# Strategic Placement of Distributed Generation Units to Avoid Load Shedding in Overloaded Power Systems

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*Abstract:* - This paper presents an engineering algorithm to place distribution generation units in strategic locations as a solution of the system problem when subjecting to a severe disturbance. The analysis conducted in this paper has proven that this solution is more advantageous compared with many other solutions that are conventionally used by operators such as load shedding. The proposed algorithm aims to minimizing the operation cost taking into consideration the system operation constraints when applying either installing DG units or shedding loads. The algorithm is applied on the IEEE 14-bus system and the most economical and technically effective system layout is identified. The results show that the strategic placement of distributed generation units can overcome the need for load shedding and thus guarantees the continuity of the supply.

*Key-words:* Power system emergency, Load Shedding, Distributed generation.

## 1 Introduction

The minimum operating cost and the continuity of the power supply are among the most important concerns of the distribution system engineering. To avoid costly interruptions, solutions such as increasing system capacity and reconfiguration of the system are implemented. Load shedding is the last resort of the electrical power system operators; it is taken to get the system integrity sound when the system is subjected to a major disturbance. Load shedding is formulated as an optimization problem that takes into consideration the system equality and inequality constraints. The load shedding problem is classified into three categories, frequency load shedding, overload load shedding, and voltage-based load shedding [1-14].

Integrating the generation scheduling and load shedding to alleviate line overloads with the help of local optimization concept is presented in [1], [2] and [3]. A secure operating point was obtained for all overloaded lines efficiently, and a small amount of load shedding was required. The load shedding problem is formulated as minimization of the squares of the system losses in [4] and a comparison between different overload load shedding schemes is presented. An artificial Neural Network based (ANN) optimal load shedding strategy is discussed in [5]. A primal-dual approach that applies optimization techniques to minimize that operation cost after shedding subjected to system equality and inequality constraints is presented in [6-8]. The proposed optimization technique, include reactive power control and the generator characteristic equations.

In [9], an approximate event-based customer interruption cost evaluation technique been used to get the priority of the distribution feeders on a given bus during an emergency. The proposed algorithm incorporated a time dependent feeder cost priority index (FCP). In [10], an expert system for a load shedding is tested. The proposed system scheme incorporates strategies for restoring the normal operation in an interactive manner with the system operator. In [11] and [12], a simplified model of the power system, is employed to detect major disturbances and a multi-stages load shedding strategy is applied. In [13], the author used Kalman-filter to obtain the instantaneous frequency deviation. Kalman filter analyzed this deviation into a random pulse plus a random ramp process, the slope of this random ramp presented the average rat of frequency decay when the power system is subjected to a severe overloading.

The integration of distributed generation with the load shedding problem is done for the first time in [17], where the authors developed a new approach for a load shedding scheme that is capable of determining the optimal load shedding and its conduction time. The proposed algorithm was applied on a simple distribution system that was equipped with distributed generation (DG), a linear relationship between the generation contingency and the optimal load shedding time has been found. In systems with higher DGs penetration, the optimal load shedding time would be dictated by generation loss amount and not the installed capacity.

Therefore, the installation of DG units in distribution systems would open the door for new strategies of the power management of distribution systems. A quick and reliable solution for an expected increase in the demand would be installing and running a DG unit in parallel with the system. In addition, the technology for this DG can vary from gas turbines to fuel cells or even ocean energy according to the available resources and the environmental considerations. On the other hand, during the application of any type of the load shedding techniques to the system with distributed generation, the load shedding might lead to sub problems of the distribution system operation.

## 2 Problem Formulation

This paper addresses the steady-state overload load shedding problem of distribution systems with distributed generation. A novel algorithm that determines the appropriate size and location of DG units equivalent to the amount of the load to be shed for minimum operating cost of the system. The algorithm is implemented on the IEEE 14-bus test feeder for different operating conditions and the results obtained are presented. The detailed description of the proposed algorithm is given in Section 2. The results of the implementation of the proposed algorithm are presented in Section 3 followed by the conclusions drawn from the studied cases.

