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Determination of Size and Location of Shunt Capacitor Banks Using Grid Oriented Multi-objective Harmony Search Algorithm to Improve Voltage Profile and Loss Reduction in Sub-transmission System

Pramod Kumar[1], Nagendra Kumar Swarnkar[1], Om Prakash Mahela[2]
[1]Department of Electrical Engineering, Suresh Gyan Vihar University, Jaipur, India
(Email: pkrajdan@gmail.com, swarnkar.n123@gmail.com)
[2]Power System Planning Division, Rajasthan Rajya Vidyut Prasaran Nigam Ltd., Vidyut Bhawan, Jaipur, India
(Email: opmahela@gmail.com)

Abstract— This paper formulated a grid-oriented harmony search algorithm (GOMOHSA) for determination of size and effective location of shunt capacitors in a practical transmission network to achieve reduction in active power loss, reactive power loss and minimization of total voltage deviations on the network buses. Performance indexes like real power loss index (PLI), reactive power loss index (QLI), and voltage deviation index (VDI) are designed to estimate performance of GOMOHSA. This is established that losses of active power and reactive power in the network have been reduced significantly and summation of voltage deviations on all the buses has been minimized. Effectiveness of GOMOHSA is established to be better relative to genetic algorithm (GA) for optimal localization of capacitors of optimal size in practical test network. Study is performed using the MATLAB software.

Keywords— *Active power loss; Capacitor bank; Grid-oriented multi-objective harmony search algorithm; Reactive power loss; Transmission network; Voltage profile.*

1. Introduction

The capacitor are connected in network of distribution and sub-transmission system in the form of shunt capacitor banks which helps to provide compensation of reactive power. Deployment of shunt capacitor banks helps to reduce the loos in active power loss and reactive power. This also effective to improve voltage regulation of network buses, release in line capacity and improvement in power quality (PQ). The problem of connection of capacitors includes decision of size (kVAR ratings) and nodes for connection of capacitors [1]. Determination of best location for deployment of capacitor will help to reduce reactive power requirement in addition to keeping the voltage profile within permissible limits [2]. Different traditional and advanced techniques have been reported in the literature for deployment of optimally sized capacitor banks on appropriate nodes of the distribution and sub-transmission network. In [3], authors designed a hybrid technique by combination of the genetic algorithm (GA) and State transition technique known as particle swarm optimization (PSO) for achieving effective capacitor deployment in power network. Connection of capacitors at appropriate places of the accurate quantity is achieved using the proposed method. In [4], authors proposed a method which designed by the use of evolutionary algorithms such as memetic technique which uses a hierarchical arrangement of population in the form of overlapped clusters for suitable sizing and allocation of capacitors. Characteristic of special selection and reproduction

Correspondence to: Pramod Kumar, Department of Electrical Engineering, Suresh Gyan Vihar University, Jaipur, India
Corresponding author. E-mail addresses: pkrajdan@gmail.com

schemes improved the performance of algorithm. This technique effectively tested on an IEEE-13 nodes test system for loss minimization and improving the voltages of various nodes. In [5], authors designed a fast and efficient capacitor deployment techniques which provides the mesh-sensitivity supported decoupling capacitor size determination and integration to grid. Two goals achieved are (i) highlighted the comparative impact of decoupling capacitors integrated at different nodes in the form clusters (ii) use of analytical sensitivity knowledge in a gradient supported Sequential Quadratic Programming (SQP) approach to obtain appropriate sized capacitors at appropriate location. In [6], authors introduced a technique, which considered the capacitor size determination and parasitic match considering the common-centroid capacitor layout generation at same time. This helped to minimize the power consumption satisfying the circuit accuracy/performance. Experimental validation of results is also achieved to establish the efficacy of the technique. In [7], authors designed technique for capacitor integration to grid and size determination using loss sensitivity concept and genetic algorithm. A factor of power loss sensitivity is designed which provides logical information about each feeder section and assess the capacitor requirement using study of load flow. In this feeder section, power loss sensitivity with high merit is selected for connection of capacitors to grid. The GA considers the multi-fold goal function to achieve power loss reduction and improvement of voltage pattern for determination of optimal size of capacitors. In [8], a fuzzy set theory is utilized for capacitor deployment in the power network. This technique is used the distribution functions for optimal capacitor sizing and placement. The implemented fuzzy solution gives more suitable means to evaluate the high quality of results based on uncertain data. Method is implemented effectively on the test practical sub-transmission network. In [9], authors designed a GA oriented technique for optimal placement and size determination of the capacitors to achieve an objective of minimization of losses and voltage profile enhancement. Efficacy of the technique is validated on an IEEE 33-node distribution test feeder. Different solutions for network of power utility are reported in [10]-[20].

