved PSO, modified firefly method, cat swarm optimization, and a new multi-objective index (IMO)-based analytical approach was proposed for finding optimal location as well as size DG in balanced radial distribution system (RDS) [23-33].

Many research works was carried out by researchers for finding the optimal allocation of DG in balanced RDS with an objective of VPI and RLL. But, few papers are available in the literature that has analyzed URDS with DG placement. Also, voltage stability analysis of URDS in the presence of DG and its impact on the P-V, Q-V curve needs to be analyzed. This paper presented a technique to find economic size of DG and its optimal placement in URDS with an objective of VPI and RLL. The P-V, Q-V curves are also obtained and plotted for finding the improvement of active as well as reactive loading capability of the network with DG placement. The impact of DG power factor is also analyzed for obtaining VPI and RLL and thereby improving the loading capability of the feeders. The loading capability enhancement with DG may result the reduction of cost of construction of newly high voltage transmission as well distribution lines with increase of load. A complete cost analysis with DG is also carried out. The results have been determined for IEEE 25 bus unbalanced radial distribution system [35].

2. COST FUNCTION OF ENEERY AND DG AND SAVINGS

With DG integration, there is considerable reduction in the losses. The cost can be determined for the energy loss reduction. The cost of DG power can also be calculated to find the overall savings of energy in the distribution system.

A. *Cost of Energy Loss (CEL)[1]*

$$\text{CEL} = (\text{Total Real power Loss}) * (E_c * T) \quad \$ \qquad (1)$$

E_c : Energy rate ($/kWhr)

T : Time duration (hr)

$E_c = 0.06$ $/kWhr, $T = 8760$ hr

B. *Cost of DG*

The Cost component of DG for real power:

$$C(Pdg) = a * Pdg^2 + b * Pdg + c \quad \$/\text{MWhr} \qquad (2)$$

Cost coefficients are taken as:

a=0 b=20 c=0.05

C. *Savings in Cost of Energy Loss ($)*

Net Saving ($) =CEL ($) in base case - (CEL ($) with DG + Cost of DG ($)) (3)

3. ALLOCATION OF DG IN URDS

Most favorable location of DG in URDS is obtained using Combined Power Loss Sensitivity index (CPLS) [1]. The CPLS profiles of 25 bus URDS is obtained and shown in Fig.1. The bus with high CPLS value is selected as optimum bus for DG placement. CPLS is maximum in 10th branch i.e 9th bus for 25 bus URDS.

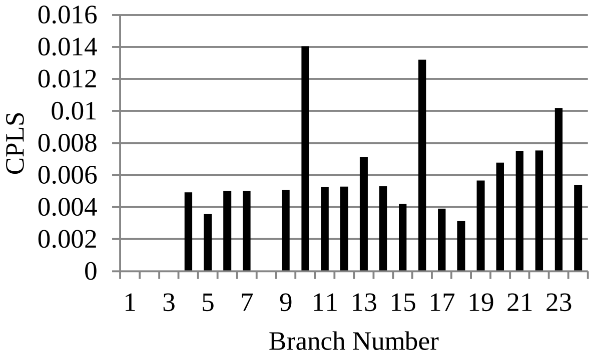

Figure1. CPLS profile for finding best location of DG in 25 bus URDS

Following are the steps for finding the size of DG using variational algorithm:

- First, place the DG at the bus based on 9th bus.
- Vary DG size from zero to the rating equivalent to feeder reactive loading capacity in constant steps and record the losses with each rating of DG.
- Select the DG rating that offers least amount of losses.

Economic rating of DG is determined based on variational algorithm subjected to minimization of total cost as explained in the flow chart shown in Fig.2. The mathematical equations for solving the load flow of URDS are derived in [34]. The variation of cost of energy loss, cost of DG and total cost with various sizes of DG operating at unity power factor (UPF), 0.9 power factor, and 0.85 power factor (lag) is specified in Table 1 and its graphical representation is shown in Fig.3, Fig.4 and Fig.5 respectively.

As observed from the Table 1 and Fig.3 with DG of 450 kW size, losses are higher compared to DG of size 550 kW, however total annual cost saving including energy loss cost and DG cost is economical with 450 kW DG as highlighted in Table 1. Therefore, 450 kW DG at UPF is selected as most appropriate size from economic point of view. Further, the analysis has been carried out for voltage profile improvement, reduction of line losses, released feeder capacity calculation, cost analysis and obtaining P-V and Q-V curves for finding the active as well as reactive loading capability.