### 2.1 The Proposed Algorithm

The algorithm designed for the solution of this problem can be executed in the following steps:

- Study the optimal power flow of the system. Check that the system is operating in a feasible region. If it is ready in feasible region,
- Begin the system deterioration by subjecting it to small step by step increasing of loads,
- Stop increasing load when the system enters the infeasible region. Thus, the system operates around bifurcation conditions, where the system operation is in the infeasible region but it is much closed to feasible region,
- Allocate a DG with apparent power generation to different buses; and add the installation cost of this DG [22] to the system cost per MW-load,
- The bus that gives less cost per MW-load and less percentage losses will be sensitive to power change. These buses are strongly recommended to receive either load shedding or installing DG units to get back into the feasible operation,
- Apply treatment method either by installing DG units or by shedding loads with the same power change at the system buses, compare between the two methods at different buses from the cost and losses points of view.
- At each bus, increase the power variation either by installing DG unit or shedding loads and record the cost and losses against these power variations,
- Determine the size of the recommended DG to be used to give less cost and losses, and
- Formulate the cost per MW-load as a function of the power variation,

### 2.2 System under Study

The system under study is shown in Fig. 1. It consists of 14-buses, it has 5-generators that are located at buses 1, 2, 3, 6, and 8, also, there are 11-local loads connected to different buses. There are 20-tielines existing in this system. Bus number 1 is considered the slack bus, buses 2, 3, 6, and 8 are PV-buses, and the other buses are PQ-buses.

MATPOWER package is used to simulate the system under study. The optimization algorithm of generalized reduced gradient (GRG) is applied to the system. The objective function is the total cost of real generation per MW load; the objective function includes the installation cost of the DG unit in case of installing DG as instead of shedding loads. These costs may be defined as polynomials or as piecewise-linear functions of generator output. The goal is to minimize cost function F; the details of this method are illustrated as follows,

$$F = \left(\sum_{i=1}^{N_G} F_i(P_{gi}) / Load\right) + DG\,Installation\,Cost \qquad (\$/\text{MW-hr}) \quad (1)$$

Where,

NG is the number of generator buses,

Pgi is the active generation on bus i.

This optimization technique is subjected to the system constraints,

- Load flow equation and the power balance at any bus should be taken into consideration.

$$\sum_{n=1}^{N} \left| Y_{in} \cdot V_i \cdot V_n \right| \cdot \cos(\theta_{in} + \delta_n - \delta_i) - P_{gi} - P_{di} = 0 \qquad (2)$$

Where,

Yin: the admittance between bus i and bus n,

Vi: the voltage magnitude at bus i,

Vn: the voltage magnitude at bus n,

θin: the admittance angle,

Pdi: the demand at bus i,

N: the number of the system buses.
the power system constraints:

$$
\begin{aligned}
f_{\min} &< f < f_{\max} \\
V_{\min} &< V < V_{\max} \\
P_{\min\, ij} &< P_{ij} < P_{\max\, ij}
\end{aligned}
\qquad (3)
$$

Where, f is the system frequency and Pij is the active power flow from bus i to bus j.

Installing DGs increases the system constraints' equations, these constraints are determined according to the type of the DGs, there are two constraints of the dispatchable DGs. these constraints are the output of DGs and the ramp rate of these DGs. it must be pointed out that minimum output of some generation is an important constraints because of cogeneration. They must generate certain power to ensure the heat supply. The ramp rate exists because the generator needs certain time to increase its output.

$$
\begin{aligned}
P_{DG_{MIN}} &\le P_{DG} \le P_{DG_{MAX}} \\
\Delta P_{DG_t} &\le \Delta P_{DG_{\lim it}}
\end{aligned}
\qquad (4)
$$

Where, $\Delta P_{DGt}$ is the increasing output from moment (t-1) to moment (t).

There may be third constraint, that the total generated power from DGs must not exceed 20% of the total generated power in the whole power system.

The optimization algorithm is described in the following flow chart of Fig. 2 [21], this method depends on Lagrange multiplier and it is applied in both cases of installing generator or shedding load to determine the optimum operating conditions of the system understudy.

