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Study of Economical-Technical Impacts of Distributed Generation on Medium-Voltage Grid

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Abstract

The development of Science and Technology has spurred the development of distributed generation, as well as the application of new renewable energy sources. DG connected to the grid can alter the power flow on the grid, reduce voltage loss and grid capacity loss; and also enhance the incident and reliability of grid power supply. When the number of DG connected to the grid increases, capacity direction varies depending on the distribution and consumption at specific time. Consequently, capacity losses in the grid can be reduced. Besides, DG connected to the grid is closely linked to the matters of environmental pollution and degradation, economic growth and living standard. This paper will discuss the impacts of grid-distributed generation on economic and technical indicators, which mainly focus on the relationship between degree of penetration and location of DG connection to the grid, regarding voltage and capacity losses in the line. The proposed model is calculated and tested via a 56-bus radial distribution system in the DELPHI7 programming language.

Keywords: *distributed generation (DG), impact*

1. Introduction

Besides the traditional structure of distribution network providing connection from intermediate substations to electric users, with support of the development of alternative energy sources, environmental factors, new technologies, power quality, and power system reliability, etc., the initiation of DG is considered practical to meet energy needs of a modern and developed society, to complement and to respond rapidly to power load.

DG is an electric power source connected directly to the distribution grid or consumer side of the meter. This method allows a collection of various energy sources (such as gas turbines, combined heat and power, Fuel Cells, solar energy and wind energies) to generate electricity. Therefore, DG can enjoy the advantages of transmission reduction, lower distribution cost, minimized power loss, flexibility and reliability enhancement of DS, improvement of differential voltage at nodes as well as reduction of environmental pollution [1].

Energy resources used by DG are mostly renewable; hence the most basic benefits of DG are to reduce and to eliminate greenhouse effect. Another benefit is that fuel costs are very low (or virtually equal 0 in the exercise of solar and wind energy). This helps avoiding operating costs and operational risk. On the other hand, the main disadvantage is that of the low performance, also, the ratio of initial capital investment per unit of capacity is often larger than that of non-renewable DG. For example, the system building cost for gas thermal power is 500EUR/MW, while it takes 900EUR/MW for wind power system to be constructed [2]. In addition, issues associated with the establishment of renewable energy for DG are expenses on connection, measurement and balance.

DG is connected to distribution grid through connection points (CP) and point of common connection (PCC). A working model of DG allocation to the distribution network is demonstrated in Figure 1. Equipment employed for DG to the grid connection depends on the

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applied criteria grid. However, at the output of the connected station, DG always includes switchgear, protection and measuring equipment.

DG is generally connected with medium-voltage distribution network at voltage level of 6kV and 35kV, respectively. DG connected to the grid can alter the power flow on the grid; and vary grid capacity loss (either increase or decrease) depending on its position on the grid and grid configuration (voltage level, grid diagram, etc.).

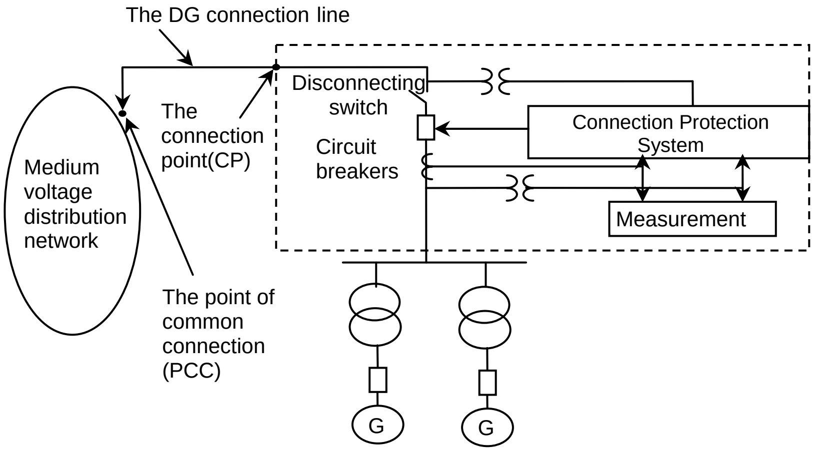

Figure 1. The Connection Points (CP) and the Point of Common Connection (PCC)

Previous studies have shown that, with penetration range from 10 to 15%, distribution resources in the grid will not perform any significant changes on structure grid and electrical systems [3]. Nonetheless, when the penetration level of DG is high, the output power of DG will affect the power flow not only in the grid but also in the transmission grid [4]. As the penetration level of DG increases, the influences on the grid also get greater. In this context, besides the economics impact on the grid, pros and cons, as well as issues related to environment and climate change, penetration of DG on the grid also raises multiple must-be-considered technical issues, as follows:

(1) Characteristic of voltage changes across the network depends on power consumption

(2) The excessive voltage will occur due to the practices of connecting and disconnecting generators, and could even happen during the running process of operation-dispersed generators.