Descriptive review of literature included in above section demonstrates that optimal deployment of capacitor banks in the sub-transmission network results in loss reduction in the network and improves voltage pattern. This is considered as the point of research investigation and following are important contributions:-

- A grid oriented multi-objective harmony search algorithm (GOMOHSA) is designed for optimal deployment of capacitors in the sub-transmission network of practical utility network.
- Performance indexes like PLI, QL) and VDI are designed to assess performance of the GOMOHSA for minimization of loss and voltage pattern enhancement.
- This is established that losses of active and reactive power have been reduced in the network by 50% approximately and voltage profile has been improved significantly.
- Performance of GOMOHSA is superior relative to GA considering loss minimization, voltage pattern enhancement and performance indexes.
- Study is validated in the MATLAB software.

Correspondence to: Pramod Kumar, Department of Electrical Engineering, Suresh Gyan Vihar University, Jaipur, India
Corresponding author. E-mail addresses: pkrajdan@gmail.com

2. Test Transmission Network

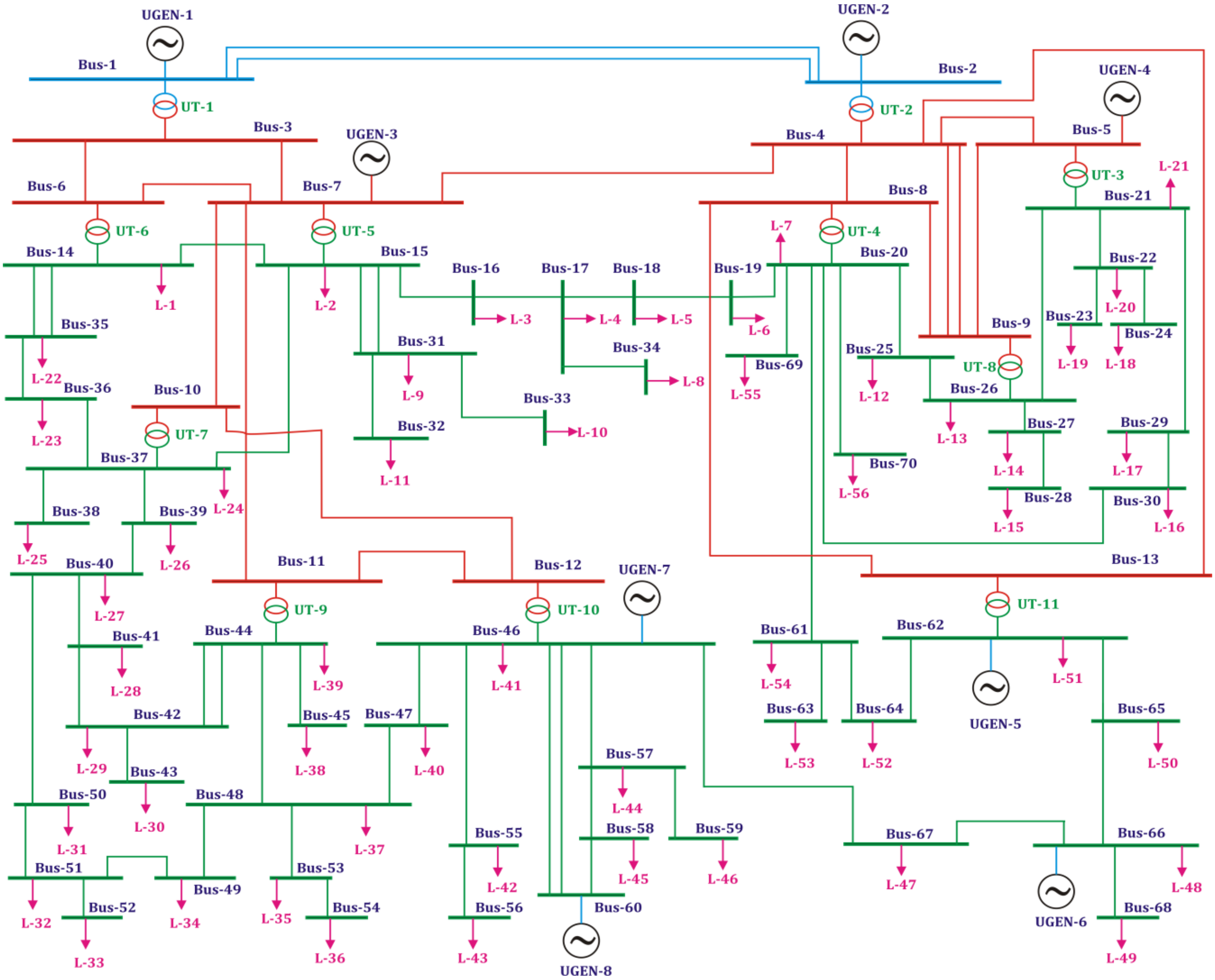

Fig. 1 Practical test sub-transmission system considered for validation of GOMOHSA

Technical parameters and data of transmission lines and transformers reported in [21]-[22] are used to perform the study. There are total 70 nodes/buses in the network. Two buses are maintained on the 400kV voltages. Eleven buses are maintained at 220 kV voltages and 68 buses are maintained at 132 kV voltages. All loads are integrated on the 132kV buses are simulated using the PQ type of loads. These loads are designated by the symbols ranging from L-1 to L-57. Total system load equal to 499.12MW is used in this study. Generators integrated to the network are designated by symbols Gen-1 to Gen-8.

