Effect of optimal multi-DG siting and sizing in transmission system using hybrid optimization technique for voltage control

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ABSTRACT
The advancement of Distributed Generation (DG) technologies have caused great impact to power system operation. Inappropriate installation of DGs may lead to over-compensation or under-compensation situation. Thus, a reliable optimization is urgent to avoid any unwanted effect. This paper analyses the installation impact of different types-multi-DGs determined using a pre-developed hybrid optimization technique termed as Immunized-Brainstorm-Evolutionary Programming (IBSEP). It is imperative to study the effect of multi-DGs installation such that a relevant utility can make a correct decision, whether its installation is worth or vice versa. Rigorous study has been conducted in terms of identifying the optimal location and sizing, installed on transmission system for voltage control involving different DG types. Comprehensive results are embedded in this paper to demonstrate the effect of multi-DGs installation in transmission system which in turns beneficial to the utility.

Keywords: Distributed generation, Hybrid optimization, Immunized-brainstorm-evolutionary programming, Voltage control, Multi-DG

1. INTRODUCTION
Voltage profile of a power system is one of important parameters to be controlled by power system provider. While power system losses could be translated into monetary loss to the power provider, uncontrolled voltage profile could cause imbalance network and threaten the network safety. Voltage level is easily affected by changes in reactive load. Failing to retain the voltage level to a permissible limit may results in voltage collapse. Ways to avoid this adverse effect had been studied by other researchers that involve installing static VAR compensator in power network, controlling the voltage and VAR output of generators and denial of demand during critical under-voltage event [1].

Distributed generation (DG) is generally defined as small-scale electricity generation. Due to its size, a DG is usually located at the distribution side of power system, to be as close as possible to the consumer side, although DG placement at the transmission side is also permissible [2, 3]. Assessments on DG penetration to power network were continuously done by many researchers that conclude carefully selected DG size and location may enhance the voltage profile and reduce power loss of that network [4-7]. Commonly done at the distribution side, studies on the effects of optimally selected DG installation were conducted at the transmission network as well [8-12]. These works concluded that medium sized DGs, in particular the pure real power delivering DGs, were able to reduce transmission network loss with improved voltage profile. Few studies were conducted to assess effect of installing other DGs that have the
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ability to deliver or absorb reactive power [13, 14]. These studies found that different type of DG will affect power network performance differently.

Inventing robust and reliable optimization technique to determine optimal DG location and size is currently trending in the researchers community, aiming at alleviating setbacks in the existing optimization techniques [15-20]. Apart from finding higher probability of optimum solution towards meeting the objective functions, new optimization algorithms are developed to reduce computational burden in the classical optimization techniques [21, 22].

Brainstorm Optimization (BSO) is a newly developed algorithm that made its appearance in 2011. An algorithm that mimics the collective behavior of human has caught attention of many researchers. Though it is proven reliable in solving science and engineering problems, it does has high computational burden due to its K-means clustering technique as well as easily trapped in the local maxima [23-26]. In this paper, an optimization technique that embed Artificial Immune System (AIS) optimization technique and BSO into the frame of Evolutionary Programming (EP) algorithm is used to determine optimal locations and sizes of multiple DGs, of different power delivering capabilities, in power transmission system for voltage control. The hybrid technique is termed as Immunized-Brainstorm-Evolutionary Programming (IBSEP).

2. RESEARCH METHOD

Main objective of this study is to compare the capabilities of different types of DGs in improving transmission system’s minimum voltage profile. DGs are categorized into four major types, based on their ability to deliver power. In this paper, comparison between the performance of these four DG types to control system voltage will be investigated, based on the definition below:

**Type-1.** This type of DGs deliver only real power. Examples of Type-1 DG are photovoltaic, microturbines and fuel cells. In this paper, Type-1 DGs will be referred to as T1 from this point onwards.

**Type-2.** DGs that fall under this category are the ones able to deliver only reactive power. Example of this DG type is any DGs based on synchronous compensator. Type-2 DGs will be referred to as T2 from this point onwards.

**Type-3.** This type of DG is able to deliver both real and reactive power. Cogeneration and gas turbine are example of Type-3 DG. Type-3 DGs will be referred to as T3 from this point onwards.

