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Enhancing Hosting Capacity within Standard Operational Limits: Single-to-Uniform DG Placement and 100% BESS-Capacitor Incorporation for Reverse Power Flow Mitigation

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Abstract

The extensive penetration of distributed generation (DG), particularly solar photovoltaic (PV) systems, into low voltage distribution networks (LVDN) has introduced technical challenges such as reverse power flow (RPF), excessive voltage rise, and thermal overloading of feeder components, all of which limit the hosting capacity (HC) of the network. This work evaluates a standard IEEE-33 bus radial distribution network through steady-state load flow simulations to compare two DG allocation strategies: a single lumped DG at the weakest bus, and the same DG capacity distributed uniformly among all load buses. For both strategies, the hosting capacity was identified by incrementally increasing DG penetration until violation of voltage limits, thermal loading, harmonic distortion, voltage stability index (VSI), or reverse power flow at the substation. Battery Energy Storage Systems (BESS) and capacitor banks were then integrated at DG-connected buses to assess further improvement. Results show that single lumped DG placement causes reverse power flow and localized overvoltage at penetration levels below 5%, whereas uniform distribution delays reverse power flow and supports penetration levels above 50%. Complete (100%) BESS integration together with capacitor bank deployment, combined with uniform DG allocation, achieved the highest hosting capacity while maintaining permissible voltage, loading, and power-flow conditions. The findings demonstrate that uniform DG allocation, together with strategic BESS and capacitor bank integration, offers electric distribution companies a practical and economical planning solution for accommodating higher renewable DG penetration without extensive feeder upgrades, while improving voltage stability and overall power quality.

Keywords: Distributed Generation, Reverse Power Flow Mitigation, Uniform DG Distribution, Hosting Capacity, Battery Energy Storage System

Introduction

The rapid growth of distributed generation (DG) integration, especially solar photovoltaic (PV) systems, into low voltage distribution networks (LVDN) has considerably transformed the operation of modern power systems. While this transition supports renewable energy adoption and reduces dependency on centralized generation, it introduces several technical challenges, including reverse power flow (RPF), excessive voltage rise, and thermal overloading of feeder components. These issues directly constrain the hosting capacity (HC) of a distribution network, which is defined as the maximum DG capacity that can be integrated while maintaining compliance with standard grid codes.

Traditional planning approaches often place a single lumped DG unit of optimal capacity at the weakest bus of a feeder. Although this approach is relatively simple to implement, it tends to escalate reverse power flow and cause localized voltage limit violations, particularly under conditions of high generation and low load demand. An alternative strategy, distributing the same DG capacity uniformly across all load buses, has been shown in the literature to alleviate these operational concerns naturally, without requiring additional hardware investment.

Beyond the DG allocation strategy itself, further improvements in hosting capacity can be achieved through the incorporation of Battery Energy Storage Systems (BESS) and capacitor banks. BESS units can absorb surplus generated power during periods of low demand, reducing reverse power flow at its origin, while capacitor banks provide reactive power support that improves voltage regulation, particularly at the far end of a feeder.

This study investigates and compares the effectiveness of single lumped versus uniform DG placement strategies in mitigating reverse power flow and enhancing hosting capacity on a standard IEEE-33 bus radial distribution network. It further examines the additional benefits achieved through complete (100%) deployment of BESS, together with capacitor banks, in extending DG hosting capacity while ensuring that all operational parameters remain within permissible limits. The objective is to provide distribution network planners with a practical and economical strategy for accommodating higher DG penetration levels without extensive feeder upgrades.

Results and Discussion

The IEEE-33 standard distribution network's parameters are already mentioned in the previous section and accordingly the architecture of the system is included in Figure 1.

Figure 1 IEEE-33 Standard Test System

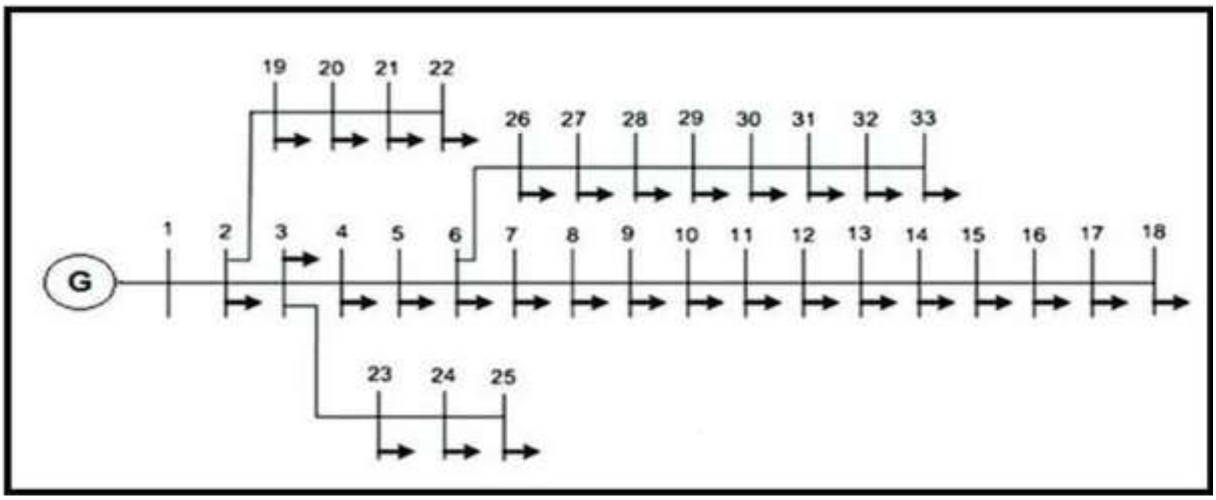
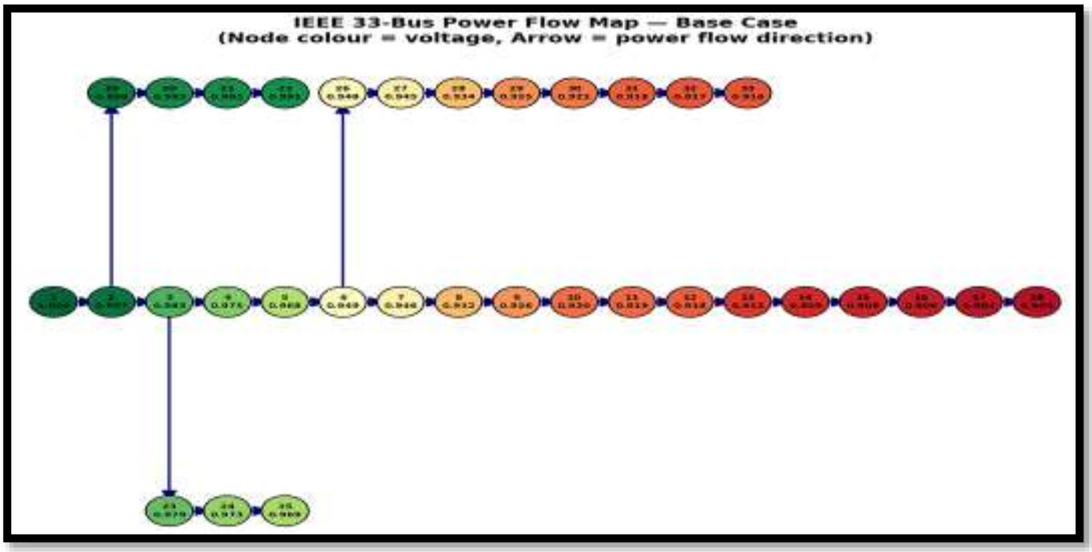


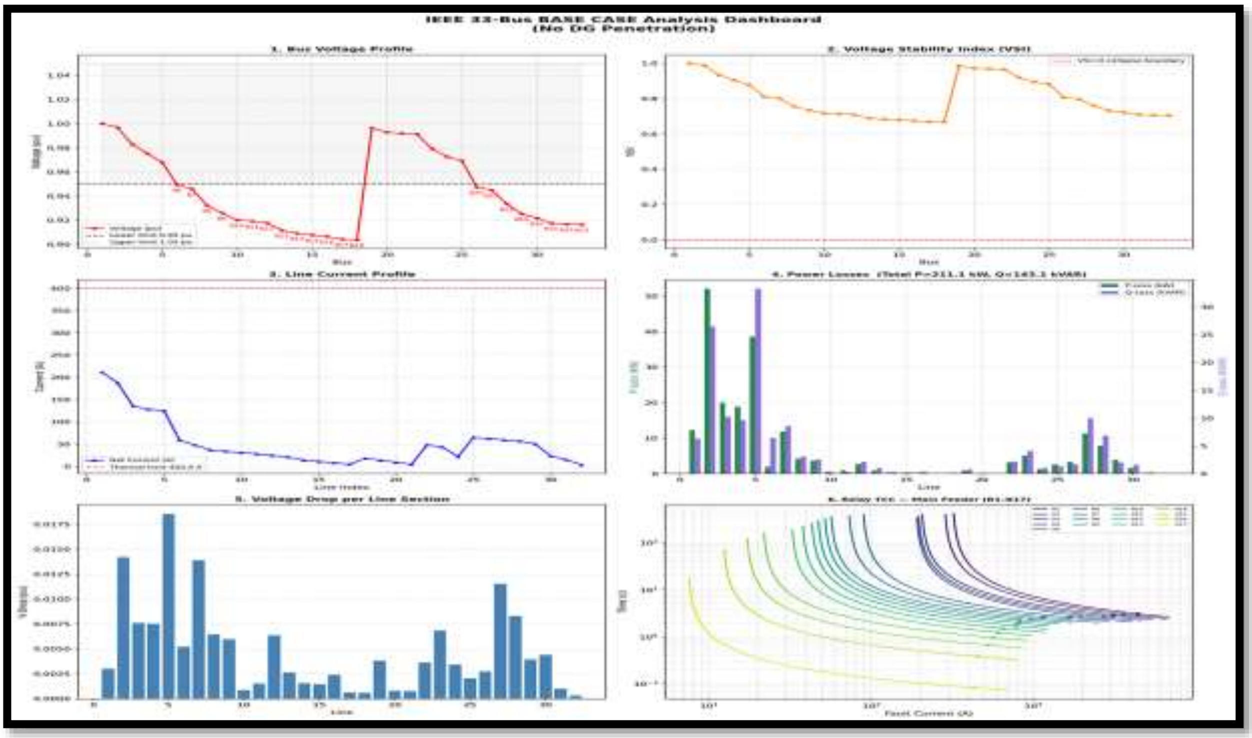
Figure 2 Power Flow Map (Base Case)



The operational parameters though mentioned in literature are checked here and verified for all operational parameters. The results are displayed as dashboard plots of all the operational parameters.