(3) Increased levels of short circuit malfunction.

(4) Protection co-operation issues between generators and the grid

(5) Power loss varies as with the different levels of load

(6) Quality, safety and reliability of power supply

In fact, the position of DG is determined to ensure that the net loss is smaller than it used to be before the DG is connected. The determination of the optimal placement for DG sources and DG capacity, under consideration of different operating conditions of the grid, will bring better answers to the matter of minimizing capacity loss on the grid. Losses will be reduced more effectively as of the DG connection in high-density load region [5].

Thanks to the presence of DG, capacity losses on distribution lines will change and can be evaluated through the coefficient of capacity losses on the line in case of DG. Capacity losses on the grid are also strongly contingent upon DG technologies being used, penetration (DG_{pen} - capacity-related) and degree of dispersion (DG_{dis} - location-related connection) of DG on the grid [6].

Penetration can be calculated by function of the total generating capacity of DG (P_{DG}) over the peak load capacity of the grid (P_L):

$$DG_{pen} = \frac{P_{DG}}{P_L} x100\,\%$$

Penetration of DG < 30% ($P_{DG} < 0{,}3.P_L$) is considered low while ideal volume is 100% ($P_{DG} = P_L$). With penetration range from 10 to 15%, distribution resources in the grid will not show any significant changes on structure grid.

In order for capacity losses in the distribution system to remain the most reasonable, DG placement and penetration level of DG into the grid can be determined via calculations.

The reliability of distribution system is an essential indicator in planning and operation system. With the emergence of DG on the grid, the reliability of power supply can be improved. Especially, the reliability of the grid can be enhanced as of peak load. Therefore, it will help extending the duration of next investment in improving grid [8]. Position and capacity of DG connected to the grid will be able to improve the reliability of the grid's power supply. For radial distribution grid, the best position of DG is at the end of the line to improve power supply reliability. Multiple DG connections per small capacity, which are distributed throughout the grid, will be more beneficial when DG is connected near the source site or to a certain position. Improvement of power supply reliability, as DG is connected to the grid, will be more effective if there is a smooth combination between flexibility and protections on the grid [9].

The determination of the number of DG, DG connection points and the extent of penetration of DG is made so that the power loss, the voltage loss reaches minimal, which is conducted as follows:

A grid has n nodes (research problem are 55 nodes, n = 55), assuming the DG can match any node, (DG links a node, with P_{DG} = 30% P_L with m = 1. DG links 2 nodes P_{DG} = 30% P_L with m = 2. DG links 3 nodes P_{DG} = 100% P_L with m = 3, etc. .... so with a level of any P_{DG} (lots of), m = 1 ÷ 55.

The number of options (case) is determined by the formula:

$$C_n^m = \frac{n!}{m!(n-m)!}$$

$n! = 1*2*3*4*.......*n$

$m! = 1*2*3*4*.......*m$

For example, if DG links to the 55 nodes with a certain level of P_L, there is only 1 case, if DG links in 2 out of 55 nodes:

$$C_n^m = \frac{n!}{m!(n-m)!} = \frac{55!}{2!53!} = 1485\text{cases}$$

If DG links in 3 out of 55 nodes:

$$C_n^m = \frac{n!}{m!(n-m)!} = \frac{55!}{3!52!} = 26235\text{cases}$$

If P_L has 3 levels, the number of cases will be 3 folds, etc…It must be for calculated all the cases to determine the IMO for each case. The closer to 1 IMO is, the better the case is.

Considering IMO is the multi-target coefficient (in this case, only voltage profile and capacity loss are set as targets), we have:

$$\begin{aligned} &IMO = p_{VP} . VP_{imp} + p_{LL} . LLI_{imp} \\ &p_{VP} + p_{LL} = 1.0 \end{aligned} \tag{1}$$

p_{VP} and p_{LL} is two over important evaluation criteria for the grid. Any project of which IMO closely reaches to 1 is considered proficient.