**Type-4.** DGs under this category are capable of delivering real power, but consume reactive power. Example of Type-4 DGs are doubly fed induction generator (DFIG) and induction generators used in wind farms. Type-4 DGs will be referred to as T4 from this point onwards.

In this assessment, multi-DG units set to be 2, 3 and 5 units for each DG type are to be inserted to the network. For T1 DG, the real power is limited to 50MW, based on the maximum PV output tabulated in [27]. In terms of apparent power $S$, each T1 DG will be limited to 50MVA, based on (1). For fair comparison, the power of other DG types are then limited to 50MVA each.

$$ S = \sqrt{P^2 + Q^2} \quad (1) $$

Where $S$ is the apparent power, $P$ is the real power and $Q$ is the reactive power of the DG.

Transmission system minimum voltage profile before DGs’ placement in the system will be compared with the system voltage profile after multiple DGs placement, for each DG type. The objective function to be met is to improve system’s minimum voltage profile, represented mathematically as (2),

$$ O, F = V_{(\text{min, opt})} > V_{(\text{min, pre-opt})} \quad (2) $$

The objective function is however subjected to power balance equality constraint as (3)

$$ \sum_{i=1}^{n} P_i = P_{\text{demand}} + P_{\text{loss}} \quad (3) $$

as well as inequality constraints:

$$ P_{i,\text{min}} \leq P_i \leq P_{i,\text{max}} \quad (4) $$

$$ V_{\text{min}} \leq V_i \leq V_{\text{max}} \quad (5) $$

where $P_{\text{demand}}$ is total system load demand, $P_{\text{loss}}$ is the total system loss, and $P_{i,\text{min}}$ and $P_{i,\text{max}}$ are minimum and maximum real power output of $i^{th}$ generator, respectively. Following IEEE standard, $V_{\text{min}}$ and $V_{\text{max}}$ should be 0.95 p.u. and 1.05 p.u. respectively.
2.1. Proposed Methodology

In this work, DGs are placed into IEEE-30 RTS to compensate system loss while load increased. In order to maximize the voltage profile enhancement, optimal sized DGs must be injected at optimal location. These optimal sized DG and optimal bus location were determined using IBSEP optimization technique. IBSEP technique is explained below.

2.1.1 Proposed Immunized-Brainstorm-Evolutionary Programming (IBSEP)

Flowchart for optimal size and location of DG to improve voltage profile using IBSEP is shown in Figure 1. The process is briefly explained afterwards:

![Flowchart for optimal DG location and sizes using IBSEP technique](image)

**Figure 1. Flowchart for optimal DG location and sizes using IBSEP technique**

**Step 1**: Initialization of population number \( n \), number of clusters \( l \), probability-to-mutate cluster, \( p_1 \) and \( p_2 \), and reactive load, \( Q_d \) and location of where \( Q_d \) will be incremented. Random DG location, \( X_n \) and size, \( S_n \) are generated. \( n \) represents DG’s unit number.

**Step 2**: Fitness of the transmission system, i.e. the minimum system’s voltage profile with optimal DG installation will be determined from load flow. Only individuals capable of increasing the minimum voltage profile are selected. These individuals, or parents, are then cloned to increase the population. The grown population is then divided into few clusters.

**Step 3**: Random number \( p_m \) and \( p_c \) are then generated. They are used to decide which cluster to be mutated. Gaussian mutation operator is used to generate new individuals, known as offspring. Load flow is then run to determine the fitness of the offspring.

**Step 4**: The offspring and the parents are then combined to compete in a tournament process. Only \( n \) numbers of individuals with best fitness will be transcribed to the next process.

**Step 5**: A convergence test will then take place. In this test, the difference between the highest and lowest fitness values will be calculated. Mathematically, it is written as

\[
Voltage_{\text{max}} - Voltage_{\text{min}} \leq 0.00001
\]  

(6)

Should this condition is met, optimal DG locations and sizes will be recorded. Otherwise, Step 2 until Step 5 are to be repeated.
3. RESULTS AND ANALYSIS

Reactive load, Q_d, on one of load buses of IEEE-30 RTS was incremented, from 0 MVar to 30 MVar. Optimal DGs are to be installed at few load buses to compensate the losses due to the increased demand. Two load buses were chosen for the added reactive loading: Bus-6 and Bus-30. These buses represent the healthy and the weak buses of IEEE-30 RTS respectively, identified from a pre-loadability test. While the reactive loading was increased, the unit of DGs was varied; 2, 3, and 5 units, for each DG types. The effect of different DG types and amount on system’s voltage profile and losses are presented below.

