Techno-Economic Analysis of Increasing PV-Wind based DG Penetration in Sub-Transmission System

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Abstract. This paper deals with techno-economic impact of increasing photovoltaic and wind power distributed generation in sub-transmission system. This paper suggests a new approach to interpret a multi-objective problem of integrating different types of distributed generation using an improved elephant herding optimization method. The main aim of this paper is to minimize the power losses and elevate the voltage profile of the electrical system. The effectiveness of improved elephant herding optimization had been tested on IEEE 30 bus sub-transmission system and is compared with results obtained with Particle Swarm Optimization method. In this paper, three cases have been considered where different types of distributed generation are integrated into the system and the best results have been obtained for case 3 where both photovoltaic and wind power are penetrated in system network. The optimal solutions obtained are compared with particle swarm optimisation and base case. The comparison shows that the proposed optimization method is favourable. The economic analysis of the corresponding distributed generation has been presented in this paper.

1. Introduction
Production of electrical power is of growing concern in today’s world. This is mainly due to rising emission levels, depletion of fossil reserves and increasing demand of energy. As a result, there is increased utilisation of renewable energy technologies such as photovoltaic (PV) and wind power. Distributed Generation (DG) is a viable solution to above mentioned problems. DG is a small scale generation unit directly connected to distribution system or sub-transmission system. Employing DG has multiple advantages such as reduced line losses, voltage profile enhancement, reduction in emission of pollutants and many more [1].

Optimal location and sizing of DG are the most important factors in the planning of power system network. Researchers have concluded that improper location and size of DG increases the system loss and disturbs the voltage stability of system. Therefore, DG should be integrated optimally in the network to increase efficiency and to enhance technical benefits in the system. Some constraints have to be considered for integrating DG into the system. Many approaches have been used for optimal deployment of DG such as analytical, classical (non-heuristic), meta-heuristic and hybrid approaches [2]. Many researchers have worked on the methods such as analytical approach [3], genetic algorithm [4], particle swarm optimisation (PSO) method [5], artificial bee colony algorithm [6], bat algorithm [7], cuckoo search algorithm [8], bacterial foraging optimization algorithm [9], firefly algorithm [10], ant lion algorithm [11], etc.
The purpose of this paper is to optimally integrate the DGs of a particular size with an objective to reduce the system losses, improve voltage profile and minimise cost of DG in the electrical network. An improved elephant herd optimization (IEHO) technique has been implemented to solve the issue of optimum allocation of DG in power system. The economic analysis of the corresponding DG is also discussed in this paper. The test system taken is IEEE 30-bus. Swarm based techniques such as PSO have been implemented in the past to solve optimisation problem. It was seen that these techniques affect convergence characteristics and leads to large convergence time to reach an optimal solution. Therefore, IEHO methodology has been proposed to solve the objective problem in this research paper. The implementation of this proposed method has not yet been explored for engineering optimisation problems. Therefore, this proposed method is being investigated for the first time systematically for engineering optimisation problems.

2. Types of DG technologies
DG technologies are classified into four types based on their capability of injecting active or reactive power into the system. The classification is as follows:

Type 1: Delivering real power only------PV
Type 2: Delivering real power and absorbing reactive power-----Doubly Fed Induction Generator in wind turbines (DFIG-WT)
Type 3: Delivering reactive power only-----Synchronous compensators
Type 4: Delivering both real and reactive power-----Small Hydro generators

In this paper, Type 1 DG (PV) with unity power factor (upf) and injecting only real power and Type 2 DG (DFIG-WT) with 0.9 lagging power factor (lpf) have been considered for study purpose.

3. Problem Formulation
In this paper, the most important objective is to find the optimal location and sizing of multiple types of DGs for minimizing the power losses and enhancing the voltage profile in the electrical network. The economic analysis due to integration of different types DG units is also considered in this paper. The level of DG penetration into the system in context with power losses has also been investigated.

3.1 Real and Reactive Power Losses
A multi-objective function considering the voltage and real power losses has been framed. Real and reactive power losses in the system are given by equation (1) and equation (2) respectively.