The above method called simplex method is to consider all possible cases.

All the above cases do not include investment in DG, yet considering DG close to any point (if necessary - which is often unrealistic). At P_{DG} = 100% P_L, each substantial load with a DG is ideal because there were no longer grid loss and a possibility of taking of grid (do not mention investment in DG). The smaller the DG is, the higher the economic effect is; but the volume needs much calculation as aforesaid.

Empirically, with the basic case, the lowest voltage node, the longest line linking PCC node, the largest total impedance, the end of the load beam with a lot of big substantial loads are usually chosen to link DG. The case that linking DG point is nearly point of common connection (PCC) is usually not effective enough, thus, we can ignore this case. (In fact, seldom is DG considered; DG is often near a certain point, then the connection these nearby nodes are required. The problem, thus, will be how to identify economic and technical effect when DG links to available points on the DG). Regarding the grid network which can be designed closed network from the beginning, the effect is similar to adding DG links.

The next parts of this paper are organized as follows: Section 2 introduces a grid computing method with objective function. Section 3 presents calculation results from the 56-bus DS. Conclusion is presented in Section 4.

2. Grid Computing Methods

Distribution capacity line is the core matter of power system analysis. It has a close relationship with voltage stability analysis in the setting mode and dynamic mode.

2.1. Equilibrium Model Power Node when DG Connected

Capacity balance equation for node k:

$$\begin{aligned}\dot{S}_k &= \sum_{m\in C_k, k\neq m} \dot{S}_{km} + \sqrt{3}\dot{U}_k . \overset{*}{I}_{sh.k} - \sum_{m\in C_k, k\neq m} \sqrt{3}\dot{U}_k . \overset{*}{I}_{Ckm} \\ &= \sum_{m\in C_k, k\neq m} \dot{S}_{km} + U_k^2 . \overset{*}{Y}_{sh.k} - j \sum_{m\in C_k, k\neq m} U_k^2 . \frac{B_{Ckm}}{2}\end{aligned} \tag{2}$$

$$\begin{aligned}P_k &= U_k^2 \sum_{m\in C_k, k\neq m} Y_{km} \cos\varphi_m - \sum_{m\in C_k, k\neq m} U_k U_m Y_{km} \cos(\theta_{km} - \varphi_{km}) + U_k^2 \operatorname{Re}\left\{\overset{*}{Y}_{sh.k}\right\} \\ Q_k &= -U_k^2 \sum_{m\in C_k, k\neq m} Y_{km} \sin\varphi_m - \sum_{m\in C_k, k\neq m} U_k U_m Y_{km} \sin(\theta_{km} - \varphi_{km}) - j \sum_{m\in C_k, k\neq m} U_k^2 . \frac{B_{Ckm}}{2} + U_k^2 \operatorname{Im}\left\{\overset{*}{Y}_{sh.k}\right\}\end{aligned} \tag{3}$$

Where:

$\dot{S}_k$: Capacity node k	$\dot{S}_{km}$: Capacity from k to m
$\dot{U}_m$, $\dot{U}_k$: Voltage wires on the node	$\dot{I}_k$: Power circuit node k
$\dot{I}_{km}$: Power circuit from node k to node m	$\dot{I}_{Ckm}$: Power circuit due to half line capacitance born
Y_{km} : Negative total lead line j link node k and node m	$Y_{sh.k}$: Total lead of the shunt element connected

C_k : Set of nodes connected to node k, contain the line connected to the node balancing