The results show the base case voltage profile, voltage stability index (VSI), line current profile, active and reactive power losses, voltage drop per line section and most important parameter is relay coordination. These are important for comparison purposes. Also, in Figure 3 the power flow map is included that shows unidirectional power flow from source to load as there is no other source connected in network.

Figure 3 Dashboard Results of Operational Parameters (Base Case)



Moreover, other harmonics related parameters are included in Figure 4 to address the power quality issues with violations of other parameters by increasing DG penetration.

Figure 4 Harmonic and THD Analysis (Base Case)

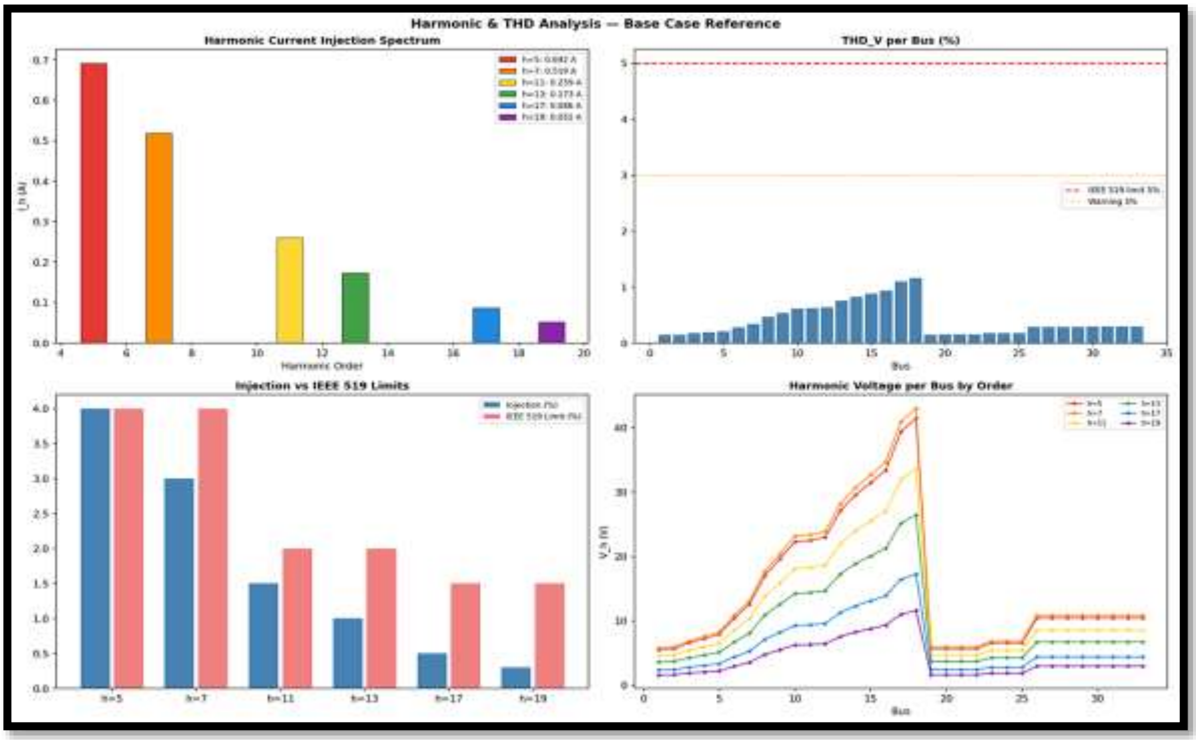


Table 1 Line Section Wise Operational Parameters (Base Case)

Line	I net (A)	Loading (%)	Power Flow (MW)	P loss (kW)	Q loss (kVAr)	Voltage Drop (pu)
1-2	211.121800	52.780000	3.926064	12.328725	6.284708	0.002989
2-3	187.644500	46.911000	3.452562	52.076244	26.524026	0.014203
3-4	135.142300	33.786000	2.370872	20.053261	10.212918	0.007594
4-5	128.403000	32.101000	2.230819	18.849967	9.600574	0.007513
5-6	125.284000	31.321000	2.151969	38.565265	33.291383	0.018545
6-7	58.868000	14.717000	1.102611	1.946190	6.433238	0.005207
7-8	48.089500	12.022000	0.900665	11.873370	8.568891	0.013886
8-9	37.155000	9.289000	0.688792	4.265726	3.064696	0.006447
9-10	34.061400	8.515000	0.624526	3.633687	2.575602	0.005963
10-11	30.952000	7.738000	0.560892	0.565042	0.186815	0.000877
11-12	28.294600	7.074000	0.515327	0.899217	0.297337	0.001527
12-13	24.857000	6.214000	0.454428	2.721099	2.140919	0.006352
13-14	21.401400	5.350000	0.391707	0.744188	0.979563	0.002621

Line	I net (A)	Loading (%)	Power Flow (MW)	P loss (kW)	Q loss (kVAr)	Voltage Drop (pu)
14-15	14.335200	3.584000	0.270963	0.364349	0.324277	0.001552
15-16	11.327700	2.832000	0.210598	0.287291	0.209800	0.001432
16-17	8.149900	2.037000	0.150311	0.256849	0.342930	0.002397
17-18	4.969700	1.242000	0.090054	0.054238	0.042531	0.000632
2-19	18.280600	4.570000	0.361174	0.164416	0.156897	0.000567
19-20	13.774900	3.444000	0.271009	0.856260	0.771557	0.003816
20-21	9.254200	2.314000	0.180153	0.105208	0.122910	0.000797
21-22	4.736000	1.184000	0.090048	0.047702	0.063071	0.000761
3-23	48.484300	12.121000	0.939614	3.181947	2.174190	0.003625
23-24	43.697800	10.924000	0.846432	5.144191	4.062078	0.006841
24-25	21.886300	5.472000	0.421288	1.287582	1.007504	0.003407
6-26	65.364400	16.341000	0.950792	2.601955	1.325331	0.002037
26-27	62.498900	15.625000	0.888190	3.330351	1.695643	0.002727
27-28	59.653500	14.913000	0.824860	11.305475	9.967821	0.011522
28-29	56.992800	14.248000	0.753555	7.836555	6.827021	0.008316
29-30	50.594300	12.649000	0.625718	3.897265	1.985109	0.003942
30-31	23.353700	5.838000	0.421821	1.594295	1.575642	0.004377
31-32	15.131700	3.783000	0.270226	0.213283	0.248590	0.000987
32-33	3.588600	0.897000	0.060013	0.013174	0.020484	0.000309

According to the above results included for base case the weakest bus in the network is the far end last bus of main feeder i.e. bus 18 where the bus voltage and voltage stability index is minimum and hence it is given DG support. So, now to improve the voltage profile, VSI and other operating parameters of network, single concentrated lumped value DG is connected at weakest bus in various proportions. For the verification of performance of network in presence of DG the penetration sweep from 1 percent to 100 percent in an incremental step of 1 percent is carried out which produces total 100 other cases, but for the sake of understanding we discuss one case from where reverse power flow is observed. The case is considered as maximum hosting capacity because the operational parameters are improving yet the reverse power flow occurs which is not desirable.

Figure 5 Power Flow Map (Single DG 3 Percent Capacity)

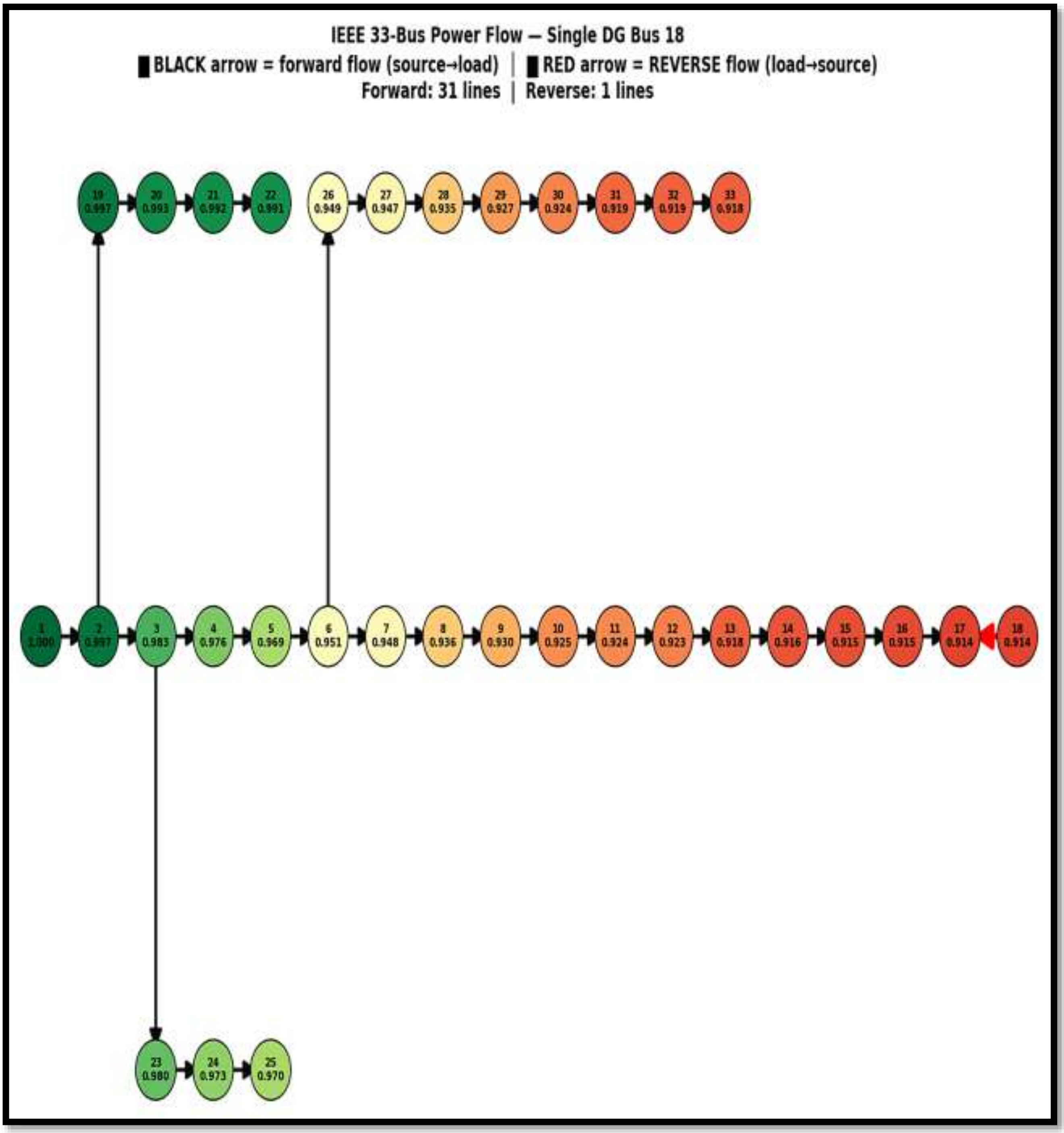


Figure 6 Dashboard Results of Operational Parameters (Single DG 3 Percent Capacity)