Total Real Losses(TRL) = \[ \sum_{k=1}^{N} (I_k r_k^2) \] (1)

Total Reactive losses (TQL) = \[ \sum_{k=1}^{N} (I_k x_k^2) \] (2)

where k=0, 1, 2, ..., N (total number of lines in the network). The current flowing in the transmission line is represented as I_k. The resistance and reactance of the line are represented as r_k and x_k respectively.

3.2 Voltage Deviation Index (VDI)
The third objective function considered is to improve the voltage profile in the network. The VDI is computed as follows as shown in equation (3).
Voltage Deviation Index (VDI) = \[ \frac{\sum_{k=1}^{N} (1 - V_k)^2}{V_k} \] (3)

Where, N= Total number of buses in the system and V_k is the rated voltage of kth bus.

The multi-objective function is given by equation (4).

Minimise \[ f = w_1 TRL + w_2 TQL + w_3 VDI \] (4)

And, \[ w_1 + w_2 + w_3 = 1 \] (5)

Where, \[ w_1 = 0.5, w_2 = 0.2, w_3 = 0.3 \] are the chosen weighted functions for the multi-objective problem in accordance with total real losses (TRL), total reactive power losses (TQL) and VDI respectively [12].

3.3 System Constraints

System operational constraints have been considered for optimization. The voltage levels at each bus should be well within the limits as shown in equation (6). The real power generated by DG should be between its minimum and maximum power limits as mentioned in equation (7). The reactive power generated by DG should be between its minimum and maximum power limits as mentioned in equation (8).

\[ 0.95 \leq V_k \leq 1.00 \] (6)
\[ 50 \leq P_{DG} \leq 3000 \] (7)
\[ 20 \leq Q_{DG} \leq 1000 \] (8)

Where, where the P_{DG} limits are in kW and Q_{DG} limits are in kVAR respectively.

The total real power generated at each bus should be equal to the sum of demand and real power losses. This constraint has been imposed using equation (9). A similar equation has been formulated for reactive power in equation (10).

\[ \sum_{k=1}^{N} P_{gk} + \sum_{k=1}^{N} P_{DG} = \sum_{k=1}^{N} P_{Dk} + TRL \] (9)
\[ \sum_{k=1}^{N} Q_{gk} + \sum_{k=1}^{N} Q_{DG} = \sum_{k=1}^{N} Q_{Dk} + TQL \] (10)

P_{gk} is the real power generated at k\textsuperscript{th} bus, P_{Dk} is the real power demand at k\textsuperscript{th} bus and P_{DG} is the real power generated by type 1 or type 2 DG. Q_{gk} is the real power generated by k\textsuperscript{th} bus, Q_{DG} is the reactive power absorbed by type 2 DG. Q_{Dk} is the reactive power demand at k\textsuperscript{th} bus [13].

3.4 Economic analysis

The cost component of DG power has been computed based on the mathematical model explained as follows in equation (11).

\[ C(P_{DG}) = aP_{DG}^2 + bP_{DG} + c \] $/kWh (11)

The value of cost coefficients is chosen as a=0, b=20 and c=0.25 [14].
The cost of reactive power supplied by DG is calculated based on maximum complex power supplied by DG is given by equation (12) and equation (13).

\[ C(Q_{DG}) = \left[ C(S_{g_{\text{max}}}) - C\left(\sqrt{S_{g_{\text{max}}}^2 - Q_{DG}^2}\right) \right] \quad (12) \]

\[ S_{g_{\text{max}}} = \frac{P_{g_{\text{max}}}}{\cos \phi} \quad (13) \]

The power factor is chosen as one at unity power factor for type 1 DG and 0.9 (lag) at lagging power factor for type 2 DG to undertake techno-economic analysis.