2.2. Newton Raphson Algorithms in Distributed Generation Capacity Calculation

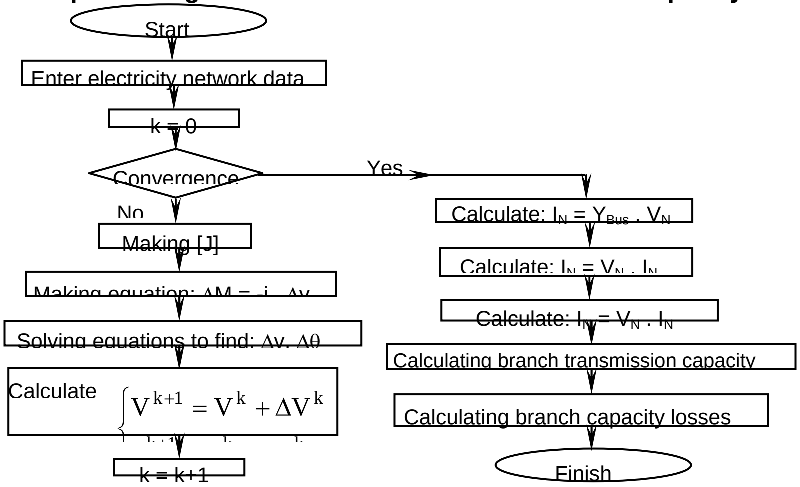

Figure 2: Newton-Raphson Method

2.3. DG Location and Capacity Effect on Power Loss Reduction and Voltage Profile Improvement of Distribution Network

2.3.1. Criteria for Evaluating the Effectiveness of Improving Voltage Profile

A production line includes many load points; each load point is characterized by the value voltage and capacity at node. In fact, each different type of load has different static features, thus the correspondent importance degree of one to another differentiate. In general case, a characteristic measure of voltage quality is illustrated by [8]:

$$VI = \sum_{i=1}^{N} U_i P_i k_i \qquad \sum_{i=1}^{N} k_i = 1 \tag{4}$$

Where:

VI - Output characteristic of voltage line.

U_i - Voltage at node i (p.u), usually evaluated in a limited range U_{max}(1.05p.u) and U_{min}(0.95p.u).

P_i - Load at node i (p.u).

k_i - Scale showing the importance of the load at node i.

In many cases, it can simply be able to take $k_1 = k_2 = ... = k_n = 1/N$.

Accordingly, voltage quality results in two cases (with and without DG) can be compared over the following proportion:

$$VP = \frac{VI_{DG}}{VI_{KDG}} \tag{5}$$

Where:

VI_{DG} and VI_{KDG} - Voltage indicator in cases with and without DG, relatively.

VP - Quality improvement coefficient of the grid voltage.

If VP>1, DG connected to the grid is affirmed to have positive effect in improving voltage quality; and amongst many options to decide which is the optimal allocation method of DG capacity and voltage profile.

If VI_{imp} = (VP - 1) is Improving voltage coefficient, when the grid has DG the bigger the coefficient is, the better.

2.3.2. Criteria for Evaluating the Effectiveness of Capacity Losses Reduction

According to [6], the efficiency coefficient of reducing power line loss is calculated by comparing total loss in a case with DG connection over that when DG is not connected:

$$LLI = \frac{LL_{DG}}{LL_{KDG}} \tag{6}$$

Where:

LL_{DG} - Total loss on line with DG connection

LL_{KDG} - Total loss on line without DG

LL_{DG} and LL_{KDG} can be determined as follows:

$$LL_{DG} = 3\sum_{i=1}^{M} I_{DGi}^{2}.R.D_i \tag{7}$$

$$LL_{KDG} = 3\sum_{i=1}^{M} I_{KDGi}^{2}.R.D_i \tag{8}$$

Where:

I_{DGi} and I_{KDGi} - Current distribution units on the ith line with and without DG (p.u);

R- Resistance unit of the line (p.u/km);

D_i- Length of the line (km)

M- Number of distribution lines.

On the basis of (6), it can be said that DG is only effective in reducing power line loss when LLI <1. With regard to the optimal allocation method of DG capacity to reduce power loss amongst many options, one with smaller LLI will perform better.

If LLI_{imp} = (1 - LLI) is Reducing capacity loss coefficient, when grid has DG the bigger the coefficient is, the better.