3.1. Effect of Optimal DG Placement on System Voltage Profile While Reactive Load Varies at Bus-6

Table 1 tabulates the system’s voltage profile and system’s loss without DGs insertion. Table 2 lists system’s voltage profiles with optimal DGs for each DG types and the percentage of voltage profile enhancement percentage (VEP), calculated using (7).

\[
VEP = \frac{\text{Vol}_{DG} - \text{Vol}_{pre-opt}}{\text{Vol}_{pre-opt}} \times 100\% \quad (7)
\]

| Q_d (MVar) | Pre-opt Loss (MW) | Pre-opt Voltage (p.u) | Q_d (MVar) | Pre-opt Loss (MW) | Pre-opt Voltage (p.u) |
|------------|-------------------|----------------------|------------|-------------------|----------------------|
| 0          | 17.60             | 0.9945               | 0          | 17.56             | 1.0036               |
| 10         | 17.71             | 0.9907               | 10         | 18.11             | 0.9326               |
| 20         | 17.76             | 0.9892               | 20         | 19.55             | 0.8438               |
| 30         | 17.82             | 0.9877               | 30         | 23.44             | 0.7069               |

Table 2. IEEE-30 RTS Voltage Profile and Voltage Enhancement Percentage (VEP) with Optimal DGs While Q_d Increases

Table 2 shows that IBSEP technique was able to calculate optimal location and optimal size of every DG types in order to enhance the system’s minimum voltage profile when reactive load was increased at Bus-6. T2 and T3 DGs show good consistency in enhancing the minimum voltage profile the most, as indicated by highest VEP values in bold. Except for T4 DGs, other optimal DG types were able to improve the minimum voltage profile, if not the same, when DG quantity was added.

3.2. Effect of Optimal DG Placement on System Voltage Profile While Reactive Load Varies at Bus-30

Increasing Q_d at Bus-30 had caused the network to be in not-healthy mode, as indicated in Table 1. Table 3 tabulates the effect of different optimal DG types and amount on system’s minimum voltage profile. Bold fonts indicate highest VEP value. When there is no load at Bus-30, all optimal DG types enhanced the minimum voltage profile, except when optimal T4 DGs were less than five units. As Q_d30 increases, all optimal DGs arrangements were able to increase the system’s minimum voltage profile where highest VEP was either due to T2 or T3 DGs. IBSEP technique was able to determine optimal T2 and T3 that consistently increase the voltage profile as amount of DG increases. However, increased minimum voltage profile does not mean that the network is in the healthy mode, shown by VP values for T1 DGs in italics.
Table 3. IEEE-30 RTS Voltage Profile and Voltage Enhancement Percentage (VEP) with Optimal DGs While $Q_{d30}$ Increases  

| $Q_{d30}$ (MVar) | DG Amt. (unit) | VP$_{T1}$ (p.u) | VP$_{T2}$ (p.u) | VP$_{T3}$ (p.u) | VP$_{T4}$ (p.u) | VEP$_{T1}$ (%) | VEP$_{T2}$ (%) | VEP$_{T3}$ (%) | VEP$_{T4}$ (%) |
|------------------|----------------|-----------------|-----------------|-----------------|-----------------|--------------|--------------|--------------|--------------|
| 0                | 2              | 1.0100          | 1.0100          | 1.0100          | 1.0036          | 0.64          | 0.64         | 0.64         | 0.64         |
| 5                | 2              | 0.9949          | 1.0083          | 1.0096          | 1.0000          | 6.68          | 8.11         | 8.26         | 8.26         |
| 10               | 2              | 1.0002          | 1.0100          | 1.0100          | 1.0000          | 7.24          | 8.30         | 8.30         | 8.30         |
| 30               | 2              | 0.9241          | 1.0076          | 1.0083          | 1.0000          | 9.53          | 19.42        | 19.50        | 19.50        |
|                  | 3              | 0.9492          | 1.0100          | 1.0100          | 0.9900          | 12.50         | 19.70        | 19.70        | 19.70        |
|                  | 5              | 0.9488          | 1.0100          | 1.0100          | 0.9900          | 12.45         | 19.70        | 19.70        | 19.70        |
|                  | 3              | 0.8199          | 1.0068          | 0.9994          | 1.0000          | 15.99         | 42.43        | 41.39        | 41.47        |
| 30               | 3              | 0.8430          | 1.0096          | 1.0100          | 1.0000          | 19.26         | 42.83        | 42.89        | 42.89        |
|                  | 5              | 1.0000          | 1.0100          | 1.0100          | 0.9900          | 41.47         | 42.89        | 42.89        | 40.06        |