4. DG Multi-objective Optimisation Problem

4.1 Particle Swarm Optimisation (PSO)

PSO is biology-inspired meta-heuristic technique used for optimizing the problems. In PSO, the particles (solutions) fly through the problem space in the quest of the best prospective solution. Each particle would have coordinates in the problem space which are close to the best solution it has obtained so far. This value is known as pbest. The best value attained by the particle in the whole population is known as global best or gbest [15]. All agents fly through entire search space and update its position and velocity based on their own experience and on experience of their neighbours as given in equation (14).

\[ v_{i}^{k+1} = \omega v_{i}^{k} + c_{1} \text{rand} \ast (pbest_{i} - s_{i}^{k}) + c_{2} \text{rand} \ast (gbest_{i} - s_{i}^{k}) \quad (14) \]

The current position can be modified using equation (15).

\[ s_{i}^{k+1} = s_{i}^{k} + v_{i}^{k+1}, i = 1, 2, \ldots, n \quad (15) \]

Where,
- \( s_{i}^{k} \) is current searching point,
- \( s_{i}^{k+1} \) is modified searching point,
- \( v_{i}^{k} \) is current velocity,
- \( v_{i}^{k+1} \) is modified velocity of agent i,
- \( n \) is number of particles in a group,
- \( pbest_{i} \) is pbest of agent i,
- \( gbest_{i} \) is gbest of the group,
- \( \omega \) is weight function for velocity of agent i,
- \( c_{1} \) is weight coefficients for each term.

In the next iteration, updated velocities and positions are used as the current velocities and positions.

4.2 Basic Elephant Herd Optimisation (BEHO)

Elephants are social animals and they have peculiar social structures of females and calves. An elephant group consists of many clans under the leadership of a mother elephant. A clan comprises of one female with her calves or related females with their children. Females stay in family groups and male elephants choose to live in isolation. The males leave the family group when they are adults as depicted in [16].

To solve optimization problems using EHO, following rules have to be followed:

1) The elephant population consists of clans and has fixed number of elephants in each clan.
2) A fixed number of male elephants leave their family group and live in solitude.
3) The elephants in each clan has a leader mother elephant called matriarch.

4.2.1 Clan Updating Operator

For each elephant in clan \( c_i \), its next position is obtained by mother elephant (matriarch) \( c_i \). For the elephant \( k \) in clan \( c_i \), its position will be updated as given in equation (16).

\[
\text{x}_{\text{new, } c_i, k} = \text{x}_{c_i, k} + \alpha (\text{x}_{\text{best, } c_i} - \text{x}_{c_i, k}) \times r
\]  

(16)

Where, \( x_{\text{new, } c_i, k} \) and \( x_{c_i, k} \) are the new position and old position for elephant \( k \) in clan \( c_i \), respectively. \( \alpha \) varies between 0 and 1. It is a factor that evaluated the impact of mother elephant \( c_i \) on \( x_{c_i, k} \). \( x_{\text{best, } c_i} \) depicts the fittest elephant in clan \( c_i \). \( r \) ranges between 0 and 1. The fittest elephant in each clan can be upgraded using equation (17).

\[
\text{x}_{\text{new, } c_i, k} = \beta \times x_{\text{center, } c_i}
\]  

(17)

Where, \( \beta \in [0,1] \) is a factor that depicts the effect of the \( x_{\text{center, } c_i} \) on \( x_{\text{new, } c_i, k} \). \( x_{\text{center, } c_i} \) is the centre of clan \( c_i \).

4.2.2 Separating Operator

In elephant group, male elephants abandon their family and live in isolation when they grow up. This separation process can be modeled as a separating operator. The elephant individuals with the worst fitness will have a separating operator as given in equation (18).

\[
x_{\text{worst, } c_i} = x_{\text{min}} + (x_{\text{max}} - x_{\text{min}} + 1) \times \text{rand}
\]  

(18)

Where, \( x_{\text{max}} \) and \( x_{\text{min}} \) refers to the upper and lower bounds of the position of elephant individual respectively. \( x_{\text{worst, } c_i} \) is the worst elephant individual in clan \( c_i \). \( \text{rand} \) varies between [0, 1] and uniform distribution has been considered.

4.3 Improved Elephant Herd Optimization (IEHO)

In this section, limitation to basic EHO have been discussed and the related improvement in basic EHO has been illustrated in the form of mathematical equations [17].