3. Results and Discussions

3.1. Diagram and Parameters of Distribution System

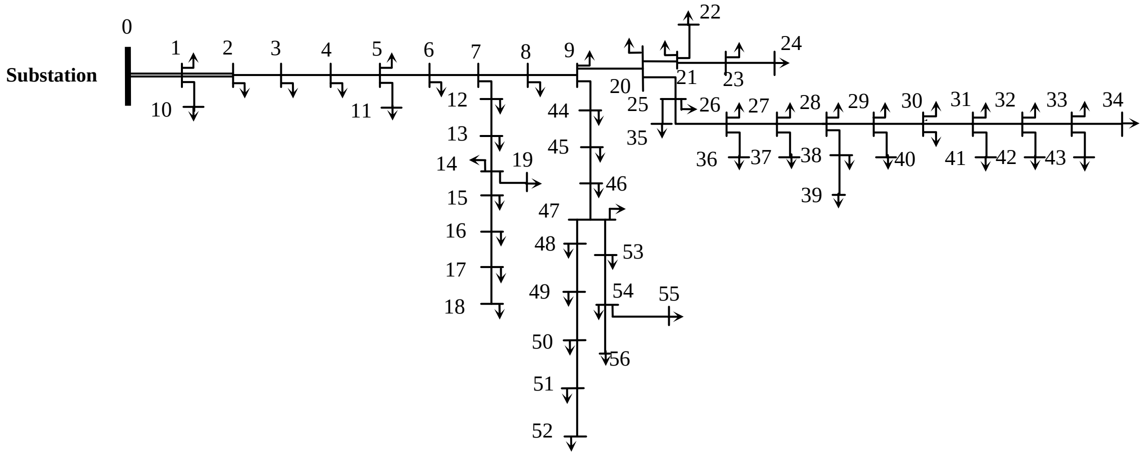

Figure 3. Diagram of Radial Distribution System

3.2. Calculation of Node Voltages and Capacity Losses without DG Connection

Such testing grid should be defined at the maximum time as this load voltage loss, power loss during operation reach the largest and quality in the absence of DG voltage is the least, and the power loss is the largest. With this additional load on the grid DG improving power quality (voltage stability) and reducing power loss, enhancing the reliability of power supply will be the most effective way.

Firstly, we will take into consideration the case when DG is not connected; assuming DG's connection node is PV.

According to calculation outcomes shown in Figure 4, it is recognizable that the voltage at node 43 is the lowest. The assessment criteria of voltage quality improvement are:

$$VI = \sum_{i=1}^{N} U_i P_i k_i = 0.315565 \text{ (p.u)}$$

$$\sum_{i=1}^{N} k_i = 1$$

The total loss on the grid is:

$$LL_{KDG} = 3\sum_{i=1}^{M} I_{KDGi}^2 .R.D_i = 0.071409\text{(p.u)}$$

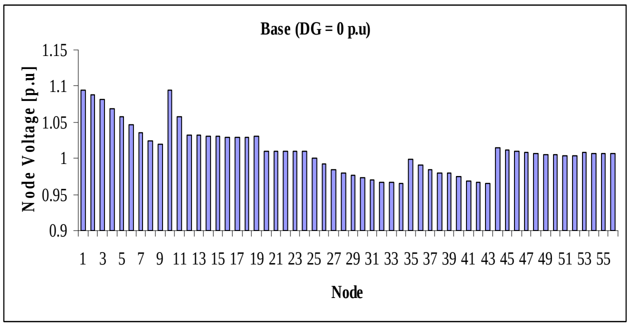

Figure 4. Diagram of Node Voltage on the Grid

3.3. Calculation of Node Voltages and Capacity Losses with DG Connection

In order to evaluate the effects of penetration and location on the quality criteria of power grid, DG will be arranged in the following cases:

(1) Case 1: penetration P_{DG} = 30%P_L link node 43
(2) Case 2: penetration P_{DG} = 50%P_L link node 43
(3) Case 3: penetration P_{DG} = 100%P_L link node 43
(4) Case 4: penetration P_{DG} = 30%P_L evenly spread node 43, 52
(5) Case 5: penetration P_{DG} = 30%P_L evenly spread node 43, 52, 25
(6) Case 6: penetration P_{DG} = 50%P_L evenly spread node 43, 52
(7) Case 7: penetration P_{DG} = 50%P_L evenly spread node 43, 52, 25
(8) Case 8: penetration P_{DG} = 100%P_L evenly spread node 43, 52
(9) Case 9: penetration P_{DG} = 100%P_L evenly spread node 43, 52, 25

3.3.1. Improving Voltage Profile Assessment

Cases summary:

Table 1. Voltage Improment after DG is Connected

Case	Voltage improvement after DG is connected		
	VI	VP	The increase (%)
Base	0.99858		
1	1.05358	1.05509	5.51
2	1.03318	1.03465	3.46
3	1.68661	1.68901	68.9
4	1.06649	1.06801	6.8
5	1.08404	1.08558	8.56
6	1.08038	1.08192	8.19
7	1.08059	1.08212	8.21
8	1.18139	1.18307	18.31
9	1.15381	1.15545	15.55

