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Transmission Network Loss Reduction and Voltage Profile Improvement Using Network Restructuring and Optimal DG Placement

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Abstract: This paper introduced a method using hybrid combination of network restructuring and optimal placement of optimally sized distributed generators (DG) to reduce loss and improve voltage profile in a practical transmission network for scenario of high load demand for a period of ten years. A study is performed for four study cases which includes the test transmission network without considering optimal DG placement and network restructuring, considering network restructuring, optimal placement of DG units using proposed grid parameter oriented harmony search algorithm (GPOHSA) and considering hybrid combination of network restructuring and DG placement using GPOHSA. Network restructuring is achieved by addition of a new 400 kV Grid-substation (GSS) and a 220 kV GSS along with associated transmission system. GPOHSA is obtained by a modification in the conventional harmony search algorithm (HSA) where grid coordinates are used for locating the individuals in an objective space. Performance Improvement Indicators such as real power loss reduction indicator (SPLRI), reactive power loss reduction indicator (SQLRI) and summation of node voltage deviation reduction indicator (SNVDRI) are proposed to evaluate performance of each case of study. The period of investment return is assessed to evaluate the pay back period of the investments incurred in network restructuring and DG units. It is established that hybrid combination of network restructuring and DG units placement using GPOHSA is effective to meet the increased load demand for time period of ten years with reduced losses and improved voltage profile. Investment incurred on the network restructuring and DG units placement will be recovered in a time period of 4 years. Effectiveness of the GPOHSA is better relative to the conventional genetic algorithm (GA) for DG unit placement. The study is performed using the MATLAB software on a practical transmission network in India.

Keywords: distributed generation; grid parameter oriented harmony search algorithm; real power loss; reactive power loss; utility grid network; voltage deviations

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1. Introduction

Healthy network of power system is expected to be stable at all times and it should also satisfy the operating criteria defined in the grid codes. Increasing load demands due to fast industrialization, increase in commercial and residential loads has challenged the network of modern power system. This high load demand has resulted in high congestion in the transmission lines. This has caused the instability of power system operations [1]. This problem can be solved by optimal placement of distributed generation (DG) units using the meta-heuristic techniques and optimal network restructuring which will help to maintain voltage stability, dynamic stability and steady state stability. Different approaches are reported in literature for optimal placement of DG units and network restructuring for improvement of health of power system. A bio-geography-based optimization method for reducing the system loss and voltage profile improvement in the utility network using optimal sizing and placement of DG is reported in [2]. DG units are installed near to load center which also helped to improve power factor (PF). This method has the advantage that search space for DG placement is minimized. In [3], the authors designed a hybrid Harmony Search Algorithm for determination of optimal sizes of DG units and their optimal deployment in a power system network for minimizing the power losses and enhancement of node voltages. To overcome the drawback of Harmony Search Algorithm (HSA) of slow convergence has been mitigated by the use of Particle Artificial Bee Colony algorithm (PABC) which enhanced the harmony memory vector. This method identified the suitable candidate nodes and sizes of DG units as well as shunt capacitors. In [4], the authors introduced a fast converging optimization method which is designed by modification in the firefly method. This method has been efficiently utilized for optimal size estimation and deployment of voltage controlled DG units in the balanced/unbalanced power systems. This method is effective for constrained optimization by proposing formulas for tuning the algorithm parameters and updating equations. In [5], the authors introduced an optimized framework using Differential Evolution method for optimal integration of DG units in the distribution grid network. This method has considered the power system constraints, optimized the location, sizes and power factor setting for every DG unit. This has minimized the network losses and maximized the quantum of DG integration to the grid. A detailed study of various approaches and techniques used for optimal size determination and deployment of DG units in the grid network is reported in [6]. The influence of changes in DG location on the network losses and system losses have been investigated in detail. In [7], the authors formulated an algorithm for optimal sizing and deployment of DG units in the utility network to improve network resiliency. This is achieved by the use of a unique critical infrastructure (CI) ranking scheme by prioritizing the CI nodes for DG unit deployment. This has achieved the maximum DG hosting capacity of a node, improve system resiliency and minimized the system active power loss. In [8], the authors designed a multi-objective function which considers maximum network load-ability and network loss for voltage stability improvement, power loss minimization and maintaining good voltage profile by optimal deployment of DG units and network reconfiguration. A method for optimal restructuring of a power transmission network for improving the power system flexibility (PSF) is reported in [9]. A power system restructuring flexibility index (PSRFI) is formulated using the node voltage deviations and network loss for assessing flexibility level of the transmission network. In [10], the authors proposed a network restructuring approach for a transmission network by creating new grid substation (GSS) of 400/220 kV and additional transmission lines of 400 kV and 220 kV voltage levels which helped in meeting the increased load demand. In [11], the authors suggested an optimized restructuring of transmission system to meet increased load demand due to installation of refinery and petrochemical complex. In [12], the authors designed a method for optimal sizing of Multiple renewable energy (RE) generators considering PV Inverter reactive power control to address the environmental, technical, and economic issues. It is established that design approach helps to achieve carbon emission reduction, better technical aspect, annual saving, and grid power alleviation. In [13], the authors presented a Genetic algorithm (GA) supported Newton–Raphson power flow approach for power loss minimization in practical distribution network at Kabul city by optimal use of rooftop solar PV as distributed generation. Voltage deviation minimization is also achieved using this method. In [14], the authors designed a multi-objective method for optimal multi-configuration and placement of step-voltage regulators (SVR), capacitor, centralized wind farm, and energy storage system in a practical distribution network. The study is validated on 162-bus distribution network in Kabul city. In [15], the authors introduced a Multi-objective method for time-variant and optimal placement of automatic and fixed type capacitor bank in a distribution network to minimize capacitor switching steps. In [16], the authors presented a multi-objective multi-verse optimization (MOMVO) method for optimal coordination of centralized and distributed RE generators equipped with battery storage system into a distribution network. The study is validated on 68-bus practical distribution network in Kabul city.

A detailed review of the existing literature is discussed in above paragraph; it is pointed out that performance of practical transmission network in terms of reduced network losses and improved voltage profile can be increased by hybrid use of the network restructuring and placement of DG units using modified harmony search algorithm by incorporating the grid parameters. This is considered for investigations in this paper with following main contributions:

- This paper presented a method using hybrid combination of network restructuring and optimal placement of optimally sized DG units to reduce loss and improve voltage profile in a practical transmission network for scenario of high load demand for a period of ten years.
- Study is performed for four study cases which includes the test transmission network without considering optimal DG placement and network restructuring, considering network restructuring, optimal placement of DG units using proposed GPOHSA and hybrid combination of network restructuring and DG placement using GPOHSA.
- Network restructuring is achieved by addition of a new 400 kV GSS and a 220 kV GSS along with associated transmission system.
- GPOHSA is obtained by a modification in the conventional HSA where grid coordinates are used for locating the individuals in an objective space.
- Performance Improvement Indicators such as SPLRI, SQLRI and SNVDRI are proposed to evaluate performance of each case of study.
- It is established that hybrid combination of network restructuring and DG units placement using GPOHSA is effective to meet the increased load demand for time period of ten years with reduced losses and improved voltage profile. Investment incurred on the network restructuring and DG units placement will be recovered in a time period of 4 years.
- Effectiveness of the GPOHSA is better relative to the conventional genetic algorithm (GA) for DG unit placement.

