

Enhancement of Voltage Stability in Distribution Systems by Optimal Placement of Distribution Generator

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ABSTRACT

This article presents a methodology for optimal placement of DG units in distribution networks to guarantee the enhancement of voltage profile, maximize loadability and reduce distribution system losses. The methodology aims to find the configuration, among a set of system components, which meets the desired system reliability requirements, taking into account the stability limits. Results shown in the article indicate that the proposed formulations can be used to determine which are the best buses, where the addition of small distributed generator units can greatly enhance the voltage stability of the whole system and improve power transfer capability by reducing the system power losses. The proposed methodology is tested and compared with the existing distribution system.

Key Words: Distributed generation, distribution network, distribution system losses, maximum loadability, optimal placement, system reliability, voltage profile, voltage stability.

INTRODUCTION

Recently various kinds of distributed generation (DG) are becoming available, and it is expected that they will grow in the future years. DG includes the application of small generators, scattered throughout a power system, to provide the electric power needed by electrical customers. Such locally distributed generation has several merits from the viewpoint of environmental restriction and location limitations, as well as transient and voltage stability in the power system [1-5].

A near optimal placement technique to reduce the system loss has been presented using "B" loss coefficient [6]. The buses are ranked according to their loss sensitivity, and size of DG is found in stepwise manner. This method is basically concerned with finding the optimal location of DG, and the loss sensitivity method does not always give an accurate result. Genetic algorithm (GA) based distributed generator placement techniques used to reduce overall power losses in a distribution system are presented in [7-10], but the problems with GA are that it is computationally intensive and suffers from excessive convergence time and premature convergence. Hereford ranch algorithm is used to optimally locate the DG to reduce the system overall real power loss under the constraint of the total injection of installed dispersed generator [11], similar to the GA based methods. This method is also computationally demanding, though it addresses the issue of premature convergence and has the ability to search for a better optimal solution. The optimal location to place a DG, with unity power factor, in a radial or looped system is found while minimizing the loss [12]. This technique is basically concerned with finding the optimal location but not the optimal size. The optimal location to place a single DG is found while minimizing the loss in the system by the sensitivity method and analytical method with the power system concepts [13].

In certain industrial areas, it has been observed that under certain critical loading conditions, the distribution system experiences voltage collapse. Voltage collapse is a local phenomenon. It occurs at a node within the area with high loads and low voltage profile. Due to the rapid growth in power demand of certain industrial loads, incidence of unexpected voltage collapse has been experienced. When such incident occurs, some industrial loads will be disconnected through automatic cut-off switches resulting in severe interruptions. Hence, a major concern in power distribution systems, which has surfaced fairly recently, is the problem of voltage stability.

Literature survey shows that a lot of work has been done on the voltage stability analysis of transmission systems [14] but very little work has been reported on the voltage stability analysis of radial distribution systems. Jasmon and Lee [15] and Guleina and Strmchnik [16] have studied the voltage stability analysis of radial distribution systems (RDS). They have represented the whole system by a single line equivalent. The single line equivalent derived by these authors [15-16] is valid only at the operating point at which it is derived. It

can be used for small load changes around this point. However, since the power flow equations are highly nonlinear, even in a simple radial system, the equivalent would be inadequate for assessing voltage stability limit. Sivanagaraju et al. [17] derived the voltage stability equation to find the voltage stability analysis, in particular the use of the Voltage Stability Index (VSI). Through this index one can measure the level of voltage stability, and thereby appropriate corrective action can be initiated if the index indicates a poor level of voltage stability.

In this article, a simple method to determine the location for DG placement using the line loadability and calculating optimum size of DG by increasing the small amount of DG size around 5 kW is proposed. The methodology is computationally very demanding when comparing with existing methods [10]. The DG is considered to be located in the radial distribution system and the objective of DG placement is to enhance line loadability by reducing the power losses of the system. The sizing and placement of DG is based on single instantaneous demand at peak, where the losses are maximum. The proposed method is tested on 15 bus radial distribution system.

DISTRIBUTED GENERATION

Due to rapid increase in power generation, there have been numerous increases in electric consumption growth rates and high load densities. This growth and need for more flexible electric systems, changing regulatory and economic scenarios, energy savings, environmental impact and the need to protect sensitive loads against network disturbances are providing impetus to the development of dispersed generation and storage systems based on a variety of technologies [1]. In particular, the term DG implies the use of any modular technology that is sited throughout a utility service area (macro grid) to lower the cost of services and/or to provide power and heat to a host site. DG can comprise diesel and internal combustion engines, small gas turbines, fuel cells and photovoltaic. The purpose of these plants is to cope with the growing demand of electricity in certain areas (micro grid) and render certain activities self-sufficient in terms of power production, thus achieving energy savings [2-5, 19-21].