4.3.1 Improvement and suggestion

In basic EHO, the position of the fittest elephant leading the clan is updated by following the mean position or average information received by all elephants of that clan only as mentioned in equation (16). The expression works appropriately for the benchmark functions. But, when applied to real-life problems, the results are not satisfactory. To overcome this drawback of basic EHO, it is suggested to update the position of matriarch elephants around the current best position as shown in equation (19).

\[
x_{\text{new, } c_i, k} = x_{\text{best, } c_i} + \beta \times x_{\text{center, } c_i}
\]  

(19)

In above equation, \( x_{\text{best, } c_i} \) is the best position of the fittest elephant which is the leader of clan.

5. Results and discussion

For study purpose IEEE 30-bus system is considered as the test system. The bus data and the line data are given in [18]. IEHO proposed methodology is tested on IEEE 30 bus system and the results are compared with PSO and base case when no DG is integrated into the system. In this paper, Type 1 DG (PV) with unity power factor (upf) and injecting only real power and Type 2 DG (DFIG-WT) with 0.9 lagging power factor (lpf) have been assumed for study purpose.
5.1 Case-1 (Type-1 DG (PV) with upf)

This section considers the optimum integration of type-1 DG unit i.e. PV based DG in IEEE 30 bus system. The results have been obtained for base case when there is no DG in the test system. The objective function has been optimised using IEHO and PSO and the results have been compared. The cost component of type-1 DG (PV) has been calculated using proposed IEHO method and the results have been compared with PSO. The cost component of Type-1 DG is also calculated using proposed IEHO method and compared with results obtained from PSO. Table 1 shows the results for type 1 DG.

Table 1. Results for IEEE 30 bus system using Type-1 DG (PV).

| DG Location | Size (kW) | TRL (kW) | TQL (kVar) | Vmin (p.u.) | DG cost ($/kWh) | Computing time (secs) |
|-------------|-----------|----------|------------|-------------|-----------------|----------------------|
| IEHO        | 30        | 1014     | 110.03     | 81.68       | 0.9536          | 20.24                |
| PSO         | 30        | 1056     | 136.75     | 92.65       | 0.9445          | 35.51                |
| Base case   | --        | --       | 211        | 145.32      | 0.9356          | --                   |

As per the results in table 1, the real and reactive power losses are 211 kW and 145 kVAR respectively without installation of DG. With installation of Type-1 DG at unity pf (PV) at bus 30, the real and reactive power losses are 136.75 kW and 92.65 kVar respectively using PSO. The minimum voltage obtained using PSO is 0.9445 p.u. The DG cost computed using PSO is 35.51 $/kWh. Also the real and reactive power is decreased to 110.03 kW and 81.68 kVAR using proposed IEHO technique. The minimum voltage in the system is increased to 0.9536 p.u. when IEHO method is implemented to solve the objective problem. The DG cost computed using IEHO is 20.24 $/kWh. Figure 1 highlights the convergence characteristics of case 1 when type 1 DG is integrated in the system. It can be observed that better convergence characteristics are obtained for IEHO than that of PSO. Figure 2 shows the voltage profile of IEEE 30 bus system for case 1. It can be seen that the voltage profile improved with IEHO methodology.

![Figure 1. Convergence characteristics for case 1](image-url)
5.2 Case-2 (Type-1 DG (DFIG-WT) with 0.9 pf)

Table 2 shows the results for type 2 DG. As per the results in table 2, the real and reactive power losses are 211 kW and 145 kVAR respectively without installation of DG. With installation of Type-2 DG at 0.9 pf (DFIG-WT) at bus 29, the real and reactive power losses are 108.40 kW and 77.44 kVAR respectively using PSO. The minimum voltage obtained using PSO is 0.9450 p.u. The DG cost computed using PSO is 38.76 $/kVAh. Also the real and reactive power is decreased to 78.4 kW and 55.56 kVAR using proposed IEHO technique. The minimum voltage in the system is increased to 0.9550 p.u. when IEHO method is implemented to solve the objective problem. The DG cost computed using IEHO is 24.54 $/kWh. Figure 3 highlights the convergence characteristics of case 2 when type 2 DG is integrated in the system. It can be observed that better convergence characteristics are obtained for IEHO than that of PSO. Figure 4 shows the voltage profile of IEEE 30 bus system for case 2. It can be seen that the voltage profile improved with IEHO methodology.