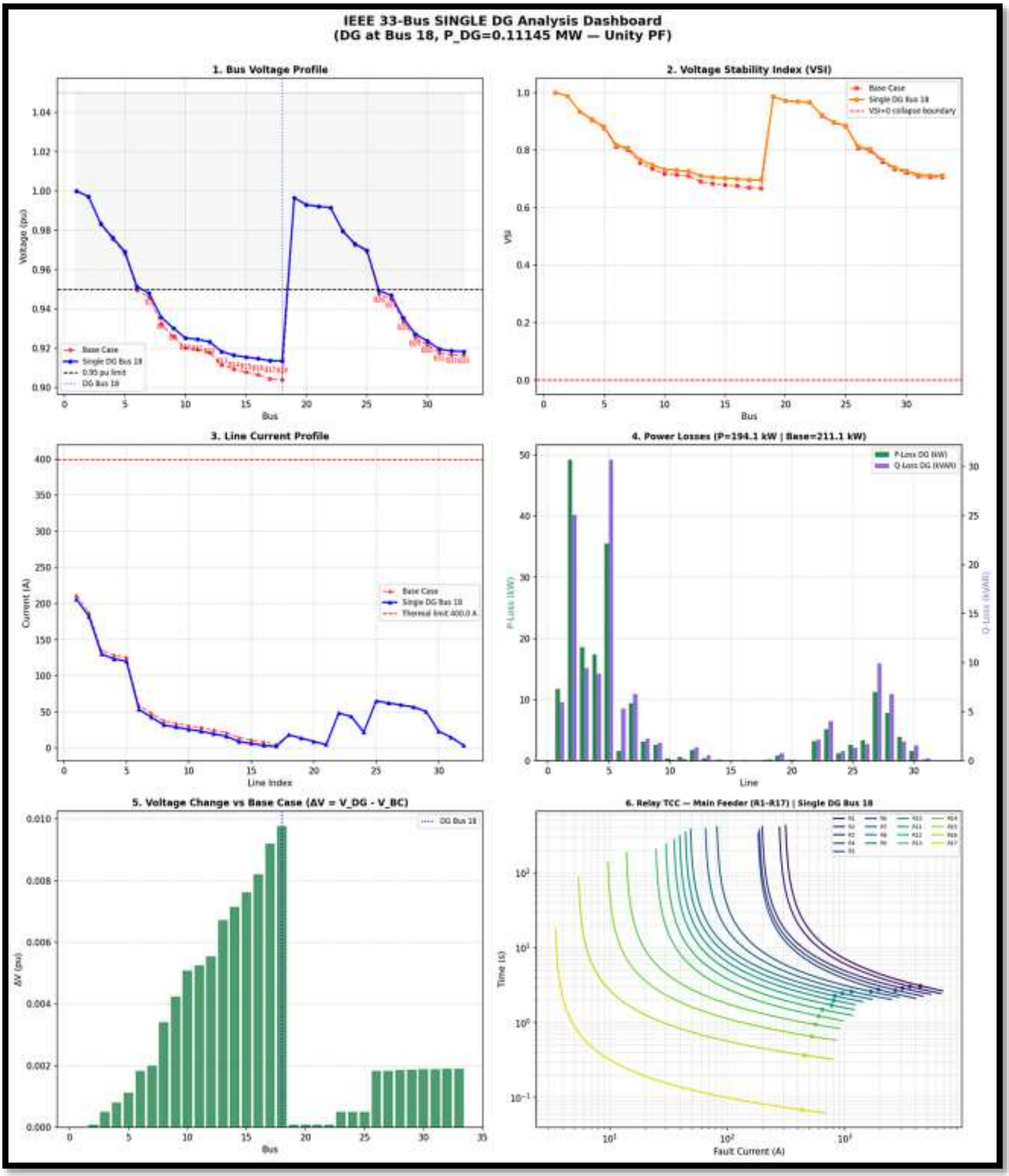


Table 2 Line Section Wise Operational Parameters (Single DG 3 Percent Capacity)

Line	I net (A)	Loading (%)	Power Flow (MW)	P loss (kW)	Q loss (kVAr)	Voltage Drop (pu)
1-2	205.872900	51.468000	3.797666	11.723318	5.976095	0.002915
2-3	182.432000	45.608000	3.324769	49.223218	25.070892	0.013809
3-4	130.106100	32.527000	2.245942	18.586500	9.465912	0.007311
4-5	123.379500	30.845000	2.107356	17.403897	8.864068	0.007219
5-6	120.277700	30.069000	2.029952	35.544742	30.683923	0.017804
6-7	53.539300	13.385000	0.983740	1.609800	5.321282	0.004735
7-8	42.786500	10.697000	0.782131	9.399090	6.783228	0.012355
8-9	31.895300	7.974000	0.572732	3.143480	2.258422	0.005534
9-10	28.851600	7.213000	0.509588	2.607122	1.847960	0.005051
10-11	25.804700	6.451000	0.446981	0.392738	0.129847	0.000731
11-12	23.139200	5.785000	0.401588	0.601386	0.198856	0.001248
12-13	19.708500	4.927000	0.340987	1.710628	1.345896	0.005037
13-14	16.259300	4.065000	0.279276	0.429542	0.565400	0.001992
14-15	9.092300	2.273000	0.158847	0.146574	0.130453	0.000984
15-16	6.333700	1.583000	0.098700	0.089815	0.065589	0.000801
16-17	3.560700	0.890000	0.038610	0.049027	0.065458	0.001047
17-18	2.265800	0.566000	-0.021439	0.011274	0.008841	0.000288
2-19	18.279100	4.570000	0.361173	0.164390	0.156872	0.000567
19-20	13.773900	3.443000	0.271009	0.856126	0.771435	0.003816
20-21	9.253400	2.313000	0.180153	0.105191	0.122890	0.000797
21-22	4.735700	1.184000	0.090048	0.047694	0.063061	0.000761
3-23	48.459500	12.115000	0.939604	3.178690	2.171964	0.003623
23-24	43.675400	10.919000	0.846425	5.138916	4.057912	0.006837
24-25	21.875100	5.469000	0.421286	1.286257	1.006467	0.003405
6-26	65.231600	16.308000	0.950667	2.591392	1.319950	0.002033
26-27	62.371600	15.593000	0.888075	3.316801	1.688744	0.002721
27-28	59.531700	14.883000	0.824759	11.259373	9.927173	0.011499
28-29	56.876300	14.219000	0.753499	7.804562	6.799150	0.008299
29-30	50.490800	12.623000	0.625695	3.881334	1.976995	0.003934
30-31	23.305600	5.826000	0.421813	1.587742	1.569167	0.004368
31-32	15.100500	3.775000	0.270226	0.212406	0.247567	0.000985

Line	I net (A)	Loading (%)	Power Flow (MW)	P loss (kW)	Q loss (kVAr)	Voltage Drop (pu)
32-33	3.581200	0.895000	0.060013	0.013120	0.020399	0.000309

The table shows in line section 17-18 the power loss as -0.021439 MW meaning -21.439 kW power flows in the reverse direction from bus 18-17 which produces localized reverse power flow in the network. The result proves that with single concentrated lumped DG just allows 2% DG hosting capacity without any operational parameter a reverse power flow violation in the network. Also, with now increase in penetration level at weakest bus will further deteriorate the network operation and hence the other approach is used for DG allocation in the network i.e. distributed DG allocation.

The uniform distribution improves the network operational parameters and at the same times mitigates the reverse power flow and improves DG hosting capacity of the network. By not running all cases and providing results for all cases here, the threshold case from where the reverse power flow is observed is included here. For the sake of comparison of 52% single lumped DG with distributed DG alongside base case the dashboard results are produced. Also, the statistical results are included in the tabular form for uniformly distributed 52% DG. The harmonic analysis is also carried out for this case and still all parameters are within tolerance limits except reverse power flow at bus 33, where power flows from bus 33 to bus 32.

Figure 7 Harmonic and THD Analysis (Single DG 3 Percent Capacity)