3. Proposed Capacitor Placement Algorithm

A grid oriented multi-objective harmony search algorithm (GOMOHSA) is designed and implemented for deployment of optimally sized capacitor banks in a practical transmission network for minimizing the active and reactive power loss and also to improve voltage pattern of network. Design of GOMOHSA method and performance indexes used to evaluate efficacy of the GOMOHSA are elaborated in the below subsections.

3.1 Objective Function Formulation

This method used to optimize the three objective functions related to reduction in active power loss, reactive power loss and minimization of voltage deviations on network buses. Active power loss reduction objective function (POF) used the concept of minimization of losses in transmission lines and transformers due to active component of the current and defined by the use of following mathematical relation:-

$$POF = \sum_{i=1}^{N} I_{i,real}^{2} \times R_i$$

The reactive power loss reduction objective function (QOF) used concept of minimization of power loss in transmission lines and transformers due to reactive component of current and defined by use of following mathematical relation:-

$$QOF = \sum_{i=1}^{N} I_{i,img}^{2} \times R_i$$

The voltage deviation minimization objective function (VOF) is defined by the use of following mathematical relation:-

$$VOF = \sum_{i=1}^{N} (1 - V_i)^2$$

3.2 Performance Indexes

Performance of the techniques is evaluated using three performances indexes which are described below:-

3.2.1 Real Power Loss Index

Real power loss index (PLI) is expressed as percentage ratio of active power loss with capacitors (P_{cap}) to active power loss without capacitor placement (P_{ncap}) as detailed below:-

$$PLI = \frac{P_{cap}}{P_{ncap}} \times 100\%$$

Low values of PLI indicates that active power loss is minimized and vice versa. Therefore, efficiency of power network will be high for the lower values of PLI.