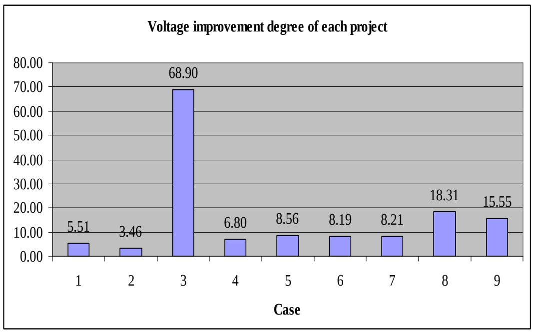

Figure 5. Voltage Degree Improvement when DG is Connected to the Grid

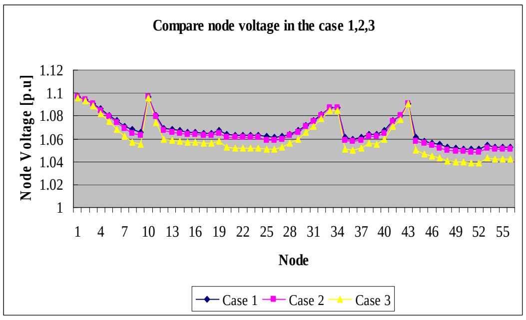

Figure 6. Node Voltage Increases along with the Penetration Level of DG

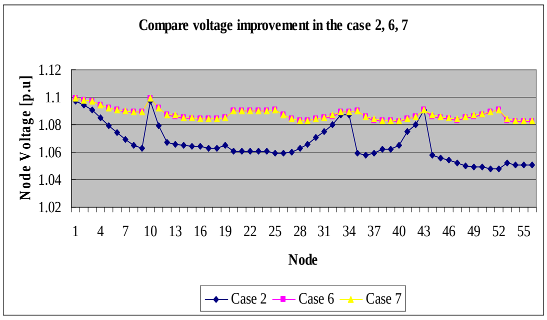

Figure 7. Voltage Node Increases along with Distribution Degree of DG

According to this outcome, all the plans are able to improve the grid's voltage (although the differences amongst cases is not great). When DG is connected at node 43 and the upload is gradually increased, it is found that level of voltage quality improvement is directly proportional to the penetration of DG into the grid (up from 30% to 50%). However, when experiment continued increasing the upload (to more 100%), the level of voltage quality improvement will decrease. This suggests that, depending on the grid structure; the penetration of DG has either positive or negative impact to voltage quality (Figure 6).

Based on the results of 3 sets of cases (case #1, case #4, case #5), (case #2, case #6, case #7) and (case #3, case #8, case #9), one can notice that: as degree of dispersion of DG when connected to the grid increases, the level of voltage quality improvement will hence increase. It is easier to be seen under the case of radial grid (Figure 7)

However, it is noticeable that under the case of #3, #8 and #9, level of improvement is higher compared to other cases, where as under the case of #5, #6 and #7, level of improvement remains equivalent.

As shown by these results and the comments above, we can see that characteristics and structure of the grid along with the level of penetration and dispersion of DG will determine whether the impact is positive or negative. The key here is to come up with suitable DG connection plans to the grid in considering design, operation and management goad of power grid.

In fact, DG sources are usually fixed at a regional position under certain natural conditions (wind, solar, etc.), thus the location of DG is not easy to be changed. In that case, we can change the point of common connection (PCC) at which DG connects to the grid. Subsequently, we can bring up these obstacles for network designer to operate and analyze in order to select the best plan, because it requires the computation of construction costs and losses on the line.

3.3.2. Reducing Capacity Losses Assessment

Summary calculation on impacts on capacity loss when the grid connected DG is shown as in Table 2.

Table 2. Reduction in Capacity Loss after DG is Connected

Case	Losses without DG: LLI_{KDG} = 0.071409 (p.u)		
	LL	LLI	Reduction(%)
Base	0.071409		
1	0.014045	0.19675	80.33
2	0.018488	0.25886	74.11
3	0.001222	0.01701	98.29
4	0.011829	0.16566	83.43
5	0.019312	0.27041	72.96
6	0.019762	0.27671	72.33
7	0.055689	0.77986	22.01
8	0.002454	0.03431	96.56
9	0.015151	0.21218	78.78