The structuring of the contents in the paper is conducted in seven Sections. The research introduction, review of existing methods, research gaps, research contributions and structuring of contents in the paper are elaborated in Section 1. The test transmission utility network and relevant parameters are discussed in Section 2. The proposed method of study, study cases, design of objective functions, GPOHSA, performance improvement indicators and limitations of study are demonstrated in Section 3. A discussion of simulation results for various study cases is discussed in Section 4. The computation of the period of investment return is elaborated in Section 5. The performance comparative study is included in Section 6. The research investigations are concluded in Section 7.

2. Test Utility Transmission Network

A part of the practical transmission network of Rajasthan Rajya Vidyut Prasaran Nigam Limited (RVPN) is modeled in the MATLAB software to perform the study. This transmission network has transmission elements which are at voltage levels of 132 kV, 220 kV, 400 kV and 765 kV [17]. This transmission network has 70 nodes which are operated on the 132 kV, 220 kV and 400 kV voltage levels which are interconnected using the 74 transmission lines (TL-1 to TL-74) operated at 132 kV, 220 kV and 400 kV voltage levels as illustrated in Figure 1. Nodes operated at different voltage levels are interconnected using the transformers (UT-1 to UT-11). Transformers UT-12 and UT-13 are added during network restructuring. Transmission lines operated on 132 kV voltage use aluminium conductor steel reinforced (ACSR) equivalent panther conductor and transmission lines operated on 220 kV voltage use ACSR equivalent zebra conductor. The transmission lines operated on 400 kV voltage use twin moose conductor. Technical parameters such as resistance, reactance and thermal rating of transmission line conductors are reported in [18,19]. Transformer parameters such as impedances of positive sequence (Z1), zero sequence (Z0), ratio of positive sequence reactance (X1) to positive sequence resistance (R1) and ratio of zero sequence reactance (X0) to zero sequence resistance (R0) reported in [18] are used for the study. All other technical parameters of test utility network such as length of transmission lines, voltage levels, generation capacity, and transformer details used for the study are reported in [17,20]. The 2 nodes are operated at 400 kV voltage, 11 nodes are operated at 220 kV voltage and 67 nodes are operated at 132 kV voltage levels. Generator details are included in Table 1.

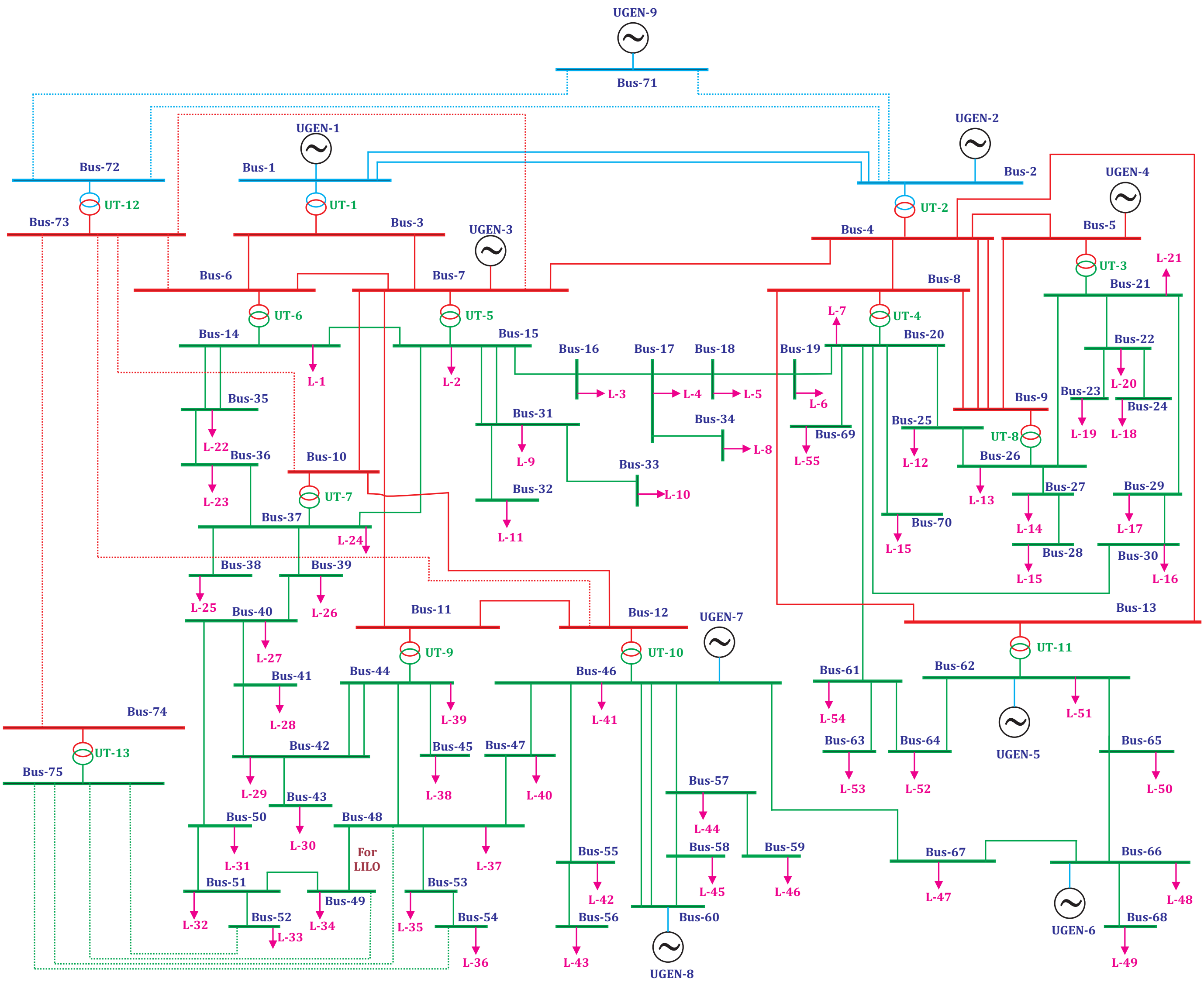

Figure 1. Test transmission utility network.

Table 1. Description of Generators.