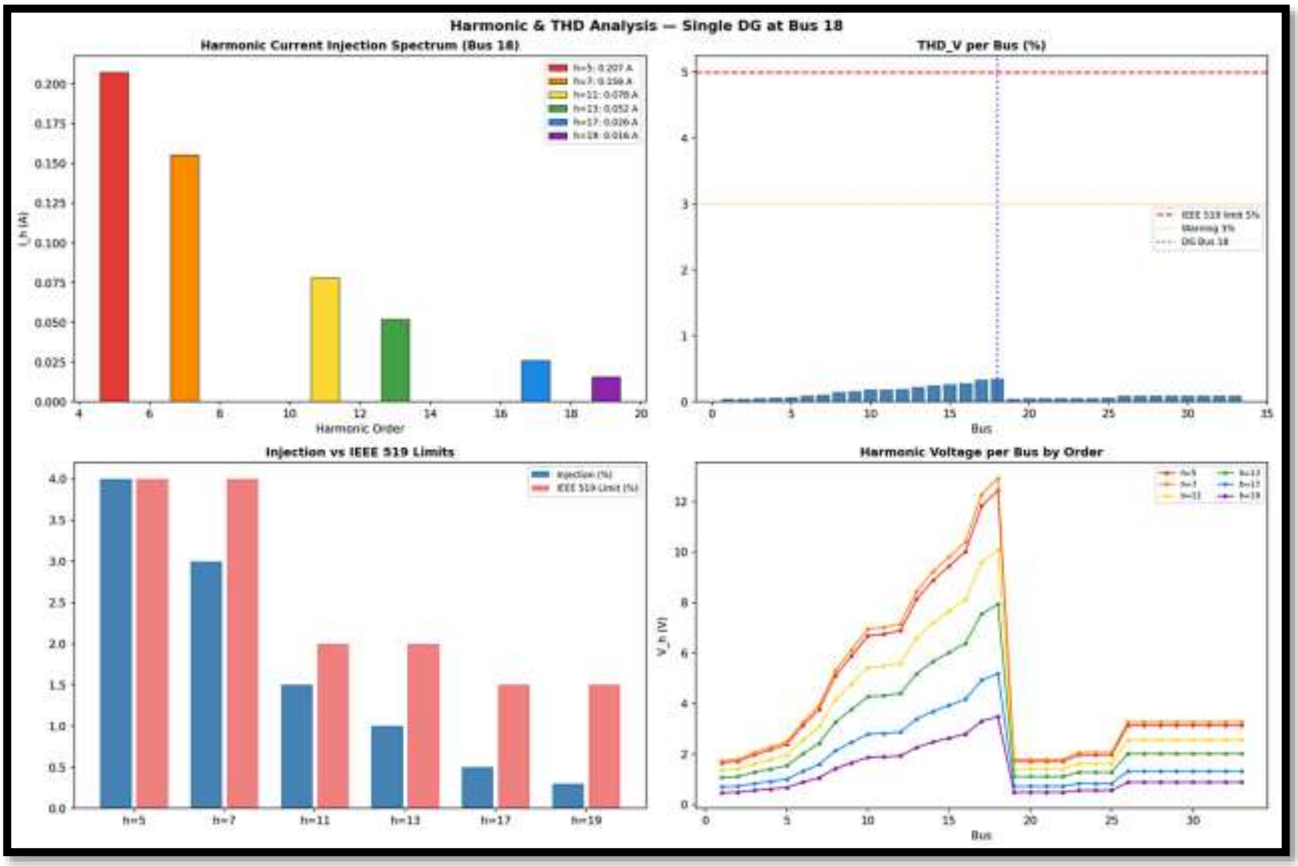


Table 3 Line Section Wise Operational Parameters (Uniform DG 52 Percent Capacity)

Line	I net (A)	Loading (%)	Power Flow (MW)	P loss (kW)	Q loss (kVAr)	Voltage Drop (pu)
1-2	137.920200	34.480000	1.875882	5.261481	2.682100	0.001953
2-3	125.178300	31.295000	1.712140	23.175347	11.803914	0.009475
3-4	85.958000	21.490000	0.903252	8.112885	4.131808	0.004830
4-5	81.387400	20.347000	0.835507	7.573120	3.857105	0.004762
5-6	80.170100	20.043000	0.828303	15.791759	13.632202	0.011867
6-7	29.420300	7.355000	0.355923	0.486094	1.606812	0.002602
7-8	21.973400	5.493000	0.215806	2.478954	1.789036	0.006345
8-9	15.179100	3.795000	0.073696	0.711948	0.511497	0.002634
9-10	14.260400	3.565000	0.073353	0.636922	0.451458	0.002497
10-11	13.343900	3.336000	0.073084	0.105019	0.034722	0.000378
11-12	12.203500	3.051000	0.088348	0.167273	0.055311	0.000658
12-13	10.661300	2.665000	0.088550	0.500574	0.393844	0.002725
13-14	9.157900	2.289000	0.088418	0.136269	0.179368	0.001122
14-15	4.518500	1.130000	0.028650	0.036199	0.032218	0.000489
15-16	4.071400	1.018000	0.028983	0.037113	0.027103	0.000515
16-17	3.196300	0.799000	0.029314	0.039506	0.052746	0.000940
17-18	2.383700	0.596000	0.029644	0.012478	0.009784	0.000303
2-19	9.487900	2.372000	0.118849	0.044289	0.042264	0.000294
19-20	7.214200	1.804000	0.089174	0.234857	0.211624	0.001998
20-21	4.937300	1.234000	0.059308	0.029947	0.034985	0.000425
21-22	2.663500	0.666000	0.029646	0.015087	0.019948	0.000428
3-23	40.675800	10.169000	0.756082	2.239560	1.530267	0.003041
23-24	38.331300	9.583000	0.724211	3.958269	3.125622	0.006001
24-25	19.194500	4.799000	0.360622	0.990342	0.774920	0.002988
6-26	50.177700	12.544000	0.456957	1.533339	0.781021	0.001564
26-27	49.124300	12.281000	0.455792	2.057488	1.047567	0.002143
27-28	48.074000	12.018000	0.454103	7.342390	6.473644	0.009286
28-29	47.230600	11.808000	0.447130	5.381860	4.688549	0.006892
29-30	42.969100	10.742000	0.382117	2.811063	1.431842	0.003348
30-31	15.321700	3.830000	0.239674	0.686238	0.678209	0.002872
31-32	9.860300	2.465000	0.149357	0.090566	0.105559	0.000643

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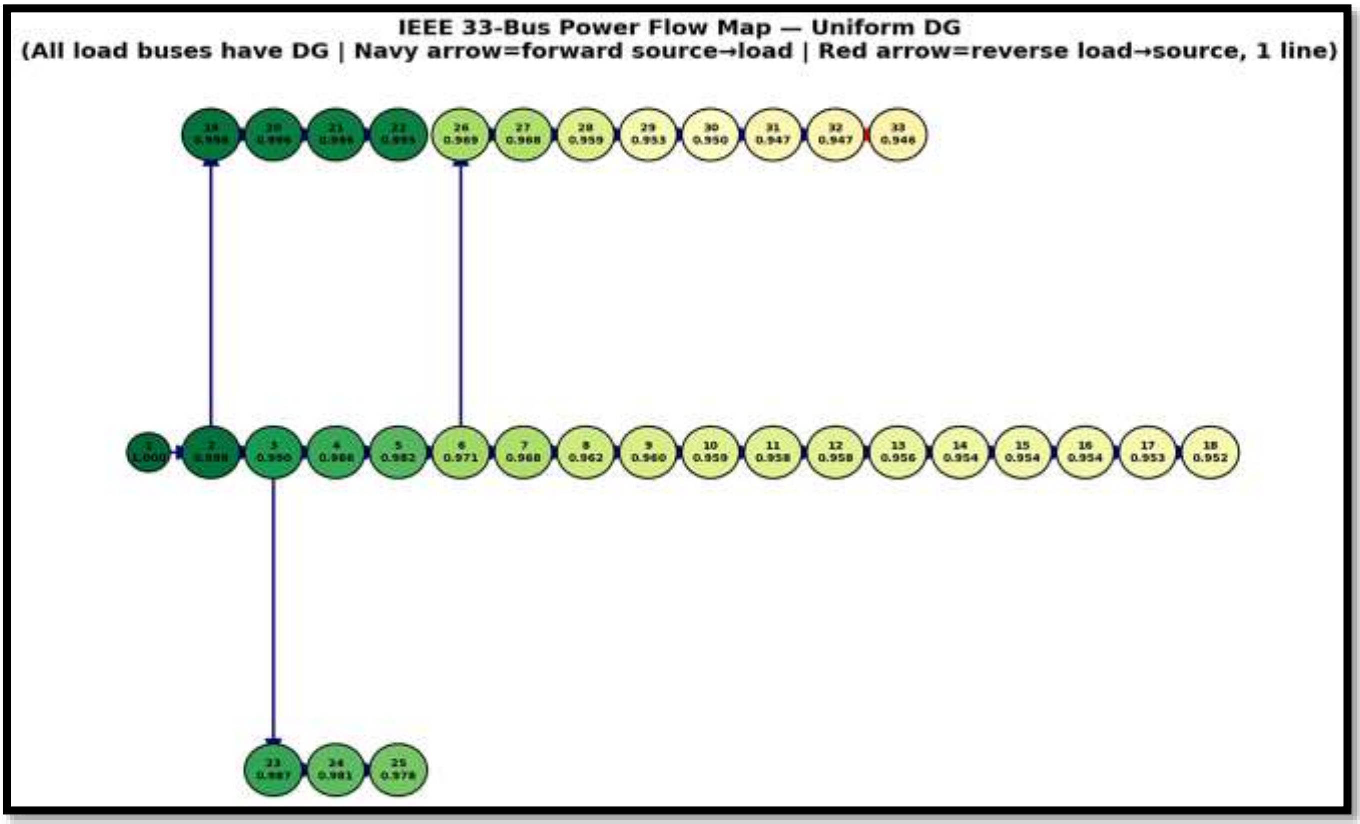
Line	I net (A)	Loading (%)	Power Flow (MW)	P loss (kW)	Q loss (kVAr)	Voltage Drop (pu)
32-33	1.927600	0.482000	-0.000365	0.003801	0.005910	0.000166

Figure 8 Power Flow Map (Uniform DG 52 Percent Capacity)



As with the 52% capacity reverse power flow initiated in the network, we have to implement any storage capacity to improve network hosting capacity because the scenario shows localized reverse power flow and to mitigate the same storage is necessary. Hence, an optimal required battery energy storage system (BESS) is advocated to keep the cost minimum and at the same time improve the hosting capacity. The prime focus is to reach to the 100% hosting capacity integration in the network and that is achieved by BESS deployment uniformly strategically.