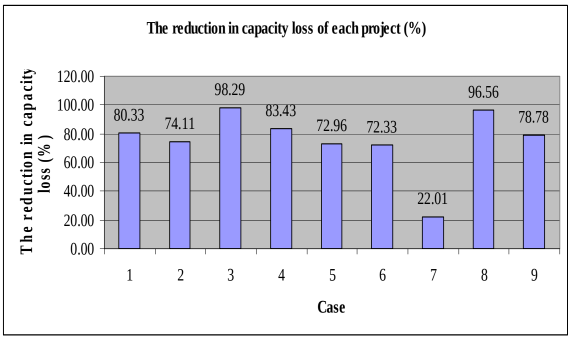

Figure 8. Reduction in Capacity Loss when DG is Connected to the Grid

Under case #3 (P_{DG} = 100%P_L at link node 43), capacity loss reduction is greatest whilst case #7 (P_{DG} = 50%P_L evenly spread to node 43, 52 and 25) experienced the worst in reducing capacity loss. Table 2 also exemplifies that: amongst couple groups of cases, of which generation capacity and degree of dispersion increased, a set of (case #1, case #3, case #4 and case #8) shows the biggest improvement. After exanimation 4 cases, it can be concluded that: for this grid configuration, the penetration degree is at best P_{DG} = 100%P_L, and best placement is at link node 43.

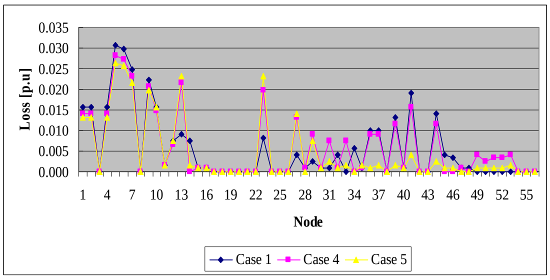

Figure 9. Shown Changes in Capacity Loss of Power System in Function of Dispersion Degree P_{DG} = 30%P_L

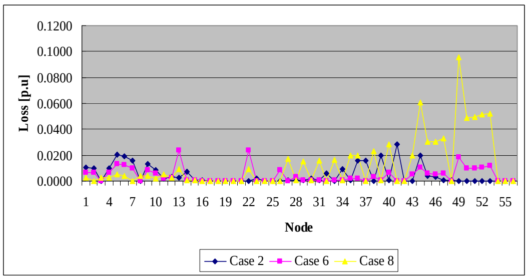

Figure 10. Shown Changes in Capacity Loss of Power System in Function of Penetration Degree P_{DG} = (30, 50, 100)% P_L

As shown by the comments above, we can see that the same methodology to connect DG (capacity and connection placement) still results in diverse benefits of voltage profile and power loss reduction due to each single project.

However, in case of this specific grid that we are taking under consideration, case #3 (P_{DG} = 100%P_L link node 43) provides the best advantage in voltage improvement aside from the best efficiency in reducing capacity loss and enhancing the reliability of power supply.

In a paper with simple grid diagrams, few branch then based on the basic plan (Figure 4) we can select the remote node connection point (node 43, 52), low voltage (node 25) to identify options for setting DG. That the result for the problem is case 3 will be the best option because when the link DG of node 43 has created a closed network from point of common connection (PCC) node to node 43, considered the longest backbone with a lot of loads in the two-source supply network. Therefore it can reduce the leaking power on some lines with the large loading, with the largest voltage loss and power loss compared to basic case. Consequently, this case has improved the quality of power (reducing voltage loss), reducing the capacity loss and power compared to other cases. It can be concluded so with this case. However, to more complex models, they must follow the simplex method as stated above, then, conclusion might be reached.

According to Table 3 and Figure 11, case #3 has been shown as the best. Nevertheless, other cases also call for consideration in order to select an option appropriated to reality.

Table 3. Project Assessment Coefficient (IMO)

Case	Project assessment coefficient (IMO) p_{VP} = 0.6 and p_{LL} = 0.4		
	VP_{imp}	LLI_{imp}	IMO
1	1.05509	0.19675	0.7118
2	1.03465	0.25886	0.7243
3	1.68901	0.01701	1.0202
4	1.06801	0.16566	0.7071
5	1.08558	0.27041	0.7595
6	1.08192	0.27671	0.7598
7	1.08212	0.77986	0.9612
8	1.18307	0.03431	0.7236
9	1.15545	0.21218	0.7781