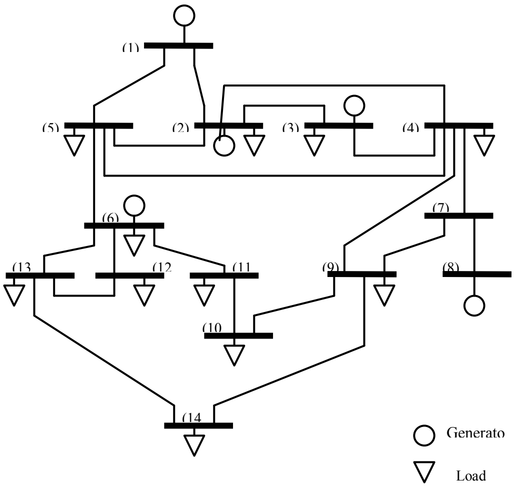

**Fig. 1:** The 14-bus System Under-Study

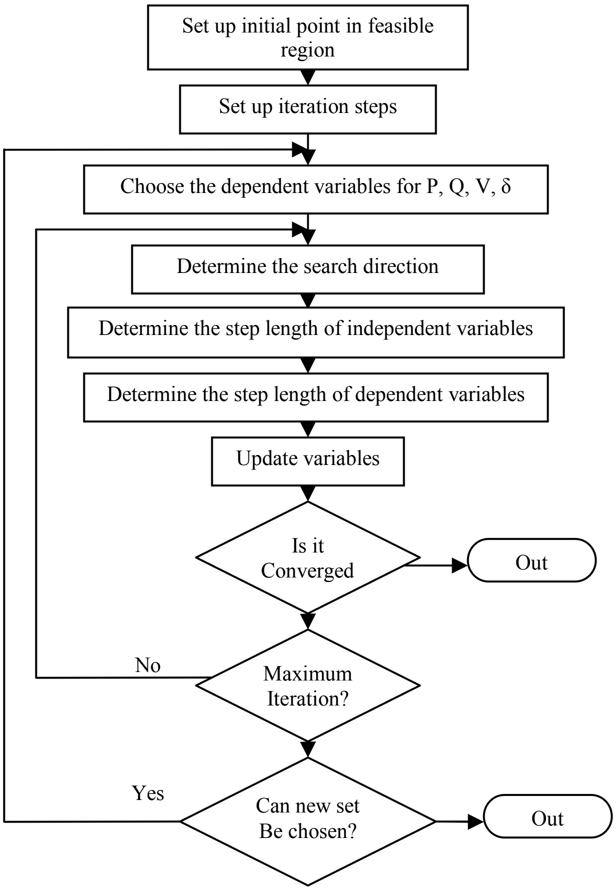

**Fig. 2:** Flow Chart of the Generalized Reduced Gradient (GRG) Method.

## 3 Results

The system is made to operate in the infeasible region, but it is very close to get back to its feasible region (Bifurcation operation). When allocating a DG with 3.6% of the base load, table 1 shows the cost and losses is smallest at bus #14, thus, bus #14 is the more sensitive bus and its location is recommended to receive any treatment. The buses in table 1 are ranked according to the cost and losses.

**Table 1:** Allocation of DG with 3.6% Apparent Power Generation

| To Bus # | (ΣPloss/Pgenerated)*100 | Cost ($/MWhr) |
|---|---|---|
| 5 | Infeasible | Infeasible |
| 6 | 1.2944 | 20.9899 |
| 9 | 1.2741 | 20.9796 |
| 10 | 1.2648 | 20.9759 |
| 11 | 1.2598 | 20.9741 |
| 12 | 1.2602 | 20.9644 |
| 13 | 1.2597 | 20.9532 |
| 14 | 1.2428 | 20.9403 |

Table 2 shows a comparison between installing DG unit at each bus and shedding loads at the same buses with 3.6% power change.

**Table 2:** Comparison between installing DG and Shedding Loads of 3.6%

| Power at bus # | Adding | | Shedding | |
|---|---|---|---|---|
| | Cost | Loss | Cost | Loss |
| 6 | 20.9899 | 1.2944 | 21.0385 | 1.3054 |
| 9 | 20.9796 | 1.2741 | 21.0282 | 1.2849 |
| 10 | 20.9759 | 1.2748 | 21.0225 | 1.2885 |
| 11 | 20.9741 | 1.2638 | 21.0225 | 1.2775 |
| 12 | 20.9644 | 1.2735 | 21.0128 | 1.2850 |
| 13 | 20.9532 | 1.2597 | 21.0015 | 1.2703 |
| **14** | **20.9403** | **1.2428** | **20.9885** | **1.2535** |

It is clear that at all buses installing DG unit with 3.6% is more economical and efficient than shedding load with the same percentage. Also, bus #14 is the recommended to receive power variation. At each bus the power change is increased in steps either by installing DG unit or shedding loads, figures 3 and 4 show the cost and losses as a functions of power change at bus #14,