3.3. Effect of Optimal DG Placement on IEEE-30 System Losses

While the objective function is to enhance minimum voltage profile, the effect of optimal DGs on system losses was monitored. The results were tabulated in Table 4 and Table 5. Along with the system losses, the percentage of losses reduction (LRP) was calculated using (8). Based on this equation, if system loss with optimal DG insertion is less than system loss without DG, then LRP value will be positive number.

$$LRP = \frac{Loss_{pre-opt} - Loss_{DG}}{Loss_{pre-opt}} \times 100\%$$ (8)

As the reactive load increases, optimal T1 and T3 DGs show their ability to consistently reduce the system loss while enhancing the minimum voltage profile. When healthy Bus-6 was burdened with increasing reactive load, T1 DGs shows better performance than T3 DGs in reducing the loss as indicated by high LRP values. Also, five T1 DGs outperform the two or three DGs units about 20 points. However, when weak Bus-30 reactive load increases, optimal T3 DGs are better than T1 DGs in many occasions and show better consistency in reducing total system loss as DG units increases. When $Q_{d30} = 30$ MVar, five optimal T1 DGs were able to put the system into the healthy-mode but caused very high system loss. As for T2 and T4 DGs, IBSEP technique was not able to determine the optimal sizes and locations such that system’s minimum voltage profile is improved and system loss is reduced indicated by a mix of positive and negative LRP values in Table 4 and Table 5. Therefore, if a utility provider is planning to improve its transmission system performance in terms of stable network while not negatively affected its total loss at any loading scenarios, then installing T3 types DGs would be a better decision. Table 6 lists all optimal DG locations and sizes determined by IBSEP technique to compensate for IEEE-30 RTS minimum voltage profile, when $Q_{d30}$ were varied.

Table 4. IEEE-30 RTS System Losses and Loss Reduction Percentage (LRP) with Optimal DGs while $Q_{d6}$ increases  

| $Q_{d6}$ (MVar) | DG Amt. (unit) | Loss$_{T1}$ (MW) | Loss$_{T2}$ (MW) | Loss$_{T3}$ (MW) | Loss$_{T4}$ (MW) | LRP$_{T1}$ (%) | LRP$_{T2}$ (%) | LRP$_{T3}$ (%) | LRP$_{T4}$ (%) |
|----------------|----------------|-----------------|-----------------|-----------------|-----------------|--------------|--------------|--------------|--------------|
| 0              | 2              | 10.21           | 17.68           | 13.53           | 14.61           | 41.96        | -0.48        | 23.11        | 17.00        |
| 5              | 3              | 10.55           | 17.81           | 11.17           | 15.277          | 40.05        | -1.23        | 36.52        | -86713       |
| 10             | 5              | 6.25            | 19.96           | 10.87           | 30.58           | 64.50        | -13.39       | 38.26        | -73.79       |
| 30             | 2              | 10.23           | 17.68           | 13.53           | 16.51           | 42.23        | 0.17         | 23.61        | 6.79         |
| 5              | 3              | 10.58           | 17.66           | 10.75           | 16.05           | 40.27        | 0.31         | 39.32        | 9.37         |
| 10             | 5              | 6.84            | 19.93           | 10.86           | 13.13           | 61.39        | -12.50       | 38.71        | 25.90        |
| 20             | 2              | 10.27           | 17.70           | 13.55           | 15.34           | 42.20        | 0.36         | 23.73        | 13.62        |
| 5              | 3              | 10.62           | 17.67           | 13.23           | 232.27          | 40.18        | 0.51         | 25.48        | -1208        |
| 30             | 5              | 10.68           | 17.69           | 13.26           | 159.54          | 40.07        | 0.72         | 25.59        | -795.42      |
| 5              | 6.92           | 19.95           | 10.97           | 73.18           | 61.13           | -11.99       | 38.43        | -310.71      |
Table 5. IEEE-30 RTS System Losses and Loss Reduction Percentage (LRP) with Optimal DGs While $Q_{30}^d$