Bus No.	Symbol of Generator	Voltage (kV)	Pgen (MW)	Qgen (MVAR)
1	UGEN-1	400 kV	120	25
2	UGEN-2	400 kV	430	20
7	UGEN-3	220 kV	210	10
5	UGEN-4	220 kV	200	10
62	UGEN-5	132 kV	60	0.02
66	UGEN-6	132 kV	31.25	0.02
46	UGEN-7	132 kV	32	10
60	UGEN-8	132 kV	60	15
71	UGEN-9	400 kV	60	5

The loads recorded on the test nodes for the year 2017, 2018, 2019, 2020 and 2021 which is equal to 947.44 MW, 984.29 MW, 1030.85 MW, 1080.13 MW, and 1132.955 MW, respectively are used to compute the projected load for the year 2032 using the mathematical technique reported in [21,22]. This technique used the linear fit mathematical model for computation of projected average load (PAL) using the below detailed relation:

$$PAL(x) = a \times (sin(x - \pi)) + b \times ((x - 10)^2) + c \tag{1}$$

here x indicates the load projection year (2032); a = 8.276; b = 0.01107; c = -4.364×10^4. Computed load on all load nodes operated at 132 kV voltage are detailed in Table 2.

The solar photovoltaic (PV) systems are used as distributed generators (DG) for this study. The solar PV systems are considered as DG units because the power system network considered for the study is located in a high solar insolation zone. Therefore, solar PV systems can be easily deployed in the system with high capacity utilization factor (CUF). The solar PV system is consists of PV arrays. The PV arrays are formed by series and parallel combination of solar cells to meet the required voltage and power levels. Solar cell is formed by a p-n junction fabricated in a thin layer of semiconductor similar to a p-n diode. The operational characteristic of the solar cell is also similar to p-n junction diode which depends on solar radiations as well as surface temperature. The single diode equivalent model of solar cell due to its simplicity and sufficient accuracy is used in this study which is illustrated in Figure 2. Detailed description and design data used for the study are available in [23,24].

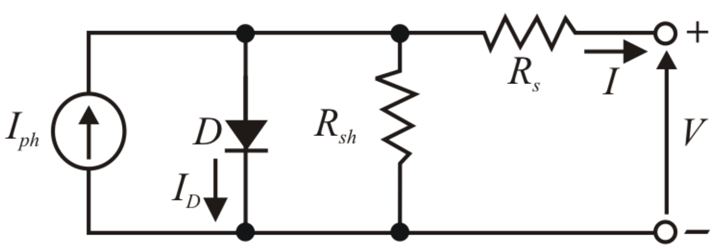

Figure 2. Representation of solar cell using Single-diode equivalent circuit.

The distributed battery energy storage system (BESS) will improve performance of the power system network. This provides life time improvement (LI), reduction in cost of system, optimal sizing (OS), mitigating power quality (PQ) issues, optimal control of power system (OCP), and peak load shifting [25]. Optimal placement of DG and BESS hybrid systems in the Indian grid is considered as future research scope.

Table 2. Quantum of Load on Different Nodes of Test Transmission Utility Network.

Bus No.	Voltage (kV)	Load Symbol	Projected Load Pload (MW)	Projected Load Qload (MVAR)	Bus No.	Voltage (kV)	Load Symbol	Quantum of Load Pload (MW)	Quantum of Load Qload (MVAR)
14	132 kV	L-1	14.647	7.093	42	132 kV	L-29	26.672	12.918
15	132 kV	L-2	98.622	23.493	43	132 kV	L-30	14.647	7.093
16	132 kV	L-3	41.792	13.788	44	132 kV	L-39	13.380	3.255
17	132 kV	L-4	34.400	19.637	45	132 kV	L-38	15.798	9.257
18	132 kV	L-5	36.724	20.378	46	132 kV	L-41	73.206	26.082
19	132 kV	L-6	14.647	7.093	47	132 kV	L-40	17.527	9.413
20	132 kV	L-7	83.771	39.363	48	132 kV	L-37	26.169	11.611
21	132 kV	L-21	66.223	23.854	49	132 kV	L-34	41.080	12.449
22	132 kV	L-20	33.684	15.253	50	132 kV	L-31	34.371	11.36
23	132 kV	L-19	18.943	9.174	51	132 kV	L-32	14.227	1.094
24	132 kV	L-18	20.382	11.551	52	132 kV	L-33	8.699	1.152
25	132 kV	L-12	23.034	12.631	53	132 kV	L-35	14.647	7.093
26	132 kV	L-13	31.296	9.221	54	132 kV	L-36	16.815	2.334
27	132 kV	L-14	39.364	30.270	55	132 kV	L-42	10.546	5.108
28	132 kV	L-15	14.647	7.093	56	132 kV	L-43	7.188	2.069
29	132 kV	L-17	19.587	7.953	57	132 kV	L-44	14.491	8.184
30	132 kV	L-16	73.196	16.337	58	132 kV	L-45	13.827	5.531
31	132 kV	L-9	30.446	13.699	59	132 kV	L-46	12.694	2.5386
32	132 kV	L-11	20.388	9.384	61	132 kV	L-54	29.577	14.822
33	132 kV	L-10	24.529	15.638	62	132 kV	L-51	48.315	24.313
34	132 kV	L-8	14.647	7.093	63	132 kV	L-53	31.813	7.036
35	132 kV	L-22	49.965	24.200	64	132 kV	L-52	13.828	5.533
36	132 kV	L-23	51.118	14.572	65	132 kV	L-50	14.647	7.093
37	132 kV	L-24	56.020	22.829	66	132 kV	L-48	26.008	16.118
38	132 kV	L-25	20.945	6.581	67	132 kV	L-47	14.647	7.093
39	132 kV	L-26	14.647	7.093	68	132 kV	L-49	14.647	7.093
40	132 kV	L-27	15.027	7.278	69	132 kV	L-55	14.649	7.065
41	132 kV	L-28	7.274	0.647	70	132 kV	L-56	12.449	6.029

3. Proposed Method of Study

The study is performed for four cases. This section details the study cases, DG placement method using grid parameter oriented harmony search algorithm (GPOHSA), network restructuring, mathematical formulations of the method and performance improvement indicators. The proposed study is performed to support the long term planning to mitigate transmission constraints in the southern part of Rajasthan, India with objective of minimum losses and better voltage profile. Hence, 24-hours and yearly variations of the load has not been considered. The study is focused on the peak loading conditions so that network may suffice in high loading scenario on time horizon of 10 year. The approach used to perform the study included in this paper is elaborated in Figure 3.