The main reasons for the increasingly widespread use of dispersed generation can be summed up as follows [3]:

- DG units are closer to the customer so that transmission and distribution costs are reduced.
- The latest technology has made available plants ranging in capacity from 10 kW to 15 MW.
- It is easier to find sites for small generators.
- Usually DG plants require shorter installation times and the investment risk is not so high.
- CHP (Combined Heat and Power) groups do not require large and expensive heat network.
- Natural gas, often used as fuel in DG stations is distributed almost everywhere and stable prices are to be expected.
- DG plants yield fairly good efficiencies especially in cogeneration and combined cycles.
- DG offers great values as it provides a flexible way to choose a wide range of combinations of cost and reliability.

For these reasons, the first signs of a possible technological change are beginning to arise on the international scene, which could involve in the future the presence of a consistent generation produced with small and medium size plants directly connected to the distribution network (LV and MV) and characterized by good efficiencies and low emissions. This will create new problems and probably the need of new tools and management of these systems.

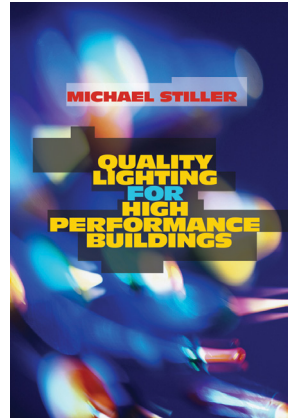
MATHEMATICAL FORMATION OF LINE LOADABILITY INDEX (LLI)

A distribution system operator would always like to know whether the network is close to the line maximum loadability limit. This article presents an index that indicates the maximum additional load that may be supplied by a feeder. Consider a typical branch pq of RDS as shown in Figure 1 for which the sending end bus is p and receiving end bus q and respective voltages are $V_p \angle \delta_p$ and $V_q \angle \delta_q$. The receiving end bus load is $P_{Lq} + jQ_{Lq}$ and the power flow in the branch pq is $P_q + jQ_q$ from [18].

QUALITY LIGHTING FOR HIGH PERFORMANCE BUILDINGS

Michael Stiller

In the U.S., buildings account for 40% of primary energy use, 72% of electricity consumption, and 39% of CO₂ emissions. Indoor lighting accounts for a large portion of our energy use, and we sorely need better, more efficient systems to illuminate our large structures as well as our homes. But as we seek greater efficiency and meet new green construction codes, it is imperative that we avoid sacrificing lighting design that enhances our productivity, comfort, and health. This is an overview of the basic concepts of quality, indoor lighting, visual comfort and interest, and integrated design as they relate to the practice of lighting design. Energy efficient lighting technologies, including LED lighting and digital control systems, and design strategies that increase visual comfort and productivity are discussed in plain language, to give all readers, whether architects, interior designers, engineers, building trades professionals, or students, a broad understanding of the art and science of energy efficient quality lighting.



ISBN: 0-88173-775-1

6 x 9, 256 pp., Illus.
Hardcover, \$125

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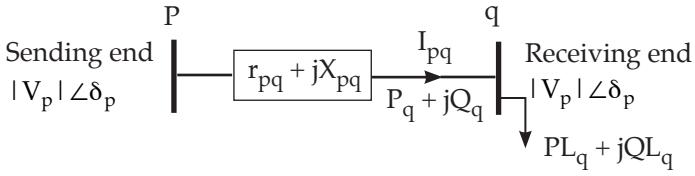


Figure 1. Equivalent model of RDS of a typical branch pq

From Figure 1, current flowing through branch between nodes p and q is given by

$$I_{pq} = \frac{|V_p| \angle \delta_p - |V_q| \angle \delta_q}{r_{pq} + jx_{pq}} \tag{1}$$

or $I_{pq} = \frac{P_q - jQ_q}{(V_q \angle \delta_q)^*}$ (2)