| $Q_{30}$ (MVar) | DG Amnt. (unit) | $X_{71}$ (Bus) | $X_{72}$ (Bus) | $X_{73}$ (Bus) | $S_{71}$ (MVA) | $S_{72}$ (MVA) | $S_{73}$ (MVA) | LRP$_{11}$ (%) | LRP$_{12}$ (%) | LRP$_{13}$ (%) | LRP$_{14}$ (%) |
|-----------------|-----------------|----------------|----------------|----------------|----------------|----------------|----------------|----------------|----------------|----------------|----------------|
| 0               | 2               | 7.26           | 7.26           | 12.21          | 12.17          | 35.7           | 8.0            | 35.7           | 8.0            | 36.4           | 43.0           | 7.8            | 1.6            |
| 1               | 3               | 4.7            | 7.9            | 15.21          | 9.12           | 4.6            | 35.7           | 8.0            | 24.2           | 31.4           | 41.1           | 33.6           | 0.7            | 0.2            |
| 10              | 5               | 19.25          | 3.3            | 3.3            | 30.3           | 22.0           | 34.5           | 47.4           | 25.0           | 46.9           | 24.8           | 35.9           | 43.8           | 4.6            | 0.5            |
| 20              | 2               | 15.3           | 22.25          | 22.25          | 30.3           | 43.2           | 24.7           | 35.9           | 43.8           | 45.6           | 30.4           | 45.6           | 30.4           | 14.7           | 0.7            |
| 30              | 5               | 30.25          | 22.27          | 22.27          | 26.2           | 42.1           | 38.4           | 24.7           | 18.6           | 48.2           | 18.4           | 47.8           | 24.7           | 18.6           | 0.5            |
| 0               | 2               | 10.3           | 6.29           | 6.29           | 30.3           | 2.9            | 27.1           | 18.6           | 48.2           | 18.4           | 47.8           | 24.7           | 18.6           | 0.5            |
| 1               | 5               | 15.25          | 22.25          | 22.25          | 27.29          | 18.4           | 8.1            | 49.4           | 42.6           | 48.9           | 34.1           | 45.6           | 30.4           | 14.7           |
| 10              | 2               | 30.25          | 28.26          | 19.25          | 26.2           | 42.1           | 38.4           | 42.3           | 34.5           | 42.1           | 14.7           | 45.6           | 30.4           |
| 20              | 3               | 15.25          | 22.25          | 22.25          | 27.29          | 47.7           | 38.8           | 12.5           | 23.6           | 21.8           | 34.1           | 27.9           | 27.4           |
| 30              | 5               | 30.25          | 28.26          | 19.25          | 29.6           | 29.3           | 47.6           | 26.6           | 7.6            | 0.3            |
| 0               | 2               | 10.3           | 6.29           | 6.29           | 19.3           | 2.9            | 27.1           | 18.6           | 48.2           | 18.4           | 47.8           | 24.7           | 18.6           |
| 1               | 5               | 15.25          | 22.25          | 22.25          | 27.29          | 47.7           | 38.8           | 12.5           | 23.6           | 21.8           | 34.1           | 27.9           | 27.4           |
| 10              | 2               | 30.25          | 28.26          | 19.25          | 29.6           | 29.3           | 47.6           | 26.6           | 7.6            | 0.3            |
| 20              | 3               | 15.25          | 22.25          | 22.25          | 29.6           | 44.1           | 28.2           | 22.0           | 34.5           | 21.8           | 34.1           | 43.5           | 36.8           |
| 30              | 5               | 16.30          | 22.29          | 22.29          | 17.9           | 4.3            | 42.2           | 49.4           | 42.6           | 48.9           | 42.1           | 42.8           | 47.0           |

4. CONCLUSION

This paper has presented effect of multiple different optimal DG types in terms of power delivering capabilities towards transmission network minimum voltage profile while monitoring the system’s total loss. It can be concluded that optimal DGs that provide reactive power could enhance the minimum voltage profile the most in many scenarios. Other DG types may compensate the voltage profile degradation in most cases, but may cause more power loss. IBSEP optimization technique was able to determine optimal sizes and location for all DG types and amount, in order to fulfill the objective function of increasing minimum voltage profile.
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