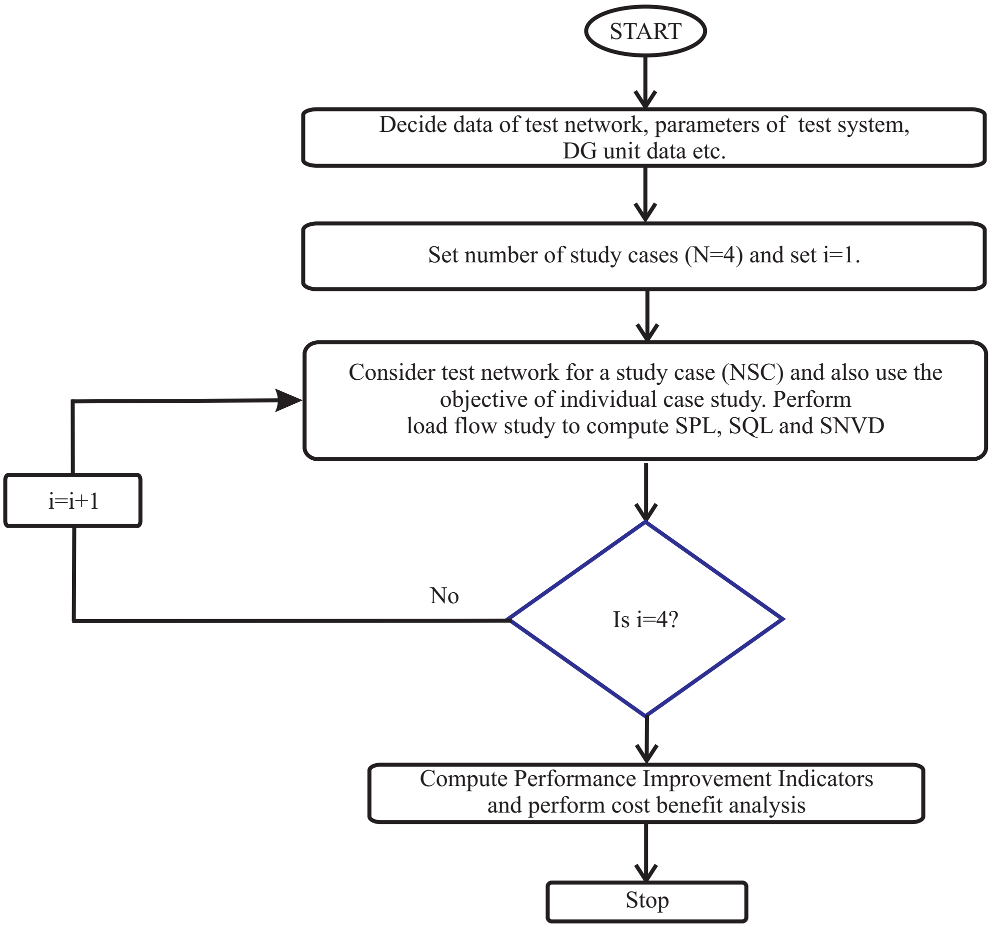

Figure 3. Approach to perform the study.

3.1. Study Cases

Study is performed for the following four cases of study.

- Study Case-1: Test network for the condition of year 2032 without considering optimal DG placement and network restructuring.
- Study Case-2: Test network for the condition of year 2032 considering network restructuring.
- Study Case-3: Test network for the condition of year 2032 considering optimal DG placement.
- Study Case-4: Test network for the condition of year 2032 considering both the optimal DG placement and network restructuring.

3.2. Design of Objective Function

The main objectives of this study are to minimize summation of real power loss (SPL) of all transmission elements, minimize summation of reactive power loss (SQL) of all transmission elements, and minimize summation of node voltage deviations (SNVD). Hence, there are three objective functions which can be minimized using the DG placement or network restructuring. The function expressing minimization of summation of real power loss (SPL) of all transmission elements is described in below expression:

$$SPL = \Sigma_{i=1}^{m}(I_{i.real}^{2} \times R_i) \quad (2)$$

Function expressing minimization of summation of reactive power loss (SQL) of all transmission elements is described in below expression:

$$SQL = \Sigma_{i=1}^{m}(I_{i.img}^{2} \times R_i) \quad (3)$$

The function expressing minimization of summation of node voltage deviations (SNVD) for all nodes of test network is described in the below expression:

$$SNVD = \Sigma_{i=1}^{m}(1 - V_i)^2 \tag{4}$$

The constraints for the objective functions are as detailed here. Limits of network node voltages is expressed by below expression. As per Indian Electricity grid codes (IEGC), the voltage limits are considered between 97% to 103% of rated value.

$$V_i^{min} \leq V_i \leq V_i^{max} \tag{5}$$

The constraints of transmission line thermal limits are expressed in terms of maximum permitted currents. These limits are in accordance with the planning criteria defined by the Central Electricity Authority (CEA), India.

$$I_{i,j} \leq I_{rated} \tag{6}$$

The RE power generation limits are defined by below relation. The maximum and minimum limits for RE generators is taken as 50 MVA and 200 MVA, respectively.

$$S_{DG_i}^{min} \leq S_{DG_i} \leq S_{DG_i}^{max} \tag{7}$$

3.3. Grid Parameter Oriented Harmony Search Algorithm

The grid parameter oriented harmony search algorithm (GPOHSA) is obtained by a modification in the conventional harmony search algorithm (HSA) where grid coordinates are used for locating the individuals in an objective space. Detailed mathematical formulation of harmony search algorithm available in [26] are used for optimal DG unit placement. Following are steps of implementation of GPOHSA for optimal DG placement:

- Simulate the test network of study case-1 without restructuring and test network of study case-2 considering restructuring. Compute all the parameters such as real power loss, reactive power loss, voltage deviations and voltages network buses.
- Simulate the test network of study case-1 without restructuring and test network of study case-2 considering restructuring along with DG placement using GPOHSA. Objective functions elaborated in Section 3.2 are computed and position as well as size of the DG units is iteratively changed to minimize the objective functions. The constraint boundaries of objectives are identified in entire population for setting the grid structure of objective functions.
- Minimum and maximum bounds of grid in objectives are computed using below detailed relations [27].

$$ll_k = P_m^{min} - \frac{\left(P_m^{max} - P_m^{min}\right)}{2 \times NDOS} \tag{8}$$

$$ul_k = P_m^{max} + \frac{\left(P_m^{max} - P_m^{min}\right)}{2 \times NDOS} \tag{9}$$

  here ll_k: Lower limit of kth objective; ul_k: Upper limit of kth objective; NDOS: number of divisions of objective space; P_m^{min}: Minimum range of kth objective; P_m^{max}: Maximum range of kth objective.
- The fitness is computed using the three grid dependent criteria which includes the grid ranking (GR), grid crowding distance and grid coordinate point distance are used by the GPOHSA to rank the individuals with better fitness. Convergence is computed utilizing the GR and grid coordinate point distance (GCPD). Grid crowding distance (GCD) is utilized for computing the diversity of entities.
- Size and location of DG units corresponding to minimum values of objective functions is suggested as optimal solution.

3.4. Performance Improvement Indicators

Improvement in the SPL, SQL and SNVD for the study cases-2, 3 and 4 is estimated with the help of three performance improvement indicators which are designated as SPL reduction indicator (SPLRI), SQL reduction indicator (SQLRI), and SNVD reduction indicator (SNVDRI). These performance indicators are described in this section.