Figure 9 Dashboard Results of Operational Parameters (Uniform DG 52 Percent Capacity)

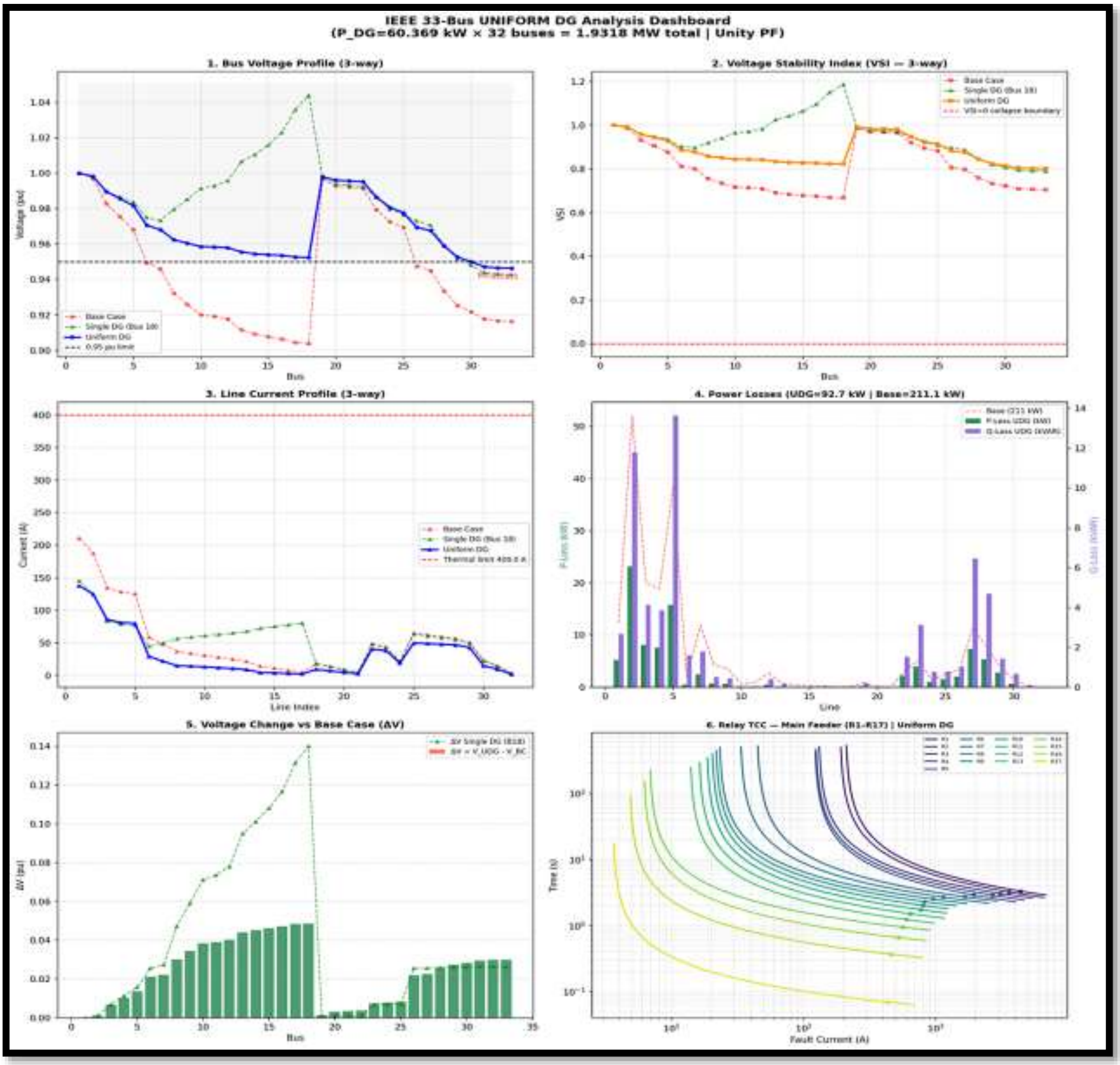


Figure 10 Harmonic and THD Analysis (Uniform DG 52 Percent Capacity)

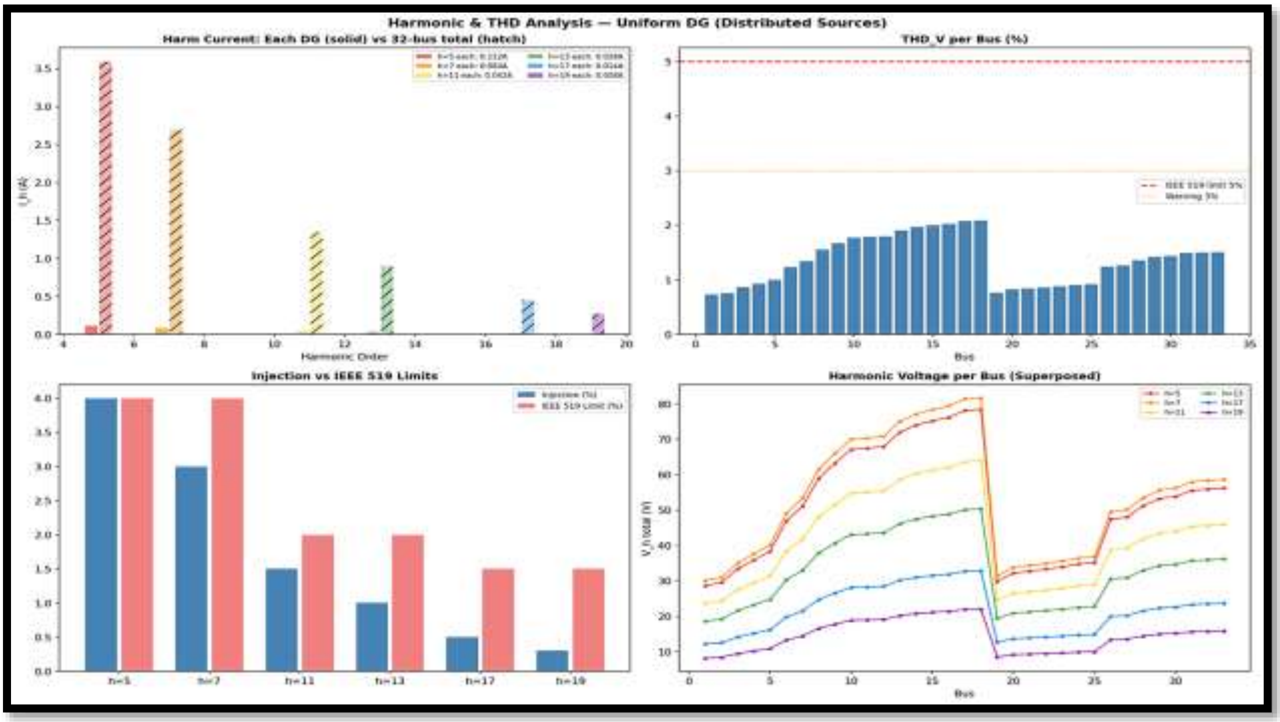


Table 4 Line Section Wise Operational Parameters (Uniform DG 100 Percent + BESS 50 Percent Capacity)

Line	I net (A)	Loading (%)	Power Flow (MW)	P loss (kW)	Q loss (kVAr)	Voltage Drop (pu)
1-2	140.181100	35.045000	1.952729	5.435398	2.770756	0.001985
2-3	127.118500	31.780000	1.777187	23.899317	12.172654	0.009622
3-4	87.281000	21.820000	0.958203	8.364531	4.259969	0.004905
4-5	82.639800	20.660000	0.887886	7.807974	3.976719	0.004835
5-6	81.385600	20.346000	0.878125	16.274206	14.048674	0.012047
6-7	30.226300	7.557000	0.384069	0.513094	1.696060	0.002673
7-8	22.588000	5.647000	0.241603	2.619568	1.890516	0.006522
8-9	15.492600	3.873000	0.097030	0.741666	0.532847	0.002688
9-10	14.558000	3.640000	0.094335	0.663783	0.470498	0.002549
10-11	13.624000	3.406000	0.091718	0.109474	0.036194	0.000386
11-12	12.512800	3.128000	0.104656	0.175859	0.058150	0.000675
12-13	10.960200	2.740000	0.102527	0.529031	0.416234	0.002801
13-14	9.443300	2.361000	0.100044	0.144892	0.190719	0.001157
14-15	4.680800	1.170000	0.037946	0.038846	0.034573	0.000507
15-16	4.204300	1.051000	0.035954	0.039575	0.028900	0.000532

Line	I net (A)	Loading (%)	Power Flow (MW)	P loss (kW)	Q loss (kVAr)	Voltage Drop (pu)
16-17	3.306000	0.826000	0.033962	0.042264	0.056429	0.000973
17-18	2.456100	0.614000	0.031966	0.013247	0.010388	0.000313
2-19	9.738400	2.435000	0.128153	0.046659	0.044525	0.000302
19-20	7.400000	1.850000	0.096154	0.247108	0.222663	0.002050
20-21	5.058100	1.265000	0.063953	0.031430	0.036719	0.000436
21-22	2.719700	0.680000	0.031969	0.015730	0.020798	0.000437
3-23	40.966200	10.242000	0.763132	2.271653	1.552196	0.003063
23-24	38.532500	9.633000	0.728907	3.999924	3.158515	0.006032
24-25	19.295400	4.824000	0.362954	1.000779	0.783087	0.003003
6-26	50.613700	12.653000	0.475828	1.560103	0.794653	0.001578
26-27	49.518700	12.380000	0.472315	2.090659	1.064456	0.002161
27-28	48.425100	12.106000	0.468271	7.450039	6.568556	0.009354
28-29	47.535600	11.884000	0.458868	5.451584	4.749291	0.006936
29-30	43.209200	10.802000	0.391463	2.842559	1.447885	0.003367
30-31	15.593400	3.898000	0.246668	0.710788	0.702472	0.002923
31-32	10.036400	2.509000	0.154004	0.093829	0.109361	0.000655
32-33	1.932100	0.483000	0.001957	0.003819	0.005938	0.000167

The results of the scenario with 50 percent uniformly distributed BESS will allow 100 percent uniformly distributed DG deployment in the network. Still the power quality issues and harmonics are within check with such huge penetration. One more thing here noted is that solar DG injects only active power in the network. So, to improve the network performance the final scenario of placing capacitor for reactive power support is considered. The approach further improves DG hosting capacity of the network.

Figure 11 Dashboard Results of Operational Parameters (Uniform DG 100 + BESS 50 Percent Capacity)