3.3 GOMOHSA

The GOMOHSA used the concept of Harmony search algorithm for deployment of capacitors in a practical sub-transmission network by optimizing the three objective functions related to minimization of losses of active power and eactive power. Further, voltage deviations on the network nodes is also achieved. Following are the steps to use GOMOHSA for capacitor deployment:-

- Simulate the test network without capacitors and compute loss of active power and reactive power loss and also the summation of voltage deviations on all nodes from unity.
- Place the capacitor banks on the different nodes and computes active & reactive power loss and total voltage deviations. Iteratively relocate the capacitor banks on different nodes by changing their sizes using the harmony search algorithm (HSA). Mathematical formulation of the HSA available in [23]-[25] is used for this study.

3.2.2 Reactive Power Loss Index

Reactive power loss index (QLI) is expressed as percentage ratio of reactive power loss with capacitors (Q_{cap}) to reactive power loss without capacitor placement (Q_{ncap}) as detailed below:-

$$QLI = \frac{Q_{cap}}{Q_{ncap}} \times 100\%$$

Low values of QLI indicates that reactive power loss is minimized and vice versa. Therefore, efficiency of power network will be high for the lower values of QLI.

3.2.3 Voltage Deviation Index

Voltage deviation index (VDI) is defined as percentage ratio of total voltage deviation with capacitors (VD_{cap}) to the total voltage deviation without capacitors (VD_{ncap}) as detailed below:-

$$VDI = \frac{VD_{cap}}{VD_{ncap}} \times 100\%$$

Low values of VDI indicates that total voltage deviation is minimized and vice versa. Therefore, voltage profile of power network will be improved for the lower values of VDI.

- Relocation and sizing of the capacitors is done using HSA till the optimal results in terms of loss minimization and minimum voltage deviations are achieved.
- Compute the performance indexes to evaluate the effectiveness of the GOMOHSA.

4. Simulation Results and Discussion

Results demonstrating optimal placement of capacitors having optimal sizes are detailed in this section.

4.1 Test Network Without Capacitor Banks

The objective function designed to perform the study is focused to minimize losses of active power & reactive power in sub-transmission network and total voltage deviations of the network buses is optimized using the proposed GOMOHSA algorithm and without the capacitor placement. Objective function indicating active power loss, reactive power loss and voltage deviations is depicted in Fig. 2. This is established that objective function is minimized with the values of losses of active & reactive power and voltage deviations equal to 7233.742kW, 17219.276kVAr, and 0.055pu respectively. Objective values for this case of study are detailed in Table 1.

Correspondence to: Pramod Kumar, Department of Electrical Engineering, Suresh Gyan Vihar University, Jaipur, India
Corresponding author. E-mail addresses: pkrajdan@gmail.com