Equating eqns. (1) and (2) and separating real and imaginary parts of above equation, the real part is

$$|V_p| |V_q| \cos(\delta_p - \delta_q) = |V_q|^2 + P_q r_{pq} + Q_q x_{pq} \tag{3}$$

and the imaginary part is

$$|V_p| |V_q| \sin(\delta_p - \delta_q) = P_q x_{pq} - Q_q r_{pq} \tag{4}$$

From equation (4)

$$P_q = \frac{|V_p| |V_q| \sin(\delta_p - \delta_q) + r_{pq} Q_q}{x_{pq}} \tag{5}$$

For calculating $|V_p|$, substitute P_q value from eqn. (5) in eqn. (3) and rearrange the equation. The possible solution for $|V_p|$ is given by

$$|V_p| = \frac{- \left[|V_q| \left\{ \left(\frac{r_{pq}}{x_{pq}} \right) \sin \delta - \cos \delta \right\} \right] + \sqrt{\left[|V_q| \left\{ \left(\frac{r_{pq}}{x_{pq}} \right) \sin \delta - \cos \delta \right\} \right]^2 - 4Q_q \left\{ \left(\frac{r_{pq}^2}{x_{pq}} \right) + x_{pq} \right\}}}{2} \tag{6}$$

Where $\delta = \delta_p - \delta_q$

The active and reactive power losses in branch "pq" are given by

$$LP_{pq} = \frac{r_{pq}(P_q^2 + Q_q^2)}{|V_q|^2} \quad (7)$$

$$LQ_{pq} = \frac{x_{pq}(P_q^2 + Q_q^2)}{|V_q|^2} \quad (8)$$

For calculating the line loadability index, eliminate the angles from eqns. (3) and (4) and then rearrange the equation

$$|V_q|^4 + 2\left(r_{pq}P_q + x_{pq}Q_q - \frac{|V_p|^2}{2}\right)|V_q|^2 + (r_{pq}^2 + x_{pq}^2)(P_q^2 + Q_q^2) \quad (9)$$

When the discriminant of eqn. (9) is greater than or equal to 0, that is,

$$\left(r_{pq}P_q + x_{pq}Q_q - \frac{|V_p|^2}{2}\right)^2 - (r_{pq}^2 + x_{pq}^2)(P_q^2 + Q_q^2) \geq 0$$

Rearrange the above equation

$$\frac{|V_q|^2}{2} - \left(r_{pq}P_q + x_{pq}Q_q + \sqrt{(r_{pq}^2 + x_{pq}^2)(P_q^2 + Q_q^2)}\right) \geq 0 \quad (10)$$

Maximum loadability is reached when $P_q + jQ_q$ is increased to make the left term of eqn. (10) equal to zero. In order to determine that point, the power flow $P_q + jQ_q$ is replaced by the term $LLI \times (P_q + jQ_q)$ assuming a constant load power factor, where LLI is a real number factor; we obtain

$$LLI = \frac{|V_p|^2}{2\left(r_{pq}P_q + x_{pq}Q_q + \sqrt{(r_{pq}^2 + x_{pq}^2)(P_q^2 + Q_q^2)}\right)} \geq 1 \quad (11)$$

LLI varies from infinite (no loading) to one (maximum loading). $LLI \times S_q$ and $(LLI - 1) \times S_q$ represent the line maximum loadability (LML) and the line loading margin, respectively, where

$$S_q \sqrt{P_q^2 + Q_q^2}.$$

The voltages at the sending bus and the power flow at the receiving bus for all lines in a distribution system can be obtained by load flow calculations [18]. Then the LLI of each line can be calculated easily and quickly. The line with the minimal LLI is the weakest line, and its receiving bus is the weakest bus. When its LLI approaches 1.0, the line, and thus the system, will become critical to lose voltage stability.

The preceding analysis is for a line in a RDS that may have any number of nodes and depicts only the megavolt ampere (MVA) capacity of a line to carry load. As an example, consider a distribution line as shown in Figure 2.