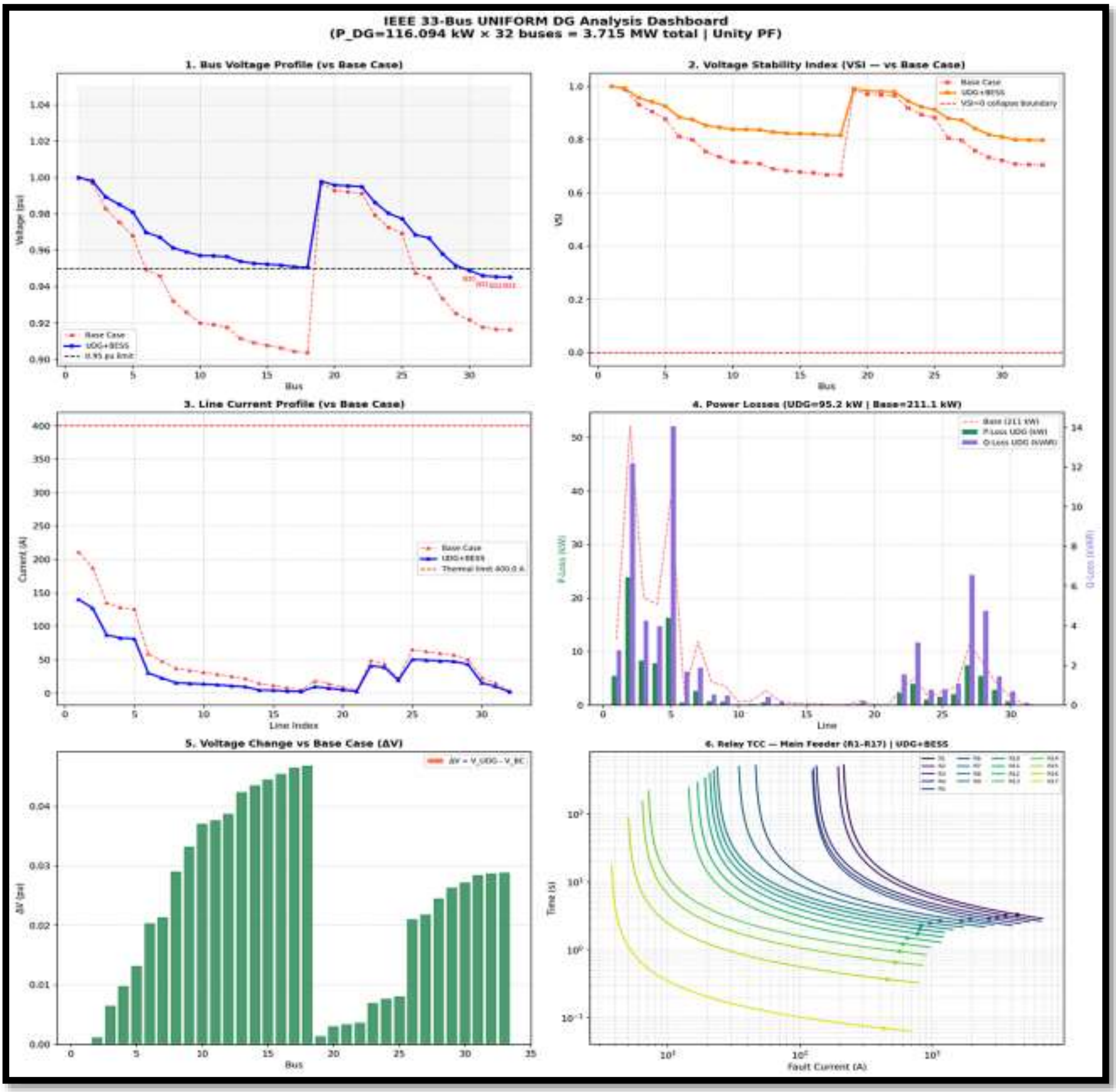


Figure 12 Power Flow Map (Uniform DG 100 + BESS 50 Percent Capacity)

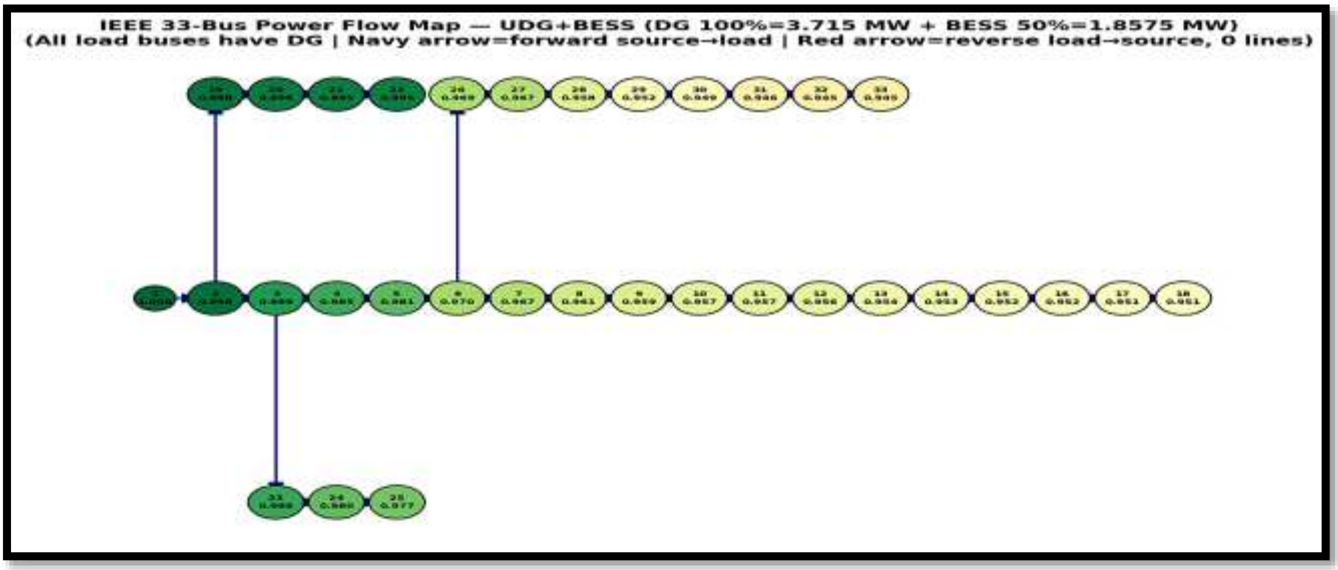


Figure 13 Harmonic and THD Analysis (Uniform DG 100 + BESS 50 Percent Capacity)

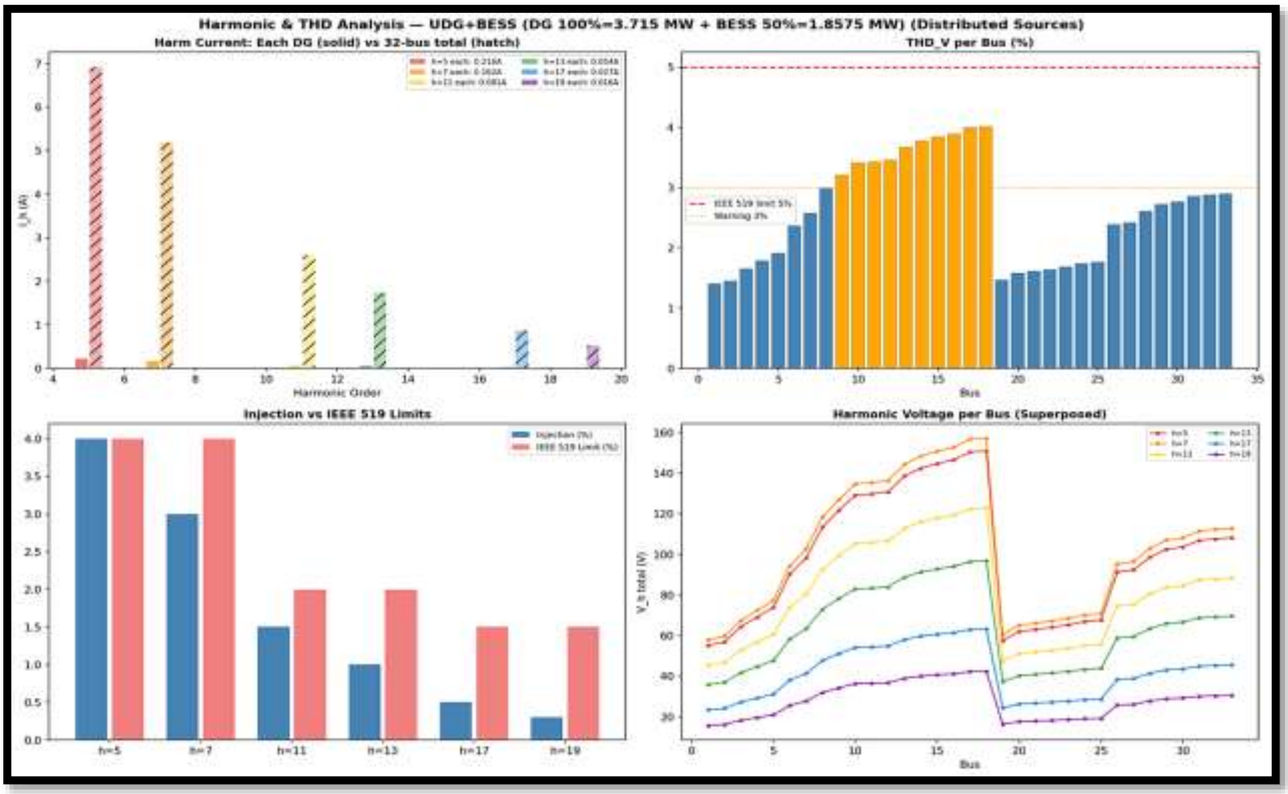


Figure 14 Power Flow Map (Uniform DG 100 + BESS 50 Percent + Capacitor)