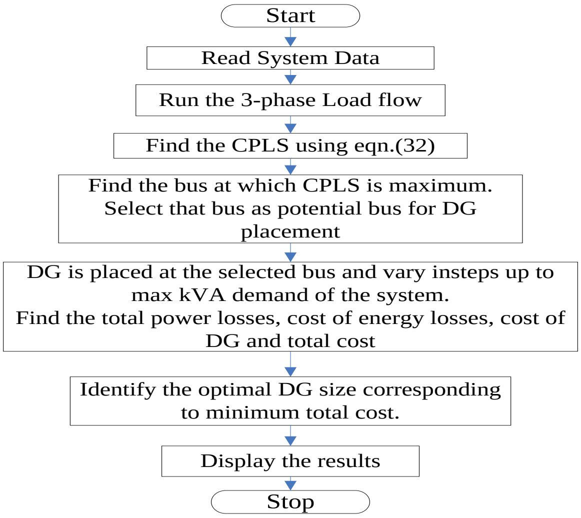

Figure 2. Flow chart for optimal allocation of DG

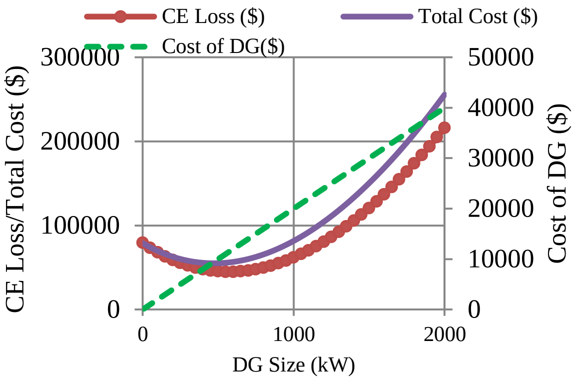

Figure 3. Determination of Economic size of DG operating at UPF for 25 bus URDS

TABLE I. DETERMINATION OF OPTIMAL ECONOMIC SIZE OF DG OPERATING AT VARIOUS POWER FACTORS FOR 25 BUS URDS

DG Size (kW)	**Cost Analysis with DG at UPF**				**Cost Analysis with DG at 0.9 PF**				**Cost Analysis with DG at 0.85 PF**			
	TPL (kW)	***CE Loss ($)***	***Cost of DG($)***	***Total Cost ($)***	***TPL (kW)***	***CE Loss ($)***	***Cost of DG($)***	***Total Cost ($)***	***TPL (kW)***	***CE Loss ($)***	***Cost of DG($)***	***Total Cost ($)***
0	150.12	78903.07	0.05	78903.12	150.12	78903.07	0.05	78903.12	150.12	78903.07	0.05	78903.12
50	138.82	72963.79	1000.05	73963.84	136.15	71560.44	1000.136	72560.58	135.93	71444.81	1000.136	72444.94
100	128.66	67623.7	2000.05	69623.75	123.38	64848.53	2000.222	66848.75	122.96	64627.78	2000.222	66628
150	119.62	62872.27	3000.05	65872.32	111.79	58756.82	3000.309	61757.13	111.17	58430.95	3000.309	61431.26
200	111.67	58693.75	4000.05	62693.8	101.35	53269.56	4000.395	57269.95	100.53	52838.57	4000.395	56838.96
250	104.79	55077.62	5000.05	60077.67	92.017	48364.14	5000.481	53364.62	91.009	47834.33	5000.481	52834.81
300	98.966	52016.53	6000.05	58016.58	83.759	44023.73	6000.567	50024.3	82.565	43396.16	6000.567	49396.73
350	94.167	49494.18	7000.05	56494.23	76.573	40246.77	7000.653	47247.42	75.196	39523.02	7000.653	46523.67
400	90.377	47502.15	8000.05	55502.2	70.419	37012.23	8000.74	45012.97	68.86	36192.82	8000.74	44193.56
450	87.562	46022.59	9000.05	**55022.64**	65.27	34305.91	9000.826	43306.74	63.533	33392.94	9000.826	42393.77
500	85.731	45060.21	10000.05	55060.26	61.103	32115.74	10000.91	42116.65	59.189	31109.74	10000.91	41110.65
550	84.852	44598.21	11000.05	55598.26	57.896	30430.14	11001	41431.14	55.806	29331.63	11001	40332.63
600	84.907	44627.12	12000.05	56627.17	55.625	29236.5	12001.08	**41237.58**	53.36	28046.02	12001.08	**40047.1**
650	85.879	45138	13000.05	58138.05	54.27	28524.31	13001.17	41525.48	51.829	27241.32	13001.17	40242.49