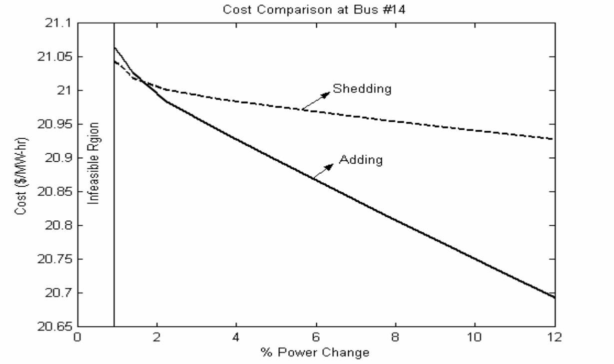

**Fig. 3:** Cost Variation with %Power Change either by Installing DG Unit or Shedding Loads at bus #14

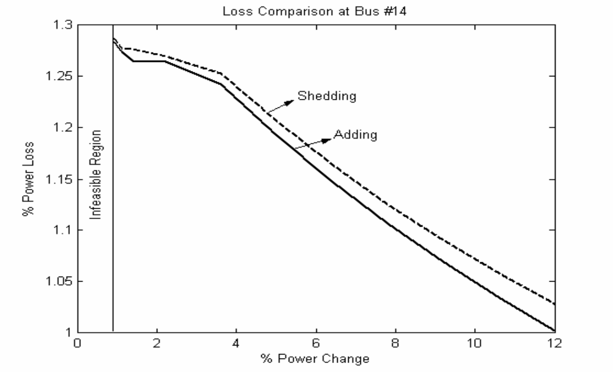

**Fig. 4:** Loss Variation with %Power Change either by Installing DG Unit or Shedding Loads at bus #14

Figures 3 and 4 show that to get the system back into the feasible region, the power variation at bus #14 should be more than 0.8%. Also, figure 3 shows that with low penetration of the DG power, the load shedding is more economical than installing DG unit. Fig. 5 shows that the size of DG unit should be more than 1.8% to get sure that installing DG unit is more economical.

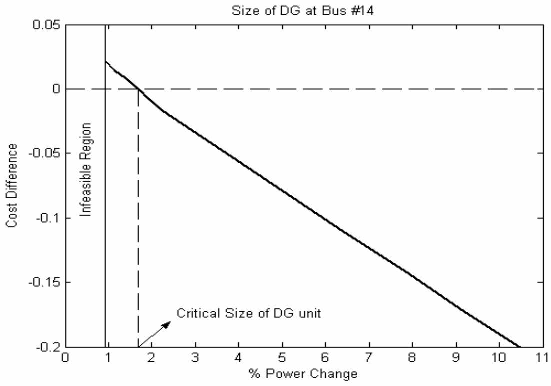

Fig. 5: Cost Difference between Shedding Loads and Installing DG unit

Thus, it is recommended to add DG unit at bus #14 with size more than 1.8% as instead of load shedding.

Figures 6 and 7 show the cost and losses as functions of power change at bus #13,

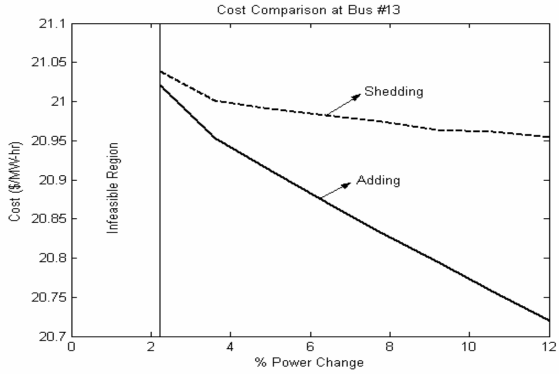

**Fig. 6:** Cost Variation with %Power Change either by Installing DG Unit or Shedding Loads at bus #13

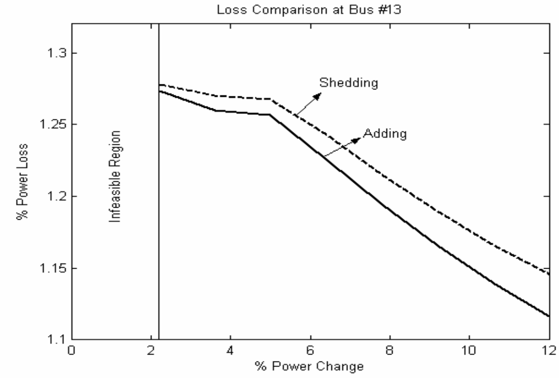

**Fig. 7**: Loss Variation with %Power Change either by Installing DG Unit or Shedding Loads at bus #13

If the power change should take place at bus #13, and to get back into the feasible region it is clear that the power change should be greater than 2.2%, the figure confirms that bus #13 is less sensitive than bus #14.

Figures 8 and 9 show the cost and losses as functions of power change at bus #12.