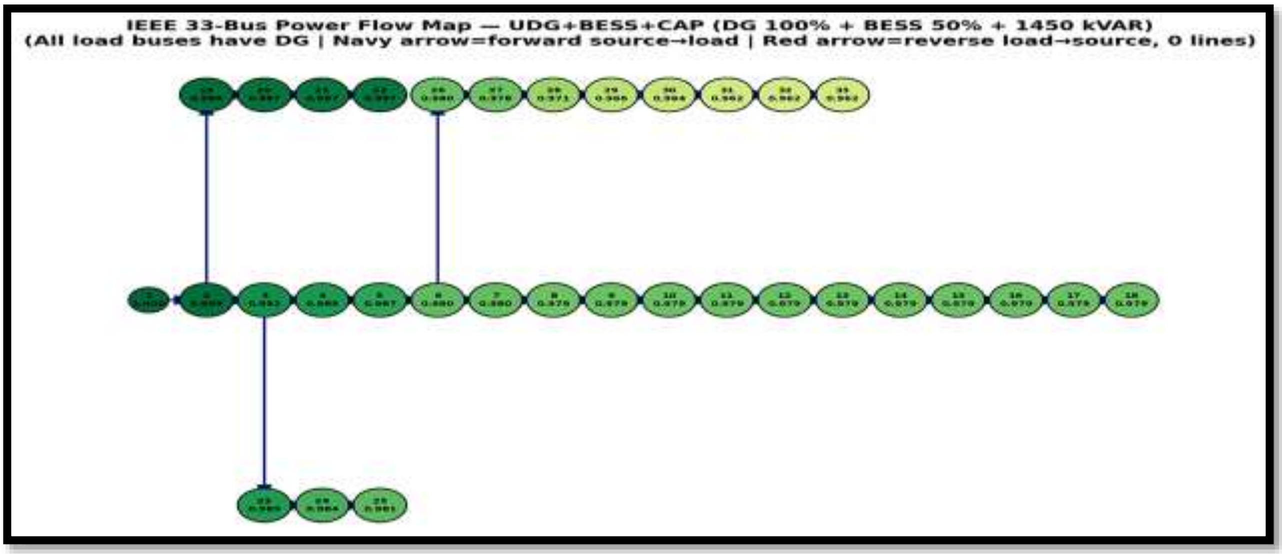


Figure 15 Hosting Capacity Limits

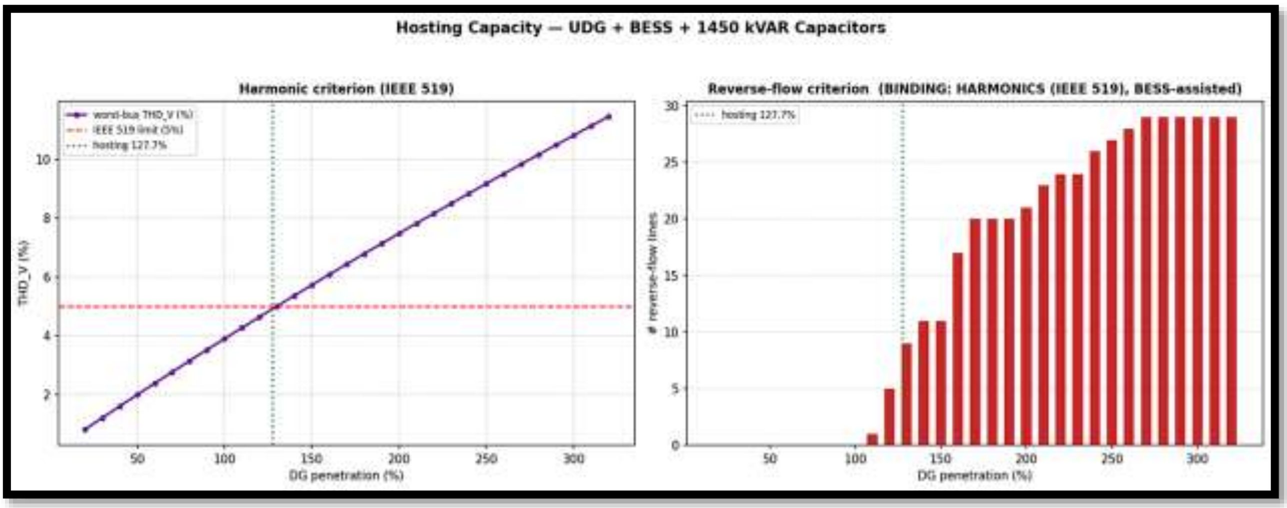


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Figure 16 Dashboard Results of Operational Parameters (Uniform DG 100 + BESS 50 Percent Capacity + Capacitor)

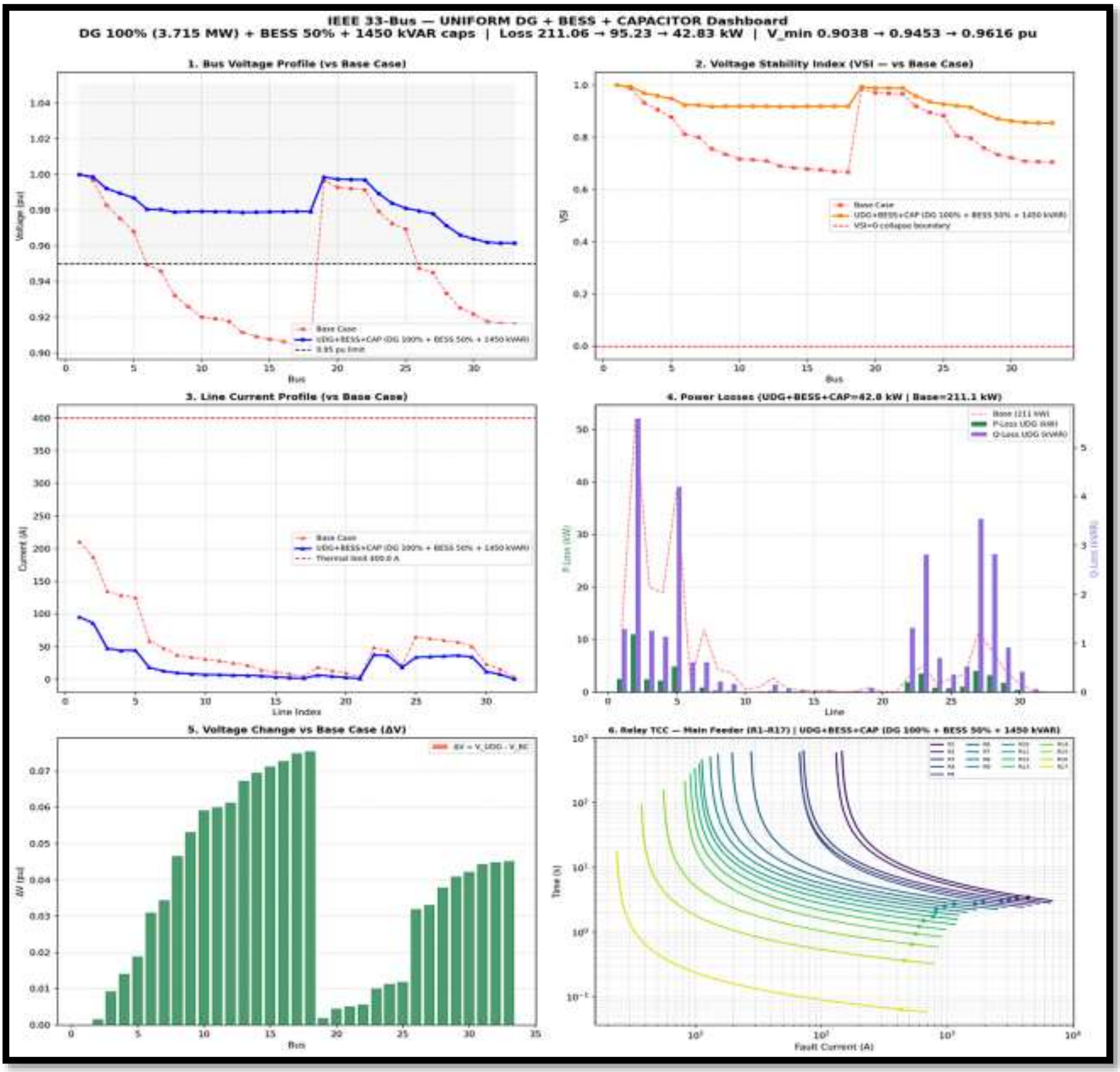

Figure 17 Harmonic and THD Analysis (Uniform DG 100 + BESS 50 Percent Capacity + Capacitor)

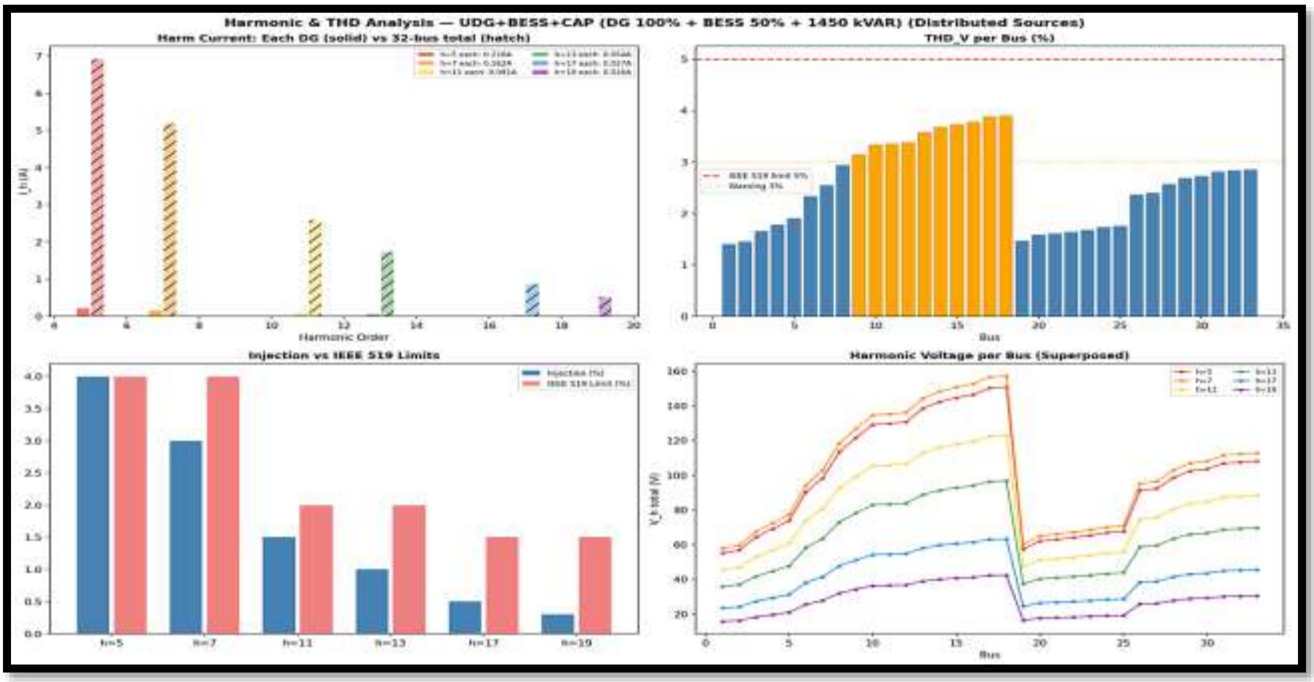

Table 5 Line Section Wise Operational Parameters (Uniform DG 100 Percent + BESS 50 Percent Capacity + Capacitor)

Line	I net (A)	Loading (%)	Power Flow (MW)	P loss (kW)	Q loss (kVAr)	Voltage Drop (pu)
1-2	95.677800	23.919000	1.900330	2.532062	1.290747	0.001355
2-3	86.157700	21.539000	1.727900	10.978850	5.591865	0.006522
3-4	47.334400	11.834000	0.922726	2.460118	1.252913	0.002660
4-5	44.162000	11.040000	0.858313	2.229757	1.135649	0.002584
5-6	44.500400	11.125000	0.854130	4.865564	4.200188	0.006587
6-7	18.162800	4.541000	0.380442	0.185265	0.612403	0.001606
7-8	12.825000	3.206000	0.238303	0.844482	0.609454	0.003703
8-9	9.876600	2.469000	0.095506	0.301420	0.216554	0.001714
9-10	8.604600	2.151000	0.093251	0.231888	0.164365	0.001506
10-11	7.378100	1.845000	0.091066	0.032107	0.010615	0.000209
11-12	7.041100	1.760000	0.104081	0.055685	0.018413	0.000380
12-13	6.484800	1.621000	0.102072	0.185202	0.145714	0.001657
13-14	5.959100	1.490000	0.099934	0.057698	0.075947	0.000730
14-15	5.416500	1.354000	0.037923	0.052017	0.046296	0.000586
15-16	3.662500	0.916000	0.035918	0.030032	0.021931	0.000463