700	87.752	46122.45	14000.05	60122.5	53.809	28282.01	14001.26	42283.27	51.193	26907.04	14001.26	40908.3
750	90.511	47572.58	15000.05	62572.63	54.224	28500.13	15001.34	43501.48	51.431	27032.13	15001.34	42033.48
800	94.152	49486.29	16000.05	65486.34	55.495	29168.17	16001.43	45169.6	52.525	27607.14	16001.43	43608.57
850	98.637	51843.61	17000.05	68843.66	57.604	30276.66	17001.52	47278.18	54.455	28621.55	17001.52	45623.06
900	103.96	54641.38	18000.05	72641.43	60.533	31816.14	18001.6	49817.75	57.203	30065.9	18001.6	48067.5
950	110.12	57879.07	19000.05	76879.12	64.265	33777.68	19001.69	52779.37	60.752	31931.25	19001.69	50932.94
1000	117.08	61537.25	20000.05	81537.3	68.784	36152.87	20001.77	56154.64	65.085	34208.68	20001.77	54210.45
1050	124.85	65621.16	21000.05	86621.21	74.073	38932.77	21001.86	59934.63	70.187	36890.29	21001.86	57892.15
1100	133.41	70120.3	22000.05	92120.35	80.119	42110.55	22001.95	64112.49	76.041	39967.15	22001.95	61969.1
1150	142.75	75029.4	23000.05	98029.45	86.905	45677.27	23002.03	68679.3	82.634	43432.43	23002.03	66434.46
1200	152.85	80337.96	24000.05	104338	94.418	49626.1	24002.12	73628.22	89.949	47277.19	24002.12	71279.31
1250	163.7	86040.72	25000.05	111040.8	102.62	53937.07	25002.21	78939.28	97.95	51482.52	25002.21	76484.73
1300	175.29	92132.42	26000.05	118132.5	111.54	58625.42	26002.29	84627.72	106.66	56060.5	26002.29	82062.79
1350	187.62	98613.07	27000.05	125613.1	121.14	63671.18	27002.38	90673.56	116.06	61001.14	27002.38	88003.51
1400	200.66	105466.9	28000.05	133466.9	131.42	69074.35	28002.46	97076.82	126.12	66288.67	28002.46	94291.14
1450	214.42	112699.2	29000.05	141699.2	142.35	74819.16	29002.55	103821.7	136.83	71917.85	29002.55	100920.4
1500	228.88	120299.3	30000.05	150299.4	153.93	80905.61	30002.64	110908.2	148.19	77888.66	30002.64	107891.3
1550	244.03	128262.2	31000.05	159262.2	166.15	87328.44	31002.72	118331.2	160.18	84190.61	31002.72	115193.3
1600	259.86	136582.4	32000.05	168582.5	179	94082.4	32002.81	126085.2	172.8	90823.68	32002.81	122826.5
1650	276.36	145254.8	33000.05	178254.9	192.46	101157	33002.89	134159.9	186.02	97772.11	33002.89	130775
1700	293.52	154274.1	34000.05	188274.2	206.52	108546.9	34002.98	142549.9	199.83	105030.6	34002.98	139033.6
1750	311.34	163640.3	35000.05	198640.4	221.17	116247	35003.07	151250	214.24	112604.5	35003.07	147607.6
1800	329.88	173384.9	36000.05	209385	236.41	124257.1	36003.15	160260.2	229.23	120483.3	36003.15	156486.4
1850	349	183434.4	37000.05	220434.5	252.22	132566.8	37003.24	169570.1	244.78	128656.4	37003.24	165659.6
1900	368.74	193809.7	38000.05	231809.8	268.6	141176.2	38003.33	179179.5	260.89	137123.8	38003.33	175127.1
1950	389.12	204521.5	39000.05	243521.5	285.53	150074.6	39003.41	189078	277.55	145880.3	39003.41	184883.7
2000	410.1	215548.6	40000.05	255548.6	303.01	159262.1	40003.5	199265.6	294.75	154920.6	40003.5	194924.1