3.4.1. SPL Reduction Indicator

Reduction in the network real power loss is estimated using the SPL reduction indicator (SPLRI). The SPLRI is defined as percentage ratio of difference in SPL of base study case-1 and particular case study to the SPL of base study case-1 as described by the below expression:

$$SPLRI = \frac{SPL1 - SPLStudyCase}{SPL1} \times 100\% \quad (10)$$

Higher is the value of SPLRI for a study case, lower is the real power loss and network performance is improved.

3.4.2. SQL Reduction Indicator

Reduction in the network reactive power loss is estimated using the SQL reduction indicator (SQLRI). The SQLRI is defined as percentage ratio of difference in SQL of base study case-1 and particular case study to the SQL of base study case-1 as described by the below expression:

$$SQLRI = \frac{SQL1 - SQLStudyCase}{SQL1} \times 100\% \quad (11)$$

Higher is the value of SQLRI for a study case, lower is the reactive power loss and network performance is improved.

3.4.3. SNVD Reduction Indicator

Reduction in the network node voltage deviation summation is estimated using the SNVD reduction indicator (SNVDRI). The SNVDRI is defined as percentage ratio of difference in SNVD of base study case-1 and particular case study to the SNVD of base study case-1 as described by the below expression:

$$SNVDRI = \frac{SNVD1 - SNVDStudyCase}{SNVD1} \times 100\% \quad (12)$$

Higher is the value of SNVDRI for a study case, lower is the summation of node voltage deviations and network performance is improved.

3.5. Limitations of Study

Following are limitations of study presented in this paper:

- The study is performed considering the transmission planning criteria where all the lines and transformers are considered in the closed conditions. All generators of the network are also considered as integrated to the network and operative. However, State Load Dispatch Center (SLDC) and National Load Dispatch Center (NLDC) issues directions time to time to keep some of the lines in open conditions and some of generators either operate at reduced capacity or might be kept off.
- The generators UGEN-1, UGEN-2 and UGEN-9 used to realize the interconnection with rest of the grid have been assigned fixed capacity in the simulation study. However, in real time scenario power interchange with the test grid and rest of the grid may change.
- The estimated cost is computed using the standard values of recent work orders placed for procurement of the material. However, prices may change depending on the supplier of the material.

- Load projections for the projected year 2032 is computed using the linear model. Hence, it may change depending on the future trends of electrical power utilization.
- The GPOHSA used three parameters (GR, GCD, GCPD) for fitness computation. However, consideration of more parameters might increase the efficiency.

4. Discussion of Simulation Results

Simulation results for the test network corresponding to scenario of 2032, test network with optimal DG placement, test network with network restructuring and test network with optimal DG placement as well as network restructuring are analyzed and discussed in this section.

4.1. Computed Parameters of Objective Function

This section details the computed parameters for all the study cases. The objective function designed to minimize summation of real power loss (SPL) of all transmission elements, summation of reactive power loss (SQL) of all transmission elements, and summation of node voltage deviations (SNVD) is computed for the study case-1, study case-2, study case-3 and study case-4. This objective function is optimized by placement of optimally sized DG units at optimal locations of the network using grid parameter oriented harmony search algorithm (GPOHSA).

4.1.1. Study Case-1

This study case-1 considers the test network for the condition of year 2032 without considering optimal DG placement and network restructuring. Objective functions for the network of study case-1 for the condition of year 2032 without considering optimal DG placement and network restructuring is elaborated in Figure 4. This is observed that minimized values of objective functions for SPL, SQL and SNVD are 14.229 MW, 33.869 MVAR and 0.0812 p.u., respectively. Minimized magnitudes of objective function parameters are provided in Table 3.

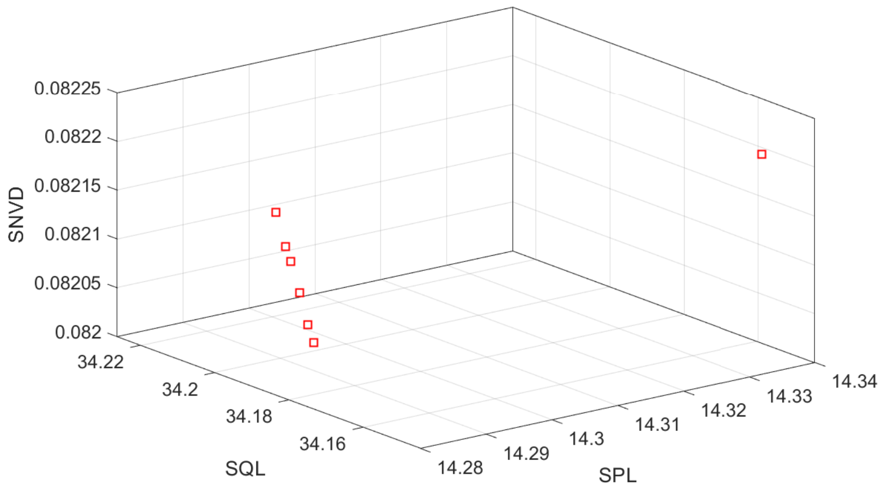

Figure 4. Objective functions for Study Case-1 (Test network for the condition of year 2032 without considering optimal DG placement and network restructuring).

Table 3. Computed Parameters of Objective Functions.

S. No.	Attribute	Study Case-1	Study Case-2	Study Case-3	Study Case-4
1	Loss of real power (MW)	14.229	13.940	4.343	2.814
2	Loss of reactive power (MVAR)	33.869	33.184	10.338	6.698
3	Summation of voltage deviation (p.u.)	0.0812	0.0764	0.0398	0.0235

4.1.2. Study Case-2

This study, case-2, considers the test network for the condition of year 2032 considering network restructuring. The following additional transmission elements are considered to restructure the network:

- 2 × 500 MVA, 400/220 kV transformer at 400/220 kV GSS Udaipur between bus-72 and bus-73.
- 90 km LILO (Line-in-line-out) of one circuit of 400 kV D/C Bhilwara (bus-71)-Chittorgarh (bus-2) line at 400 kV GSS Udaipur (bus-72).
- 2.5 kM Line-in-line-out (LILO) of 220 kV S/C Debari (Bus-7)-Amberi (Bus-6) line at 400 kV GSS Udaipur (bus-73).
- 11 kM Line-in-line-out (LILO) of 220 kV S/C Madri (Bus-10)-Banswara (Bus-12) line at 400 kV GSS Udaipur (bus-73).
- 1 × 160 MVA, 220/132 kV Interconnecting transformer (ICT) at proposed 220/132 kV GSS Dungarpur equipped with bus-73 and bus-74.
- 102 km, 220 kV double circuit (D/C) Udaipur (400 kV GSS) (Bus-73)-Dungarpur (Bus-74) line.
- 14 km LILO of 132 kV S/C Dungarpur (132 kV GSS)(Bus-48)-Sagwara (Bus-49) line at 220 kV GSS Dungarpur (bus-75).
- 30 km 132 kV S/C Dungarpur (220 kV GSS)(Bus-75)-Bicchiwara (Bus-56) line.
- 30 km 132 kV S/C Dungarpur (220 kV GSS)(Bus-75)-Seemalwara (Bus-54) line.