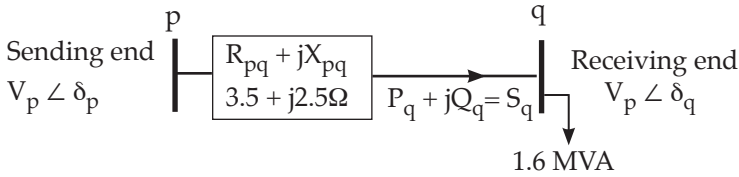


Figure 2. A simple model of RDS branch for LLI calculation

The sending end voltage is assumed to be $V_p \angle \delta_p = 1.0 \angle 0.0$. The value of LLI is evaluated for various values of power flow through the line and the results are tabulated in Table 1. For each step of loading, the fourth column of Table 1 reports the value of line loadability MVA margin. It is equal to the maximum possible additional power flow in the line when the value of LLI is greater than 1.0 or the minimum power flow decrement to establish solvability of the power flow equation when the value of LLI is less than 1.0. At a S_q of 7.10 MVA, the value of LLI is equal to 0.99. This indicates that a reduction of load to the extent of 0.066 MVA to reach 7.034 MVA restores solvability of the power flow equation for the line and increases LLI to 1.0. In a similar view, at a MVA load of 1.60, the value of LLI is equal to 4.40. This indicates that an increase of power flow by 5.434 MVA to reach

Table 1. The relationship between MVA load, LLI and Line loading MVA margin in line pq for sample model

MVA load, S_q in MVA	Voltage at bus q in p.u.	LLI	Line Loading MVA margin $= S_q \times (LLI - 1.0)$
1.60	0.93948	4.40	5.434
2.10	0.91877	3.35	4.934
2.60	0.89699	2.71	4.434
3.10	0.87394	2.27	3.934
3.60	0.84937	1.95	3.434
4.10	0.82294	1.72	2.934
4.60	0.79414	1.53	2.434
5.10	0.76220	1.38	1.934
5.60	0.72578	1.26	1.434
6.10	0.68222	1.15	0.934
6.60	0.62422	1.07	0.434
7.10	no solution	0.99	-0.066

7.034 MVA reduces LLI to 1.0 and moves the line to the point of line maximum loadability.

MATHEMATICAL FORMULATION FOR DISTRIBUTION GENERATOR PLACEMENT

The problem of capacitor placement requires the determination of the optimal capacitor placement and size such that the resulting RDS has the best loadability and the best voltage profile.

Consider any q^{th} bus in the RDS except the main substation. The q^{th} bus would be connected to several lines. However, owing to the radial nature of the RDS, only one line connected q^{th} bus to the main substation of the RDS. The value of LLI evaluated for the supply line associated with the q^{th} bus is termed as LLI_q . The actual MVA flow in the supply line associated with the q^{th} bus is defined as $LLI_q * MVA_q$. The product indicates the line maximum loadability for pq line of the RDS. The line with the least value of the product obviously is closest to the point of maximum loadability. Optimal capacitor placement

and size and maximizing the minimum of all such product values in a radial system would, therefore, move the system to achieve highest loadability state.

Mathematically the problem is stated as:

$$\text{Line Maximum Loadability by Maximizing} \\ \{\text{minimum of } LLI_q * MVA_q\} \quad (12)$$

Where:

q = all buses except the main substation bus

Bus Voltage Limits: The bus voltage magnitudes are to be kept within acceptable operating limits throughout the optimization process.

$$|V|^{\min} \leq |V_q| \leq |V|^{\max} \quad (13)$$

Where:

$|V|^{\min}$ lower bound of bus voltage limits = 0.9

$|V|^{\max}$ upper bound of bus voltage limits = 1.1

$|V_q|$ rms value of the q^{th} bus voltage

Branch Current Limit: Current magnitude of each (feeder, laterals and switches) must lie within their permissible ranges

$$|I_{pq}| \leq |I_{pq}|^{\max} \quad (14)$$

Where:

$|I_{pq}|^{\max}$ maximum rms value of the pq^{th} branch current

$|I_{pq}|$ rms value of the pq^{th} branch current

Power source limit constraint: The total loads of a certain partial network cannot exceed the capacity limit of corresponding power source.

$$P_{pq} \leq P_{pq}^{\max} \quad (15)$$

$$Q_{pq} \leq Q_{pq}^{\max} \quad (16)$$

Where:

P_{pq} and P_{pq}^{\max} maximum active and reactive power flow of the pq^{th} branch

Q_{pq} and Q_{pq}^{\max} active and reactive power flow of the pq^{th} branch

Distribution Generator Losses Constraint: The distributed generator active and reactive power losses of the network cannot exceed the total active power line losses of the network.

$$\sum_{ng} P_{Gloss} \leq \sum_{nb} P_{loss} \quad (17)$$

$$\sum_{ng} Q_{Gloss} \leq \sum_{nb} Q_{loss} \quad (18)$$

Where:

- P_{Gloss} and Q_{Gloss} distributed generation active and reactive losses
- P_{loss} and Q_{loss} active and reactive power losses in branch
- nb number of branch
- ng number of generators

DISTRIBUTION GENERATOR PLACEMENT ALGORITHM AND FLOWCHART

Figure 3 shows the flowchart which represents the algorithm for identifying the location where the minimum line loadability exists and size of the DG can be found by increasing the DG values in small steps of 5 kW by cross checking maximization of the minimum line loadability, given constraints for the RDS.