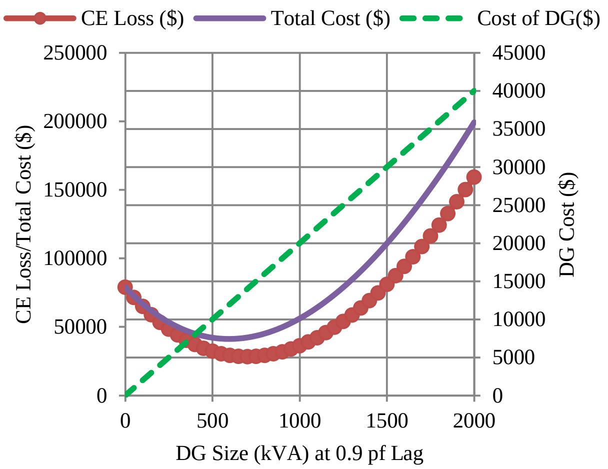

Figure 4. Determination of Economic size of DG operating at 0.9 pf lag for 25 bus URDS

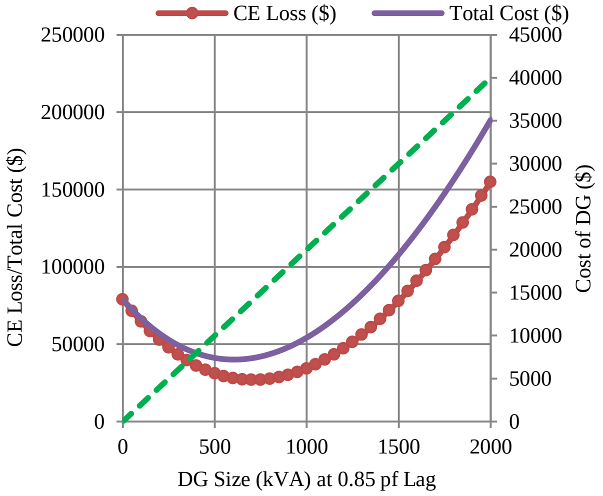

Figure 5. Determination of Economic size of DG operating at 0.85 pf lag for 25 bus URDS

Similarly, 600 kVA DG is the most appropriate size at 0.9 and 0.85 power factor (lag) as observed from Fig.4 and Fig.5. Hence, it is selected as optimal DG size at 0.9 and 0.85 power factor (lag).

4. RESULTS AND DISCUSSIONS

In addition to the loss determination, the voltage profile, cost benefit analysis, and voltage stability margin enhancement results have also been obtained for 25 bus URDS.

The total load is 1073.3+j*792 kVA in phase A, 1083.3+j*801 kVA in phase B and 1083.3+j*800 kVA in phase C. The base values used for the analysis are 30 MVA and 4.16 kV. In the base case, the total power losses in the system is 150.118+j*167.275 kVA. Due to these losses, cost of energy loss per annum is 78902.0208 $. Feeder capacity of the 25 bus URDS is 4248.2 kVA.

After placement of DG at UPF the total power losses reduced to 87.56+j*99.16 kVA and due to these losses, cost of energy loss per annum is 46022.58 $. The annual cost of 450 kW DG is 27000.15$. Net annual cost saving is 5879.3 $ as mentioned in Table 2. The released feeder capacity is 1066.8 kVA.

After installation of DG at 0.9 power factor (lag), power losses are reduced to 55.62+j*62.96 kVA and the net annual cost savings is 13661.75 $. Similarly, with installation of DG at 0.85 power factor (lag), power losses are reduced to 53.36+j*60.65 kVA and net annual cost savings is 14852.76 $.

The summary of results for each case is given in the Table 2 and the voltage profile of each bus is shown in Fig.6. It is observed from the figure that there is enhancement of voltage at each bus with DG.

The P-V curve for each phase with DG placement is determined and is shown in Fig.7. With base case, active loading capability for phase A is 620 kW, for phase B is 640 kW, for phase C is 910 kW. With DG placement it is observed that there is enhancement in loading margin and the critical active loading capability enhanced to 1070 kW in phase A, 1090 kW in phase B, 1360 kW in phase C. Also, with DG at 0.9 power factor (lag), the loading capability enhanced to 1360 kW in phase A, 1360 kW in phase B, 1670 kW in phase C. similarly, with DG at 0.85 power factor lag, the loading capability enhanced to 1360 kW in phase A, 1360 kW in phase B, 1690 kW in phase C.