The objective functions for the network of study case-2 for the condition of year 2032 considering network restructuring is elaborated in Figure 5. This is observed that minimized values of objective functions for SPL, SQL and SNVD are 13.940 MW, 33.869 MVAR and 0.0812 p.u., respectively. Minimized magnitudes of objective function parameters are provided in Table 3.

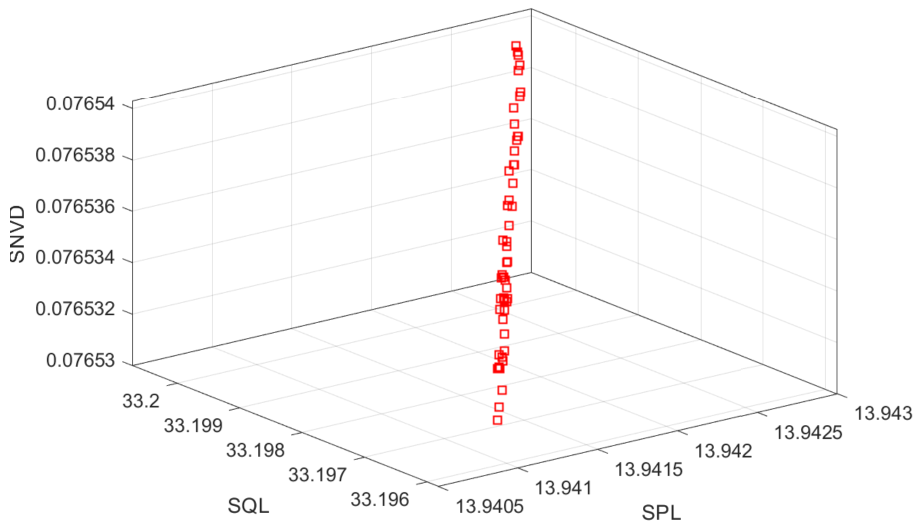

Figure 5. Objective functions for Study Case-2 (Test network for the condition of year 2032 considering optimal DG placement).

4.1.3. Study Case-3

This study case-3 considers the test network for the condition of year 2032 considering optimal DG placement using GPOHSA. The objective functions for the network of study case-3 for the condition of year 2032 considering optimal DG placement is elaborated in Figure 6. This is observed that minimized values of objective functions for SPL, SQL and SNVD are 4.343 MW, 10.338 MVAR and 0.0398 p.u., respectively. Minimized magnitudes of objective function parameters are provided in Table 3.

The sizing of DG units and node identified for placement for study case-3 using GPOHSA are illustrated in Table 4. This is observed that total DG capacity proposed for the test network is equal to 407.8326 MW.

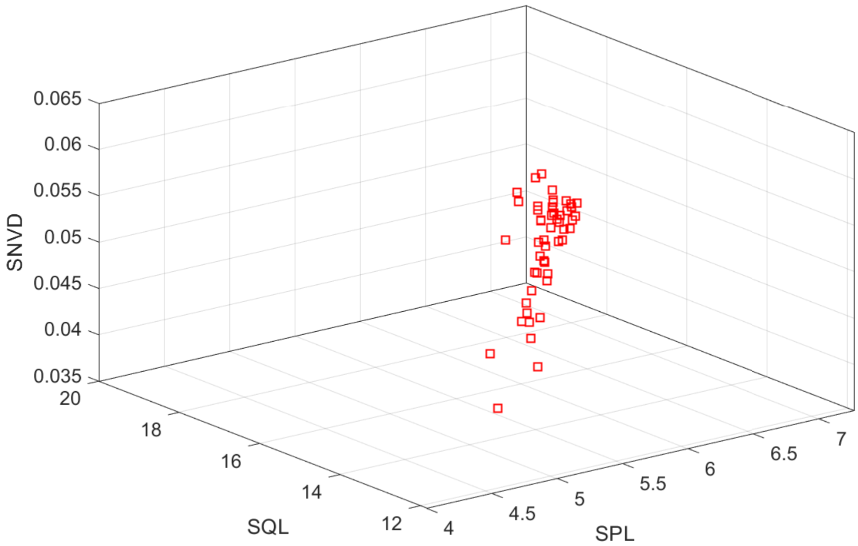

Figure 6. Objective functions for Study Case-3 (Test network for the condition of year 2032 considering network restructuring).

Table 4. Computed Capacity and Nodes for Placement of DG Units.

S. No.	Node No.	DG Capacity (MW)	
		Study Case-3	**Study Case-4**
1	19	-	51.1221
2	26	-	115.7932
3	51	51.3345	187.9960
4	52	158.0188	-
5	64	198.4793	-

4.1.4. Study Case-4

This study case-4 considers the test network for the condition of year 2032 considering optimal DG placement using GPOHSA and network restructuring using the additional transmission elements discussed in Section 4.1.2. The objective functions for the network of study case-4 for the condition of year 2032 considering both the optimal DG placement and network restructuring is elaborated in Figure 7. It is observed that minimized values of objective functions for SPL, SQL and SNVD are 2.814 MW, 6.698 MVAR and 0.0235 p.u., respectively. Minimized magnitudes of objective function parameters are provided in Table 3. The sizing of DG units and node identified for placement for study case-4 using GPOHSA are illustrated in Table 4. It is observed that total DG capacity proposed for the test network is equal to 354.9102 MW.

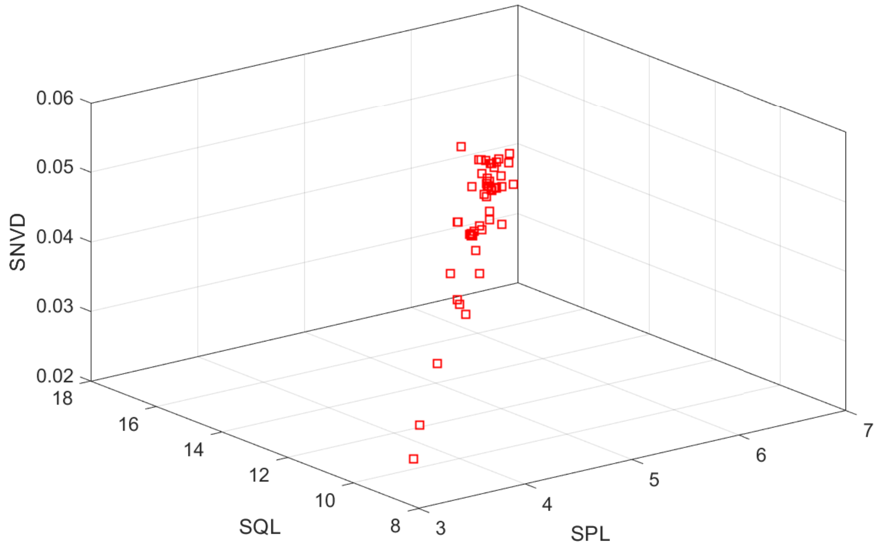

Figure 7. Objective functions for Study Case-4 (Test network for the condition of year 2032 considering both the optimal DG placement and network restructuring).