Line	I net (A)	Loading (%)	Power Flow (MW)	P loss (kW)	Q loss (kVAr)	Voltage Drop (pu)
16-17	2.442000	0.610000	0.033935	0.023060	0.030788	0.000718
17-18	1.559400	0.390000	0.031958	0.005340	0.004187	0.000198
2-19	6.662800	1.666000	0.127945	0.021841	0.020842	0.000207
19-20	4.594100	1.149000	0.095970	0.095240	0.085818	0.001273
20-21	2.958400	0.740000	0.063922	0.010752	0.012561	0.000255
21-22	1.461600	0.365000	0.031958	0.004543	0.006007	0.000235
3-23	37.734900	9.434000	0.762242	1.927421	1.316986	0.002821
23-24	36.371100	9.093000	0.728361	3.563780	2.814116	0.005694
24-25	18.210800	4.553000	0.362845	0.891434	0.697527	0.002835
6-26	33.862500	8.466000	0.466870	0.698323	0.355697	0.001055
26-27	34.707300	8.677000	0.464218	1.027038	0.522915	0.001514
27-28	35.572000	8.893000	0.461238	4.020073	3.544421	0.006871
28-29	36.651400	9.163000	0.455265	3.240905	2.823400	0.005348
29-30	34.230500	8.558000	0.390071	1.783950	0.908672	0.002667
30-31	12.000700	3.000000	0.246334	0.420993	0.416068	0.002249
31-32	7.541900	1.885000	0.153959	0.052983	0.061754	0.000492
32-33	0.483200	0.121000	0.001953	0.000239	0.000371	0.000042

Furthermore, similar results can be computed for 127.7% DG hosting capacity with capacitor bank support and still all the parameters within specified limits.

Conclusions

This research established that the spatial deployment of distributed generation resources, rather than its total capacity, improves the hosting capacity of a distribution network. On the standard IEEE 33-bus system, connecting the whole DG capacity at the weakest bus (bus 18) resulted the hosting capacity limited to 3% penetration, whereas sharing uniformly the equal amount of penetration across all buses except slack bus postponed the same issues to 52%. In those two strategies, the first issue raised was reverse power flow, not the voltage, thermal or harmonic limit, considering reverse power flow as the prime limiting factor and a better than nearly seventeen times gain achieved purely by reconfiguration, without requiring other DG, storage components or network reinforcement.

Because RPF starts from the local access of generation over local demand, a uniformly distributed BESS charging at 50% of the coordinated DG output separated it at the same bus and permitted complete 100% penetration (V_min 0.9453 p.u., VSI_min 0.7984). Adding reactive support supplied by 1450 kVAr of shunt capacitors later on that solar DG cannot, cutting the active loss from 95.23 kW to 42.83 kW (79.7% below the 211.06 kW base case), raising V_min to 0.9616 p.u. and VSI_min to 0.8549, and lowering the peak line current from 140.18 A to 95.68 A.

With reverse power flow issue completely eliminated and the voltage and thermal margins widened to maintain network operation in check, the binding constraint migrated to power quality: the network hosts 127.7% DG (4.745 MW on a 3.715 MW feeder) at the 5% THD upper limits of IEEE 519. This limit was resulted by bisection on the full harmonic model, since THD does not vary linearly with penetration. For distribution utilities, the practical finding is that hosting capacity is improved first by planning policy and only then by capital: distributed connection raised the limit from 3% to 52% at no cost, local storage carried it to 100%, and conventional reactive compensation carried it to 127.7% while cutting losses by almost eighty percent.

The whole study is limited to peak-load, steady-state, balanced situations using fixed capacitors. This investigation naturally expands to annually time-varying patterns, unbalanced operating conditions, and the protection consequences of the reverse flows described here, which conflict with the directionality assumptions of conventional overcurrent systems.

References

1. IRENA and CPI. 2025. Global landscape of energy transition finance 2025. International Renewable Energy Agency and Climate Policy Initiative, Abu Dhabi.
2. IRENA. 2025. Renewable capacity statistics 2025. International Renewable Energy Agency, Abu Dhabi.
3. REN21. 2025. Renewables 2025 global status report: Global overview. REN21 Secretariat, Paris.
4. Global Energy Monitor. 2025. Wind and solar year in review 2024. Global Energy Monitor.
5. IEA-PVPS. 2025. Trends in photovoltaic applications 2025. International Energy Agency Photovoltaic Power Systems Programme.
6. Purani, S. and Trivedi, I. 2021. Estimation of solar energy, inverter configuration and issues with penetration in distribution systems. 2021 International Conference on Electrical, Computer and Energy Technologies (ICECET), Cape Town, South Africa, 1-6.
7. De Carne, G., Buticchi, G., Zou, Z. and Liserre, M. 2018. Reverse power flow control in a ST-fed distribution grid. IEEE Transactions on Smart Grid, 9(4), 3811-3819.
8. Balamurugan, K., Srinivasan, D. and Reindl, T. 2012. Impact of distributed generation on power distribution systems. Energy Procedia, 25, 93-100.
9. Purani, S.V., Agravatt, H.M. and Trivedi, I.N. 2026. Optimal sizing, feasibility analysis and major issues of grid connected solar power plant in distribution network (pp. 71-85), in M. Elsisi, M. Amer, N. Rinanto and C.-L. Su (Eds.) Advancements in Smart Energy Systems. Springer Nature Switzerland.
10. Manditereza, P.T. and Bansal, R. 2016. Renewable distributed generation: The hidden challenges – A review from the protection perspective. Renewable and Sustainable Energy Reviews, 58, 1457-1465.
11. Telukunta, V., Pradhan, J., Agrawal, A., Singh, M. and Srivani, S.G. 2017. Protection challenges under bulk penetration of renewable energy resources in power systems: A review. CSEE Journal of Power and Energy Systems, 3(4), 365-379.
12. Karimi, M., Mokhlis, H., Naidu, K., Uddin, S. and Bakar, A.H.A. 2016. Photovoltaic penetration issues and impacts in distribution network – A review. Renewable and Sustainable Energy Reviews, 53, 594-605.
13. Santos, T.F.F. et al. 2020. Maximization of distribution network hosting capacity through optimal grid reconfiguration and distributed generation capacity allocation/control. Energies, 13(20), 5315.

14. Bangesh, K.N., F.M.E.A. and O.A.H. 2018. Manage reverse power flow and fault current level in LV network with high penetration of small-scale solar and wind power generation. 53rd International Universities Power Engineering Conference (UPEC), Glasgow, UK, 1-6.
15. Zhang, Z., Crossley, P. and Li, L. 2017. A positive-sequence-fault-component-based improved reverse power protection for spot network with PV. Electric Power Systems Research, 149, 102-110.
16. IEEE Standards Coordinating Committee 21. 2018. IEEE standard for interconnecting distributed resources with electric power systems. IEEE Std 1547-2018.
17. Nimpitiwan, N., Heydt, G.T., Ayyanar, R. and Suryanarayanan, S. 2007. Fault current contribution from synchronous machine and inverter based distributed generators. IEEE Transactions on Power Delivery, 22(1), 634-641.
18. Impran, S., Varbak Nese, S. and Oral, B. 2020. Challenges of renewable energy penetration on power system flexibility: A survey. Energy Strategy Reviews, 31, 100539.
19. Mousa, H.H.H., Mahmoud, K. and Lehtonen, M. 2024. A comprehensive review on recent developments of hosting capacity estimation and optimization for active distribution networks. IEEE Access, 12, 34567-34589.
20. Dharmasena, S., Olowu, T.O. and Sarwat, A.I. 2022. Algorithmic formulation for network resilience enhancement by optimal DER hosting and placement. IEEE Access, 10, 23477-23488.
21. Mendes, M.A., Vargas, M.C., Simonetti, D.S.L. and Batista, O.E. 2021. Load currents behavior in distribution feeders dominated by photovoltaic distributed generation. Electric Power Systems Research, 201, 107532.
22. Salimon, S.A., Adepoju, G.A., Adebayo, I.G., Howlader, H.O.R., Ayandale, S.O. and Adewuyi, O.B. 2023. Impact of distributed generators penetration level on the power loss and voltage profile of radial distribution networks. Energies, 16(3), 1483.
23. Memarzadeh, G. and Keynia, F. 2020. A new index-based method for optimal DG placement in distribution networks. Engineering Reports, 2(10), e12234.
24. Till, J., You, S., Liu, Y. and Du, P. 2020. Impact of high PV penetration on voltage stability. 2020 IEEE/PES Transmission and Distribution Conference and Exposition, 1-5.
25. Alam, M.J.E., Muttaqi, K.M. and Sutanto, D. 2013. Mitigation of rooftop solar PV impacts and evening peak support by managing available capacity of distributed energy storage systems. IEEE Transactions on Power Systems, 28(4), 3874-3884.
26. Hashemi, S. and Østergaard, J. 2017. Methods and strategies for overvoltage prevention in low voltage distribution systems with PV. IET Renewable Power Generation, 11(2), 205-214.
27. Ismael, S.M., Abdel Aleem, S.H.E., Abdelaziz, A.Y. and Zobaa, A.F. 2019. State-of-the-art of hosting capacity in modern power systems with distributed generation. Renewable Energy, 130, 1002-1020.
28. Baran, M.E. and Wu, F.F. 1989. Network reconfiguration in distribution systems for loss reduction and voltage control. IEEE Transactions on Power Delivery, 4(2), 1401-1407.
29. Thurner, L., Scheidler, A., Schäfer, F., Menke, J.H., Dollichon, J., Meier, F., Meinecke, S. and Braun, M. 2018. Pandapower—An open-source Python tool for convenient modeling, analysis, and optimization of electric power systems. IEEE Transactions on Power Systems, 33(6), 6510-6521.
30. Chakravorty, M. and Das, D. 2001. Voltage stability analysis of radial distribution networks. International Journal of Electrical Power & Energy Systems, 23(2), 129-135.
31. Baran, M.E. and Wu, F.F. 1989. Optimal capacitor placement on radial distribution systems. IEEE Transactions on Power Delivery, 4(1), 725-734.