ILLUSTRATIVE EXAMPLES

To demonstrate the effectiveness of the proposed method, consider a 15-node, 11 kV radial distribution system whose line and load data are given [22]. The total real and reactive power loads at nominal voltage are 1226.40 kW and 1250.93 kVAR respectively.

Table 2 shows the summary of test results for 15 bus RDS, including the voltage values before and after DG placement with the existing analytical method [13] at bus 4 and with the proposed method at bus 12. The minimum voltage is improved from 0.94438 to 0.96393 p.u with existing method, whereas 0.94438 to 0.96752 p.u by the proposed method. Figure 4 shows the voltage profile for base case, existing method and proposed method. Hence, there is an improvement in the minimum voltage when compared with the existing analytical method.

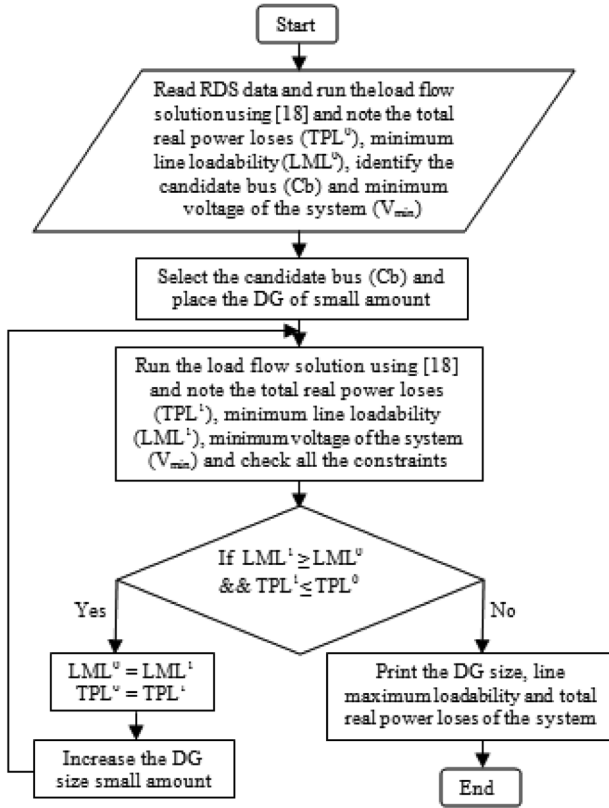


Figure 3. Flowchart for proposed DG placement method

It is also observed that total power losses are reduced from 61.78 to 38.90 kW and 57.29 to 34.99 kvar in the existing analytical method, whereas with proposed method 61.78 to 33.40 kW and 57.29 to 28.03 kvar. The percentage of the total real and reactive power loss reduction in the existing analytical method is 37.03% and 38.87%, whereas in the proposed method it is 45.93% and 51.07% respectively.

From Table 2, it can be also observed that the minimum LLI in branch 11 and branch 5 are given before and after DG placement respectively. The minimum line loadability, actual line load at the minimum line loadability, and additional line loadability in MVA at branch 11 for before DG placement are 9.33, 0.16 and 9.17. After DG placement at branch 5 for the existing method [13] they are 9.54, 0.50 and 9.04 and for the proposed method are 9.57, 0.50 and 9.07, respectively. Beyond

Table 2. The Summary of the test result for 15 bus RDS

Parameters	Before DG Placement	After DG Placement	
		Existing Method [13]	Proposed Method
Minimum Voltage (p.u)	0.94452	0.96393	0.96752
Total active power loss (kW)	61.78	38.90	33.40
Total Reactive power loss (kVAr)	57.29	34.99	28.03
DG placed Bus	-	4	12
DG size	-	831 kW	700 MVA with 0.85 pf
Line Loadability Index	57.26	19.07	19.11
Min. Line Loadability Branch	11	5	5
Min. Line Loadability (MVA)	9.34	9.54	9.57
MVA load at Min. Line Loadability	0.16	0.50	0.50
Additional MVA load at min. line Loadability	9.17	9.04	9.07

this load, a small increment in the load causes the instability of the radial distribution system.