4.1.5. Relative Study of All Study Cases in Terms of Objective Function Parameters

The computed parameters of objective functions for all the study cases are elaborated in Table 3. Detailed analysis of objective function parameters included in Table 3 indicates that both the network restructuring and DG placement reduce the SPL, SQL and SNVD. However, maximum benefits are observed after the optimal placement of DG units. Hybrid combination of DG placement and network restructuring further reduces the magnitudes of SPL, SQL and SNVD.

4.2. Computation of Real Power Loss Saving and Energy Saving

The real power loss saving (RPLS) is computed for the study cases-2, 3, and 4 compared to the study case-1 which is base case network without any change. RPLS for a particular case is computed by subtracting the SPL for that study case from the SPL for study case-1. For example, RPLS for the study case-2 (RPLS2) is computed by subtracting the SPL for study case-2 (SPL2) from the SPL of study case-1 (SPL1) as detailed below:

$$RPLS2 = SPL1 - SPL2 \tag{13}$$

Similarly, the RPLS for study case-3 (RPLS-3) and RPLS for study case-4 (RPLS-4) are also computed. Computed values of the RPLS2, RPLS3 and RPLS 4 are provided in Table 5.

Electricity energy saving (EES) is computed using the following relation by expressing the RPLS of each case study in terms of KWh/year:

$$EES(kWh/year) = RPLS(MW) \times 1000 \times 8760 \tag{14}$$

The computed values of ESS for the study cases-2, 3 and 4 are illustrated in Table 5. A careful analysis of the data included in Table 5 indicates that RPLS and EES are maximum for the study case-4 and minimum for the study case-2 compared to the base study case-1.

Table 5. Saving of Real Power Loss and Energy.

S. No.	Attribute	Study Case-2	Study Case-3	Study Case-4
1	Saving of Real Power Loss (MW)	0.289	9.886	11.415
2	Electricity Energy saving (kWh/year)	2,531,640	86,601,360	99,995,400

4.3. Voltage Profile of Network Nodes

The voltage recorded on network nodes for all the four cases of study are illustrated in Figure 8. For the study cases-1 and 3, there are 70 test network nodes and for the study cases-2 and 4 there are 75 nodes of the test network. These nodes are increased due to network restructuring. Hence, voltages on nodes 71 to 75 are considered equal to unity for study cases-1 and 3. Figure 8 depicts that voltages are minimum on the test network nodes for base case network of study case-1. Voltages are improved by implementation of network restructuring in study case-2. These voltages are further improved by optimal placement of DG units using the GPOHSA in study case-3. These voltages are further improved by hybrid combination of optimal placement of DG units using the GPOHSA and network restructuring in study case-4.

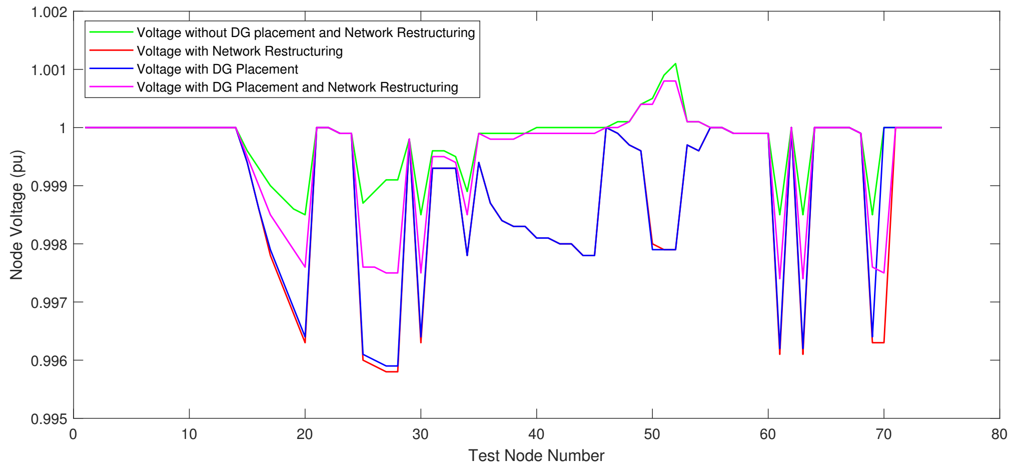

Figure 8. Computed voltages on the nodes of test network.

4.4. Computation of Performance Improvement Indicators

All the three performances improvement indicators (SPLRI, SQLRI and SNVDRI) are computed for three study cases-2, 3 and 4 which are included in Table 6. These performance indicators are computed using data included in Table 3 and mathematical expressions included in Section 3.4. SPLRI for study case-2 is computed as detailed below:

$$SPLRI = \frac{SPL1 - SPLStudyCase2}{SPL1} \times 100\% = \frac{14.229 - 13.940}{14.229} \times 100\% = 2.031\% \quad (15)$$

The SPLRI for the study case-3 and 4 are also computed using the above relation and included in Table 6. The SQLRI for study case-2 is computed as detailed below:

$$SQLRI = \frac{SQL1 - SQLStudyCase2}{SQL1} \times 100\% = \frac{33.869 - 33.184}{33.869} \times 100\% = 2.022\% \quad (16)$$

The SQLRI for the study case-3 and 4 are also computed using the above relation and included in Table 6. The SNVDRI for study case-2 is computed as detailed below:

$$SNVDRI = \frac{SNVD1 - SNVDStudyCase2}{SNVD1} \times 100\% = \frac{0.0812 - 0.0764}{0.0812} \times 100\% = 5.911\% \quad (17)$$

The SNVDRI for the study case-3 and 4 are also computed using the above relation and included in Table 6. Table 6, depicts that SPLRI is maximum for the study case-4 and minimum for the study case-2. Similar, trend is also followed for the SQLRI and SNVDRI. Hence, it is concluded that hybrid combination of DG placement using the GPOHSA and network restructuring helps to improve performance of the test network maximum compared to all study cases in terms of SPL, SQL and SNVD.

Table 6. Performance Improvement Indicators.

S. No.	Performance Improvement Indicator	Study Case-2	Study Case-3	Study Case-4
1	SPLRI	2.031	69.477	80.223
2	SQLRI	2.022	69.476	80.223
3	SNVDRI	5.911	50.985	71.059

5. Computation of Period of Investment Return

The estimated cost of erection of additional transmission system considered in the study case-2 and study case-4 is computed and included in Table 7 [28]. The cost of the erection of DG units of solar photovoltaic (PV) plants is computed considering the base cost for DG unit of capacity 10 kW which is equal to Indian Rupees (INR) 82000 [29]. This cost includes the cost of wiring charges, operation and maintenance cost. This cost used for cost estimation is tentative and it may vary depending on the period of execution of scheme. However, these changes in cost will be same for all the cases of study. Therefore, merit of study cases will not change in future time. The estimated cost of DG units for the study case-2, study case-3 and study case-4 are included in Table 8.