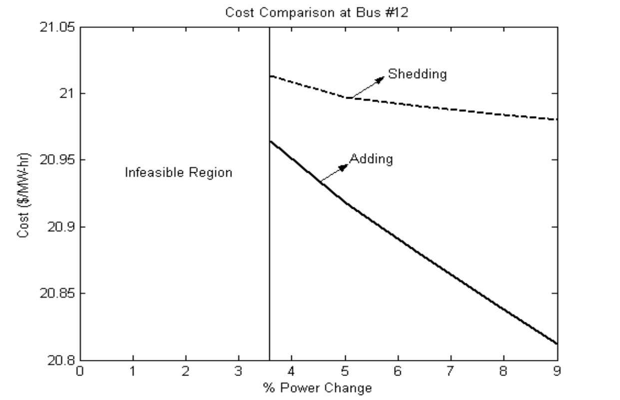

**Fig. 8:** Cost Variation with %Power Change either by Installing DG Unit or Shedding Loads at bus #12

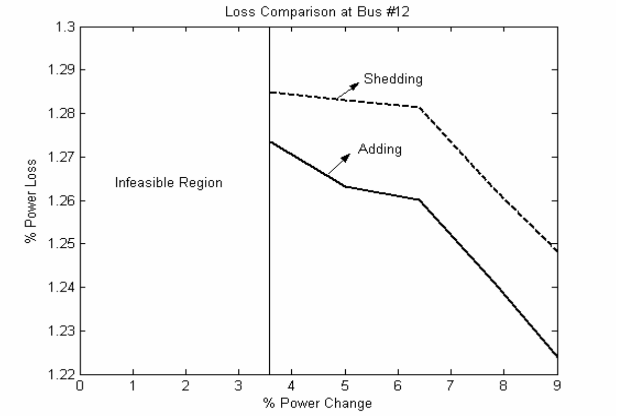

**Fig. 9:** Loss Variation with %Power Change either by Installing DG Unit or Shedding Loads at bus #12

From these figures, if the power change should take place at bus #12, and to get back into the feasible region it is clear that the power change should be greater than 3.6%, the figure confirms that bus #12 is less sensitive than buses #13 and #14.

### 3.1 Mathematical Assumption:

Figures 3, 4, and 5 show that the cost function has a negative linearly variation against the power variation, defining the following terms,

$\Delta Cost_{add}$: cost variation in case of installing DG that is resulted from certain power variation,

$\Delta Cost_{shed}$: cost variation in case of shedding loads that is resulted from certain power variation,

$\Delta Cost$: cost difference between installing DG and shedding loads, and

$\Delta Pg$: the power variation either by installing DG or shedding loads,

At bus #14:
For $\Delta Pg \geq 2\%$
$\Delta Costadd/\ \Delta Pg = -0.0297$ (\$/MW-hr) ,
$\Delta Costshed/\ \Delta Pg = -0.0074$ (\$/MW-hr),

$\boxed{\Delta Cost/\ \Delta Pg = -0.0223\ (\$/MW\text{-}hr)}$

At bus #13:
For $\Delta Pg \geq 3\%$
$\Delta Costadd/\ \Delta Pg = -0.0274$ (\$/MW-hr) ,
$\Delta Costshed/\ \Delta Pg = -0.0052$ (\$/MW-hr)

$\boxed{\Delta Cost/\ \Delta Pg = -0.0222\ (\$/MW\text{-}hr)}$

At bus #12:
For $\Delta Pg \geq 4\%$
$\Delta Costadd/\ \Delta Pg = -0.0264$ (\$/MW-hr) ,
$\Delta Costshed/\ \Delta Pg = -0.0041$ (\$/MW-hr)

$\boxed{\Delta Cost/\ \Delta Pg = -0.0223\ (\$/MW\text{-}hr)}$

Thus, it is clear that there is proportional relation between the cost saving between adding DG units and shedding loads and the percentage power variation. The proportionality constant equals 0.0223.

## 4 Conclusion

To guarantee the continuity of the supply to customers connected to distribution systems in case of overload conditions, two techniques are proposed. The first technique implements traditional load shedding to keep most of the customers connected to the system while the second technique employs the installation of small distributed generation units to avoid shedding any system load. For this purpose, a novel algorithm that determines the appropriate size and location of DG units equivalent to the amount of the load to be shed for minimum operating cost of the system is proposed. The algorithm is implemented on the IEEE 14-bus test feeder for different operating conditions.

The results obtained have proven that installing DG unit with high penetration is more efficient than shedding of loads. It decreases both the cost and losses less than load shedding. Thus, the system efficiency is increased. Also, the location and the size of the used DG unit are suggested to get optimum operation of the system under study. This comparison between the two techniques is based on the same optimization algorithm taking into consideration the installation cost of the added DG units.

In addition, the results showed that the savings in the system operational cost when implementing the

DG technique is linearly proportional to the level of MW penetration of the Dg units. This cost reduction has made the installation of DG units favorable for the system planners and operators.

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