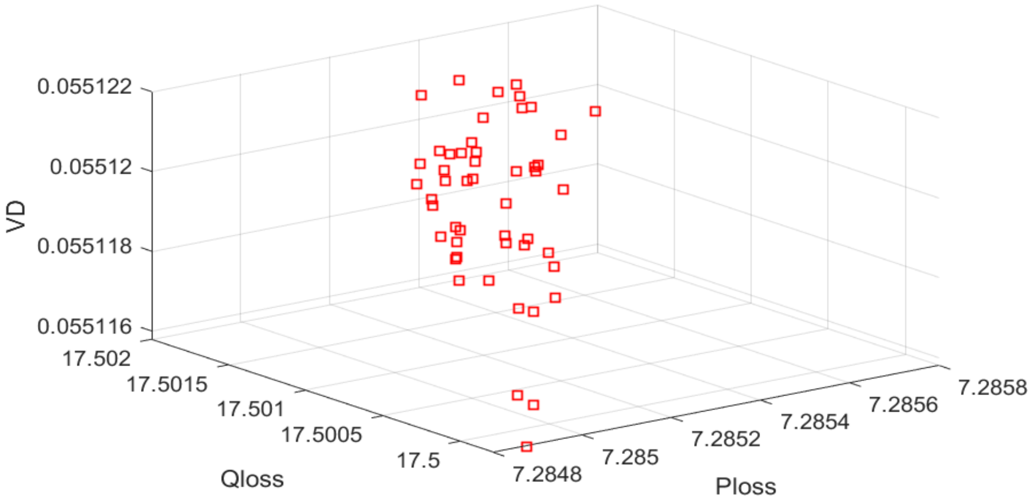

Fig. 2 Objective function for the test network without capacitor deployment

The voltage recorded on all the buses of test sub-transmission network is shown in Fig. 3. This is observed that voltage magnitude at some of the nodes is unity and at some of the nodes the voltage is low and minimum voltage equal to the 0.997pu is observed.

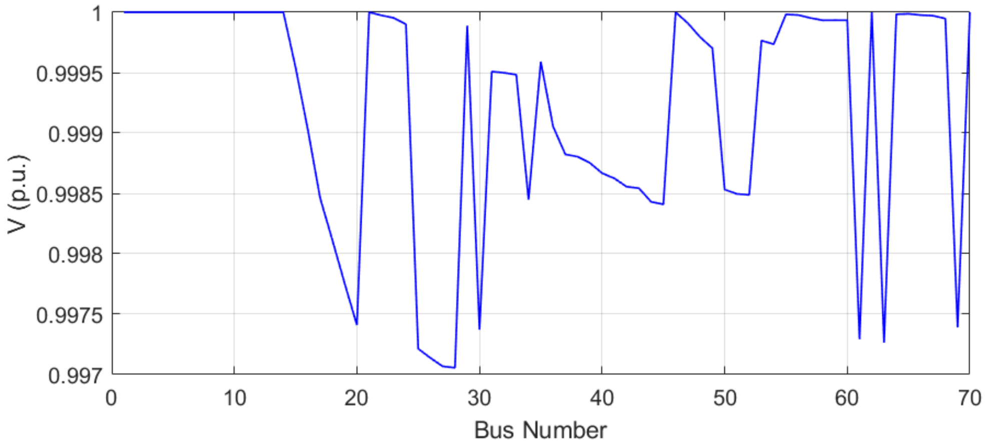

Fig. 3 Voltage on the network buses without capacitor placement

TABLE 1. System Loss and Total Voltage Deviations
TABLE 2.

Case study	**Active Power Loss (kW)**	**Reactive Power Loss (kVAr)**	**Total voltage deviations (pu)**
Network without capacitor	7233.742	17219.276	0.055
Optimal capacitor placement using GOMOHSA	3505.836	8345.341	0.024

4.2 Capacitor Bank Deployment

The objective function designed to perform the study is focused for minimizing active power loss in sub-transmission network, reactive power loss in sub-transmission network and total voltage deviations of the network buses is optimized using the proposed GOMOHSA algorithm and with the capacitor placement. Objective function indicating losses of active & reactive power and voltage deviations is depicted in Fig. 4. This is established that objective function is minimized with the values of active power loss, reactive power loss and voltage deviations equal to 3505.836kW, 8345.341kVAr, and 0.024pu respectively. Objective values for this case of study are detailed in Table 1. The computed values of the capacitor banks and respective buses are indicated in the Table 2. Capacitor banks have been suggested on 19 nodes of the test system with total capacity of 130.32 MVAR.