The Q-V curve for each phase with DG placement is shown in Fig.8. With base case the reactive loading capability for phase A is 720 kVAr, for phase B is 810 kVAr, for phase C is 930 kVAr. With DG at UPF, the critical reactive loading capability enhanced to 1150 kVAr in phase A, 1290 kVAr in phase B, 1310 kVAr in phase C.

Similarly, with DG at 0.9 power factor (lag) reactive loading capability enhanced to 1490 kVAr in phase A, 1640 kVAr in phase B, 1650 kVAr in phase C. Also, with DG at 0.85 power factor (lag) reactive loading capability enhanced to 1520 kVAr in phase A, 1670 kVAr in phase B, 1680 kVAr in phase C. The improvement of critical active and reactive loading capability is recorded for each phase and presented in Table 3.

TABLE II. COMPARISON OF RESULTS WITH DG OPERATING AT VARIOUS POWER FACTOR FOR 25 BUS URDS

Parameters	**Base Case**			**After placement of DG at UPF**			**After placement of DG at 0.9 PF Lag**			**After placement of DG at 0.85 PF Lag**		
	Phase A	***Phase B***	***Phase C***	***Phase A***	***Phase B***	***Phase C***	***Phase A***	***Phase B***	***Phase C***	***Phase A***	***Phase B***	***Phase C***
DG size	------	------	------	450 kW	450 kW	450 kW	600 kVA	600 kVA	600 kVA	600 kVA	600 kVA	600 kVA
TPL (kW)	52.81	55.44	41.86	30.73	32.37	24.46	19.58	20.49	15.55	18.81	19.65	14.90
TPL reduction (%)	------	------	------	41.82	41.61	41.51	62.92	63.04	62.85	64.39	64.56	64.39
TQL	58.29	53.29	55.69	34.41	31.59	33.16	21.88	20.05	21.03	21.09	19.30	20.26
TQL reduction (%)	------	------	------	40.96	40.72	40.45	62.46	62.38	62.23	63.80	63.77	63.62
Minimum Voltage @ 12th bus	0.9284	0.9284	0.9365	0.9563	0.9577	0.9598	0.9648	0.9650	0.9687	0.9654	0.9654	0.9694
V.R (%)	7.159	7.16	6.341	4.367	4.222	4.014	3.518	3.497	3.129	3.453	3.456	3.058
Improvement in V.R (%)	------	------	------	39	41.03	36.70	50.86	51.16	50.65	51.77	51.73	51.77
Pload (kW)	1073.3	1083.3	1083.3	1073.3	1083.3	1083.3	1073.3	1083.3	1083.3	1073.3	1083.3	1083.3
Qload (kVAr)	792	801	800	792	801	800	792	801	800	792	801	800
total active power demand (kW)	1126.11	1138.743	1125.162	654.03	665.67	657.76	552.88	563.79	558.85	582.10	592.95	588.20

total released active power demand (kW)	------	------	------	472.08	473.07	467.40	573.23	574.95	566.31	544.01	545.79	536.96
total reactive power demand (kVAr)	850.29	854.294	855.691	826.409	832.592	833.164	552.3451	559.5161	559.4971	497.0294	504.2354	504.1904
total released reactive power demand (kVAr)	------	------	------	23.88	21.70	22.52	297.94	294.77	296.19	353.26	350.06	351.50
Total Feeder Capacity (kVA)	1411.07	1423.57	1413.57	1053.90	1065.98	1061.5	781.52	794.30	790.79	765.43	778.36	774.72
Total released feeder capacity (kVA)	------	------	------	357.17	357.59	352.07	629.55	629.27	622.78	645.64	645.21	638.85
Annual CE Loss ($)	78902.0208			46022.5872			29237.0256			28046.016		
Annual DG Cost ($)	------			27000.15			36003.24			36003.24		
Annual Cost Saving ($)	------			5879.3			13661.755			14852.76		