Figure 5 shows that LLI value and voltage value is delaying while increasing the load at the minimum line loadability branches 11 and 5 for without DG and with DG placement respectively. The critical point of collapse is 9.34 MVA for the base case, whereas it is 9.57 MVA with the DG by proposed method. Also observed is that there is an increase in the minimum line loadability with DG placement with the proposed method.

CONCLUSION

This article presents methodology to place DG based on the maximization of the minimum line loadability in radial distribution systems with the view of enhancing the system stability. The methodology is fast and accurate in determining the size and location. It is established in this work that the quantities affected are (i) number of voltage limit violations, (ii) number of line current limit violations, (iii) kVA, real and reactive p.u. demand on the substation, (iv) loss reduction in real

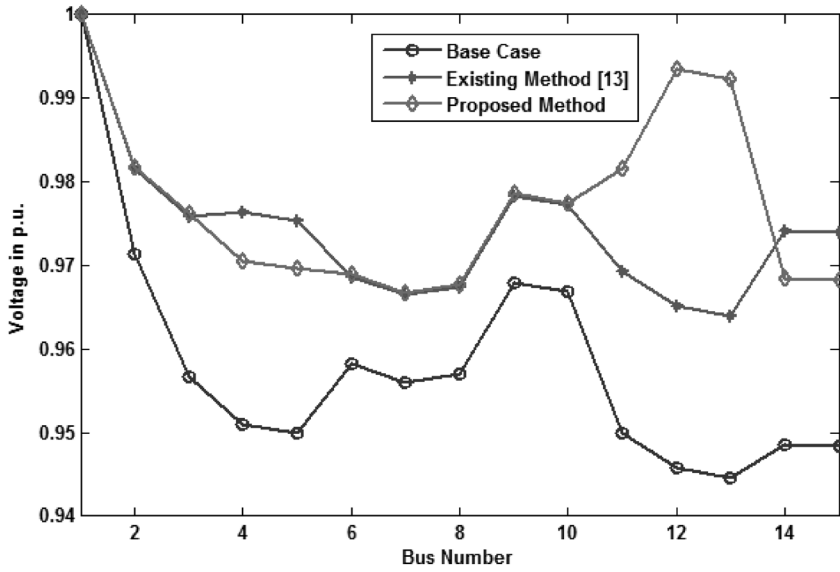


Figure 4. Voltage profiles for 15 bus RDS

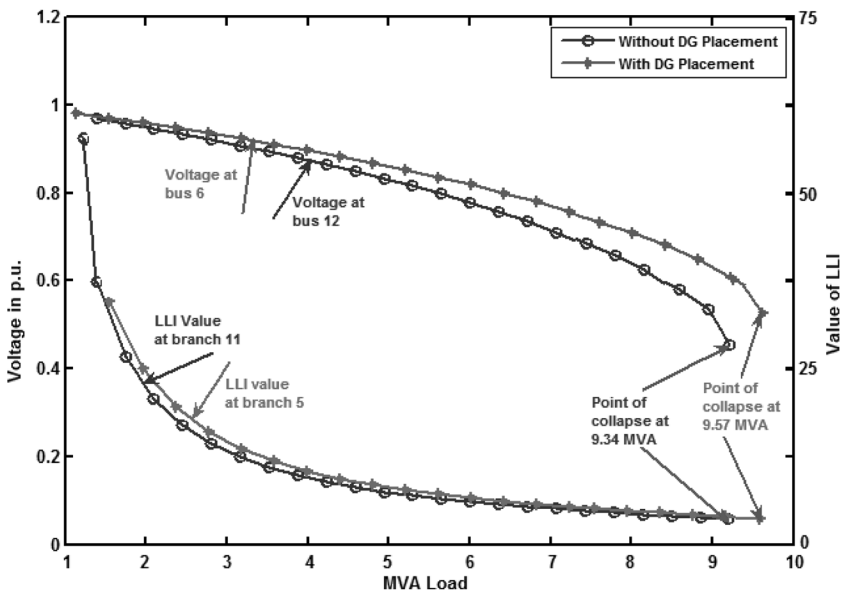


Figure 5. Variation of LLI and Voltage w.r.t change in MVA load before and after DG placement for 15 Bus RDS

and reactive power, and (v) saving of kVA capacity on the substation. It was observed that most or all of the quantities are affected. The efficacy of the proposed method has been compared with an existing method [13].

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