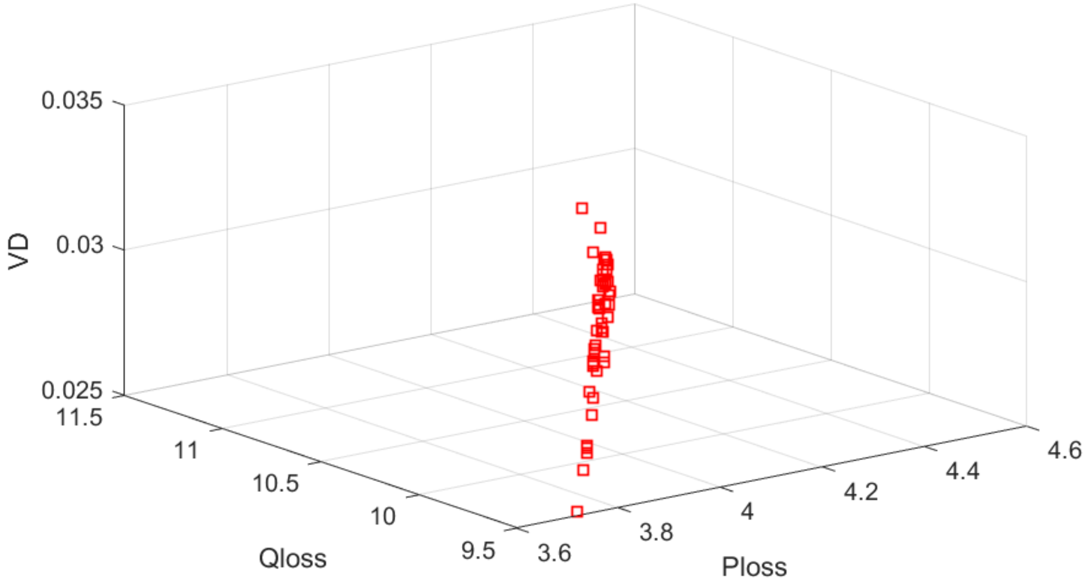

Fig. 4 Objective function for the test network with capacitor deployment

The voltage recorded on all nodes of test sub-transmission network post deployment of capacitor at various nodes of the optimal sizes is shown in Fig. 5. This is seen that voltage magnitude at all the nodes has been improved. It is unity at some of the nodes and minimum voltage equal to the 0.9984pu is observed and maximum voltage of 1.003pu is observed.

TABLE 3. Capacity and Placement of the Capacitor Banks

TABLE 4.

Sr. No.	**Bus No.**	**Quantum of Capacitor (MVAR)**
1	15	5.43
2	16	5.43
3	18	5.43
4	20	10.86
5	21	5.43
6	25	5.43
7	27	5.43
8	30	10.86
9	31	5.43
10	35	5.43
11	36	10.86
12	37	5.43
13	46	10.86
14	47	5.43
15	49	5.43
16	54	5.43
17	62	10.86
18	63	5.43
19	66	5.43
Total capacity of capacitor (MVAR)		130.32 MVAR

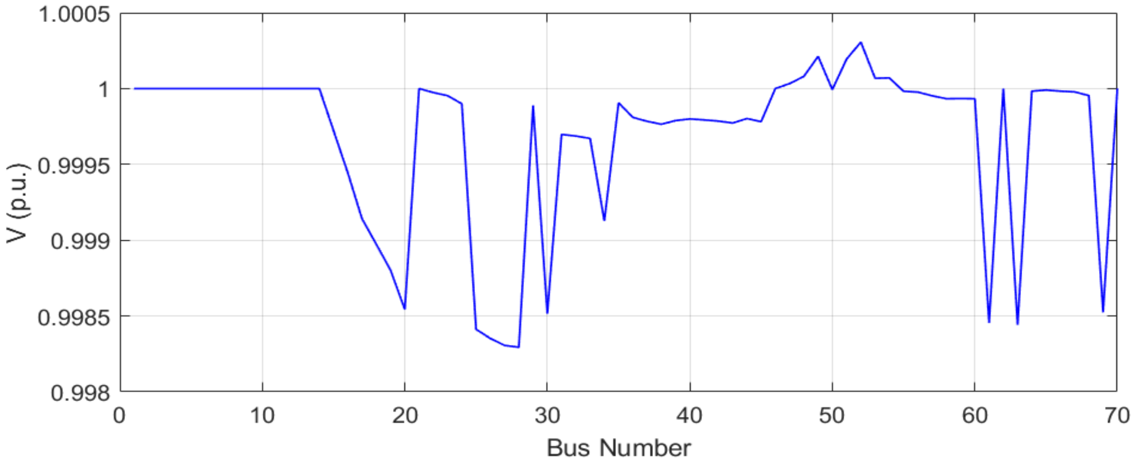

Fig. 5 Voltage on the network buses with capacitor placement

4.3 Computation of Performance Indexes

The PLI is computed considering active power loss in the sub-transmission network with and without capacitor as detailed below:-

$$PLI = \frac{P_{cap}}{P_{ncap}} \times 100\% = \frac{3505.836}{7233.742} \times 100\% = 48.465\%$$