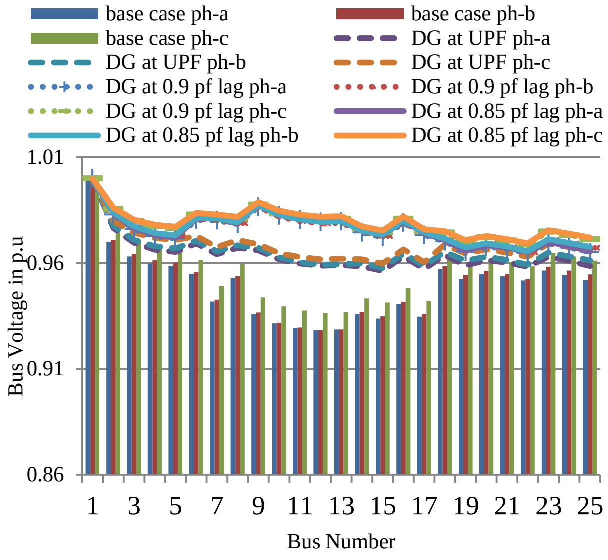

Figure 6. Comparison of voltage profile of URDS with DG placement

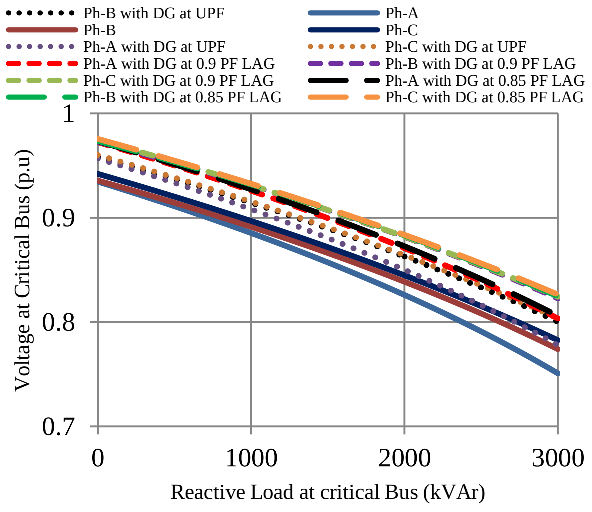

Figure 8. Comparison of reactive loading capability of URDS with DG placement

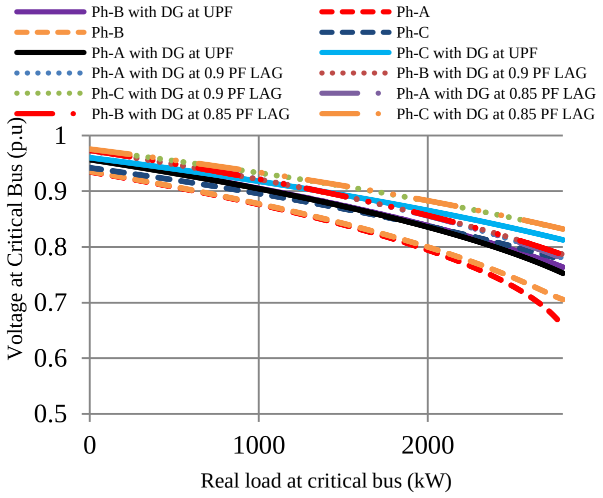

Figure 7. Comparison of active loading capability of URDS with DG placement

TABLE III. COMPARISON OF ACTIVE AND REACTIVE LOADING CAPABILITY OF 25 BUS URDS

Cases	**Ph-A**	**Ph-B**	**ph-C**	**Ph-A**	**Ph-B**	**ph-C**
	Critical Real Power Load (kW)			***Critical Reactive Power Load (kVAr)***		
Base case	620	640	910	720	810	930
DG at UPF	1070	1090	1360	1150	1290	1310
DG at 0.9 PF Lag	1360	1360	1670	1490	1640	1650
DG at 0.85 PF Lag	1360	1360	1690	1520	1670	1680

5. CONCLUSIONS

Based on analysis carried out, the proposed optimal placement of DG based on CPLS method lead to loss reduction, voltage profile improvement and net annual savings based on cost of energy loss. The obtained DG rating is economical. The study carried out in the proposed work can help the DNO to plan the better distribution system with DG integration. The following conclusions are summarized as follows:

- With the DG, there is significant improvement in voltage profile, enhancement in voltage stability margin, and reduction in power losses.
- With DG the critical loading margin enhances in each phases.
- Annual cost of energy loss savings are observed higher with the proposed method.
- There is considerable improvement in feeder capacity with DG.

The cost benefit analysis is essential for DNO operated competitive distribution companies for sustainability of DG integration and its remuneration of services in the system. The analysis carried out will provide a platform to design and plan efficient electricity market operation in terms of ancillary services.

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