Table 7. Estimated Cost of Additional Transmission System.

S. No.	Details of Element	Estimated Cost (Million INR)
1	Construction of 2 × 500 MVA, 400/220 kV GSS and associated bays/equipment	19379
2	Construction of 1 × 160 MVA, 220/132 kV GSS and associated bays/equipment	496.958
3	90 km 400 kV D/C line	4985
4	115.5 km 220 kV D/C lines	3380.711
5	65 km 132 kV S/C lines	179.20
	Total cost	28,420.869

Table 8. Estimated Cost of Additional Elements of Study Cases.

S. No.	Study Case	Estimated Cost of DG Unit (Million INR)
1	Study Case-3	3344.227
2	Study Case-4	2910.264

The electricity tariff (ET) to compute cost benefit is considered equal to Indian Rupees (INR) 7.65/kWh [30] which is present ET rate in India. Period of investment return (PIR) is estimated to find time period in which investment incurred on the network restructuring and DG unit placement may be recovered. Saving of cost in a year on account of loss saving (CLS) due to network restructuring and DG units placement is computed by below detailed relation:

$$CLS(INR/year) = EES(kWh/year) \times 7.65(INR/kWh) \tag{18}$$

Period of investment return is expressed as ratio of capital cost incurred in network restructuring and DG units placement (CCDGNR) to the saving of cost in a year on account of loss saving (CLS) and computed using the below detailed relation [31].

$$PIR(year) = \frac{CCDGNR}{CLS} \tag{19}$$

Total yearly cost saving on account of loss saving (CLS), CCDGNR, CLS, and PIR are illustrated in Table 9.

Table 9. Active Power Loss Saving and Payback Period.

S. No.	Particular	Study Case-2	Study Case-3	Study Case-4
1	CCDGNR (Million INR/year)	28,420.869	3344.227	31,331.133
2	CLS (Million INR)	193.67	6625.0	7649.65
2	PIR (year)	146.749	0.505	4.095

Table 9 details that PIR is minimum and equal to 0.505 year for the proposed case-3 and highest for the study case-2. PIR for the study case-4 is 4.095 year which is normal period of return on investment. Since, availability of power from the solar DG units in day time only whereas the peak load is recorded in the evening time. Hence, network of the study case-4 is highly recommended because this will help to meet the load round the clock.

6. Performance Comparison

Performance for the proposed GPOHSA for the study case-3 is compared with the genetic algorithm based technique reported in [32]. Detailed comparative study in terms of SPLRI, SQLRI, SNVDRI, PIR, DG capacity, and RPLS is included in Table 10.

Table 10. Comparative Study GPOHSA and GA.

S. No.	Parameter	GPOHSA	GA [32]
1	SPLRI	69.477	48.271
2	SQLRI	69.476	46.009
3	SNVDRI	50.985	36.082
4	PIR (Year)	0.505	0.724
5	DG Capacity (MW)	407.8326	588.694

Table 10 details that SPLRI, SQLRI and SNVDRI have higher values for the GPOHSA based method compared to the GA based method. PIR and DG capacity are lower for the GPOHSA based method compared to GA based method. Hence, it is established that proposed GPOHSA is superior relative to the GA based techniques for DG unit placement in the test utility network.

7. Conclusions

This paper introduces a method using hybrid combination of network restructuring and optimal placement of optimally sized DG units to reduce loss and improve voltage profile in a practical transmission network for scenario of high load demand. Four study cases are used to perform the study which includes the test transmission network without considering optimal DG placement and network restructuring, considering network restructuring, optimal placement of DG units using GPOHSA and hybrid combination of network restructuring and DG placement using GPOHSA. Performance improvement indicators such as SPLRI, SQLRI and SNVDRI are used to assess relative effectiveness of each case study to reduce network losses and improve voltage profile. This is concluded that node voltages are improved by implementation of network restructuring. These voltages are further improved by optimal placement of DG units using the GPOHSA. These voltages are further improved by hybrid combination of optimal placement of DG units using the GPOHSA and network restructuring. The network restructuring and DG placement reduce the SPL, SQL and SNVD. However, maximum benefits are observed after the optimal placement of DG units. Hybrid combination of DG placement and network restructuring further reduces the magnitudes of SPL, SQL and SNVD. RPLS and EES are maximum for the study case of simultaneous network restructuring and DG placement and minimum for the study case of network restructuring. Similar trend is also observed for the SPLRI, SQLRI and SNVDRI. A PIR of 0.505 and 4.095 are observed for the study case of DG placement using GPOHSA and hybrid combination of both the DG placement and network restructuring. Performance of GPOHSA for DG units placement is better relative to the conventional GA. The study is performed on practical transmission network using MATLAB software. The investigation of daily and annual variations of RE generation and optimal placement of hybrid combination of DG and BESS is considered as future research scope.

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Abbreviations

The following abbreviations are used in this manuscript:

ACSR	Aluminium conductor steel reinforced
BESS	Battery energy storage system
CCDGNR	Capital cost incurred in network restructuring and DG units placement
CEA	Central Electricity Authority
CI	Critical infrastructure
CLS	Saving of cost in a year on account of loss saving
CUF	Capacity utilization factor
D/C	Double circuit
DG	Distributed generators
EES	Electricity energy saving
ET	Electricity tariff
GA	Genetic algorithm
GCD	Grid crowding distance
GCPD	Grid coordinate point distance
GPOHSA	Grid parameter oriented harmony search algorithm
GR	Grid ranking
GSS	Grid-substation
HSA	Harmony search algorithm
ICT	Interconnecting transformer
INR	Indian Rupees
IEGC	Indian Electricity grid codes
LI	Life time improvement
LILO	Line-in-line-out
MOMVO	Multi-objective multi-verse optimization
NLDC	National load dispatch centre
OS	Optimal sizing
PABC	Particle Artificial Bee Colony algorithm
PAL	Projected average load
PF	Power factor
PIR	Period of investment return
PSF	Power system flexibility

PSRFI	Power system restructuring flexibility index
PV	Photovoltaic
RE	Renewable energy
RPLS	Real power loss saving
RVPN	Rajasthan Rajya Vidyut Prasaran Nigam Limited
S/C	Single circuit
SLDC	State load dispatch centre
SNVD	Summation of node voltage deviations
SNVDRI	Summation of node voltage deviation reduction indicator
SPL	Summation of real power loss
SPLRI	Real power loss reduction indicator
SQL	Summation of reactive power loss
SQLRI	Reactive power loss reduction indicator
SVR	Step-voltage regulator
TL	Transmission line
UGEN	Utility generator
UT	Utility transformer

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