The QLI is computed using reactive power loss in the sub-transmission network with and without capacitor as detailed below:-

$$QLI = \frac{Q_{cap}}{Q_{ncap}} \times 100\% = \frac{8345.341}{17219.276} \times 100\% = 48.465\%$$

The VDI is computed using total voltage deviation in sub-transmission network with and without capacitor as detailed below:-

$$VDI = \frac{VD_{cap}}{VD_{ncap}} \times 100\% = \frac{0.024}{0.055} \times 100\% = 43.636\%$$

The performance indexes computed using the results of simulation are included in Table 3. This is observed that PLI is 48.465% which indicates that active power losses after capacitor placement have been reduced to 48.465% of active power loss without capacitors. The QLI is 48.465% which indicates that reactive power losses after capacitor placement have been reduced to 48.465% of the total reactive power loss without capacitor placement. The VDI is 43.465% which indicates that total voltage deviations after capacitor placement have been reduced to 43.465% of the total voltage deviations without capacitor placement. Hence, optimal placement of the optimally sized capacitor banks has improved the voltage profile, reduced losses of active and reactive power in the sub-transmission network.

TABLE 5. Performance Indexes

Sr. No.	**Performance index**	**Computed Value of Performance Index**
1	PLI	48.465%
2	QLI	48.465%
3	VDI	43.465%

6. Performance Comparative Study

Performance of the GOMOHSA for capacitor deployment is compared with the genetic algorithm reported in [7] in terms of total capacity of proposed capacitors, active power loss, reactive power loss, total voltage deviations and performance indexes. Relative values of the performances indexes are illustrated in the Table 4.

TABLE 6. Performance Comparative Study of GOMOHSA and GA

Sr. No.	**Attribute**	**GOMOHSA**	**GA [7]**
1	Total proposed capacitors (MVAR)	130.32 MVAR	141.45 MVAR
2	Active Power Loss (kW)	3505.836 kW	3958.362 kW
3	Reactive Power Loss (kVAr)	8345.341 kVAr	9081.476 kVAr
4	Total voltage deviations (pu)	0.024 pu	0.029 pu
5	PLI	48.465%	54.721%
6	QLI	48.465%	52.740%
7	VDI	43.465%	57.272%

Correspondence to: Pramod Kumar, Department of Electrical Engineering, Suresh Gyan Vihar University, Jaipur, India
Corresponding author. E-mail addresses: pkrajdan@gmail.com

Detailed analysis of the data included in Table 4 indicates that quantum of the capacitors computed by GA is high compared to that computed by GOMOHSA. Further, network losses are high in the case of GA compared to the GOMOHSA which is also reflected in terms of the performance indexes.

7. Conclusions

This paper designed a grid oriented multi-objective harmony search algorithm (GOMOHSA) for intelligent deployment of the capacitor banks in the sub-transmission network of practical utility network. Performance indexes such as PLI, QLI and VDI are designed to assess the performance of the GOMOHSA for loss reduction and improvement of voltage pattern. This is concluded that active and reactive power losses in investigated sub-transmission network have been reduced by 50% approximately and voltage profile has been improved significantly. Quantum of capacitor computed by GOMOHSA is 130.32 MVAR. Performance of GOMOHSA is supersedes the GA in terms of loss minimization, voltage pattern improvement and performance indexes. Study is validated in the MATLAB software.

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Correspondence to: Pramod Kumar, Department of Electrical Engineering, Suresh Gyan Vihar University, Jaipur, India
Corresponding author. E-mail addresses: pkrajdan@gmail.com

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