![Figure 2. Voltage profile of IEEE 30 bus system for case 1](image)

It is observed from the results that the DG size obtained is higher at lagging power factor (case2) as compared to the size obtained at unity power factor (case 1). However, the losses are found lower with type-2 DG rather than DGs at unity power factor (Type-1). The minimum voltage (Vmin0) is more for type 2 DG as compared to type 1 DG. These results are better when computed using IEHO as compared to PSO technique which shows superiority and efficiency of IEHO over swam based methodologies.

|     | DG Location | Size (kVA) | TRL (kW) | TQL (kVar) | Vmin (p.u.) | DG cost ($/kVAh) | Computing time (secs) |
|-----|-------------|------------|----------|------------|-------------|------------------|----------------------|
| IEHO | 29          | 1255       | 78.4     | 55.56      | 0.9550      | 24.54            | 10                   |
| PSO  | 29          | 1395       | 108.40   | 77.44      | 0.9450      | 38.76            | 22                   |
| Base case | --          | --         | 211      | 145.32     | 0.9356      | --               | --                   |
5.3 Case 3 (Type 1 and Type DG installed in system)
This section considers the case where both Type-1 and Type-2 DG are integrated into the system using proposed IEHO algorithm. Table 3 highlights the results when both types of DG are integrated into IEEE 30 bus system.

Table 3. Results for IEEE 30 bus system using combination of Type-1 (PV) and Type-2 DG (WT)

| DG Location  | Size  | TRL (kW) | TQL (kVar) | Vmin (p.u.) | DG cost ($/kVAh) | Computing time (secs) |
|--------------|-------|----------|------------|-------------|------------------|-----------------------|
| *(Type-1)    | *(kW) | **(kVA)  | (Type-1)   | (Type-2)    |                  |                       |
| IEHO         | *30   | 1014     | 69.56      | 52.5        | 0.9560           | 20.24                 | 15                    |
|              | **29  | 1255     |            |             |                  |                       |
| PSO          | *30   | 1056     | 81.24      | 70.67       | 0.9499           | 35.51                 | 30                    |
|              | **29  | 1395     |            |             |                  |                       |
| Base case    | --    | --       | 211        | 145.32      | 0.9356           | --                    | --                    |
The results indicate that case 3 is the most suitable for optimum allocation and integration of DGs. Better voltage profile is obtained using both DGs in the system. The real and reactive power losses are reduced using IEHO in case 3 when both type-1 and type-2 DG are used in the system network when they are optimally located at bus 30 and bus 29 respectively.

Figure 5 shows real power losses (TRL) and reactive power losses (TQL) for all the cases using proposed IEHO. It can be concluded that there is more reduction in real, reactive power losses and improvement in voltage profile with both type-1 and type-2 DG installed in the system (case 3) using IEHO technique.

6. Conclusion

In this paper, techno-economic analysis has been done to study the increasing penetration of PV-Wind based DG in IEEE 30 bus system. The methodology has been tested on IEEE 30 bus system and the results are compared with PSO and base case when no DG is integrated into the system. This study has been conducted to minimise power losses and for voltage profile improvement. In this paper, Type 1 DG (PV) with unity power factor (upf) which is injecting only real power and Type 2 DG (DFIG-WT) with 0.9 lagging power factor (lpf) have been assumed for study purpose. The results indicate that better voltage profile is obtained using both DGs in the system. The real and reactive power losses are reduced using IEHO in case 3 when both type-1 and type-2 DG are used in the system network. The cost of DG increases by a small amount with increasing penetration of DGs in the system. The study can be further extended for type 3 and type 4 DG and their increased penetration can be analysed techno-economically in a larger bus system.

7. References

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