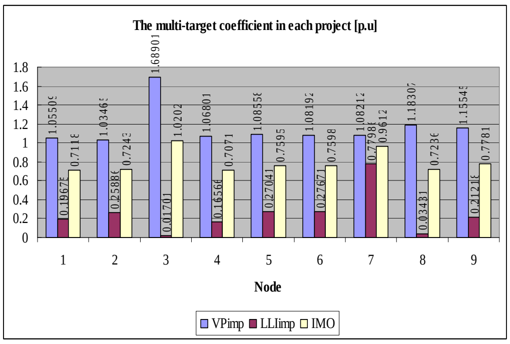

Figure 11. Application of Multi-target Coefficient in Selecting the Project

4. Conclusion

From the analysis, calculations and examples through a simple diagram which is radial diagram highway 372, 110kV transformer substation Ha Giang (Viet Nam) one can see that the characteristics and structure of the grid, penetration and dispersion of DG can bring about positive or negative impacts on power quality, capacity losses and power losses in the grid. Thereby it is found that the DG connected to the grid, especially which is complex, containing more buttons, varying degrees of penetration of various capacities; need following the method of calculation leads to very large volumes. The problem with the participation of DG should account for many other factors, such as potential, the ability to build and exploit the DG sources, the impact on the environment, people, performance, economics of power grid, power supply reliability, the ability to equip and protect confidential closed network. etc. ..., combining with experience of design and operation to be able to draw conclusions relevant to the participation of DG on the grid.

Additionally, when DG participated in the grid, the grid becomes complicated closed network with more grid supplies, changes of current direction and current work problems. Protection grid protective equipment should be oriented protection, multi-level, especially to equip the overload protection is geared for DG sources to prevent excessive overload on the grid when the power source lose.

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Appendix

Appendix 1: Parameters of radial distribution system

Node i-j	L_{ij} (km)	Rf_{ij} (Ω)	Xf_{ij} (Ω)	Node i-j	L_{ij} (km)	Rf_{ij} (Ω)	Xf_{ij} (Ω)	Node i-j	L_{ij} (km)	Rf_{ij} (Ω)	Xf_{ij} (Ω)	Node i-j	L_{ij} (km)	Rf_{ij} (Ω)	Xf_{ij} (Ω)
0-1	1.00	0.14	0.19	14-15	1.00	0.46	0.40	28-29	1.00	0.46	0.40	33-43	0.50	0.32	0.20
1-2	1.00	0.14	0.19	15-16	1.00	0.46	0.40	29-30	1.00	0.46	0.40	9- 44	2.00	0.92	0.79
2-3	0.50	0.14	0.19	16-17	1.00	0.46	0.40	30-31	1.00	0.46	0.40	44-45	1.00	0.46	0.40
3-4	1.00	0.27	0.38	17-18	1.00	0.46	0.40	31-32	1.00	0.46	0.40	45-46	1.00	0.46	0.40
4-5	1.00	0.27	0.38	14-19	0.50	0.23	0.20	32-33	1.00	0.46	0.40	46-47	1.00	0.46	0.40
5-6	1.00	0.27	0.38	9-20	1.00	0.46	0.40	33-34	1.00	0.46	0.40	47-48	2.00	0.92	0.79
6-7	1.00	0.27	0.38	20-21	1.00	0.46	0.40	25-35	0.50	0.32	0.20	48-49	1.00	0.46	0.40
7-8	1.00	0.27	0.38	21-22	0.50	0.32	0.20	26-36	0.50	0.32	0.20	49-50	1.00	0.46	0.40
8-9	0.50	0.14	0.19	21-23	0.50	0.32	0.20	27-37	0.50	0.32	0.20	50-51	1.00	0.46	0.40
1-10	0.50	0.23	0.20	23-24	1.00	0.65	0.41	28-38	0.50	0.32	0.20	51-52	1.00	0.46	0.40
5-11	0.50	0.23	0.20	20-25	1.00	0.46	0.40	38-39	0.50	0.32	0.20	47-53	1.00	0.46	0.40
7-12	2.00	0.92	0.79	25-26	1.00	0.46	0.40	29-40	0.50	0.32	0.20	53-54	1.50	0.69	0.59
12-13	0.50	0.23	0.20	26-27	1.00	0.46	0.40	31-41	0.50	0.32	0.20	54-55	1.50	0.97	0.61
13-14	1.00	0.46	0.40	27-28	1.00	0.46	0.40	32-42	0.50	0.32	0.20	54-56	1.00	0.46	0.40
												Total	51.5		

Appendix 2: Testing grid data

U = 24.2 [kV], S = 40 [MVA]

Branch	First node	End node	R [p.u]	X [p.u]	P_{pt} [p.u]	Q_{pt} [p.u]	Branch	First node	End node	R [p.u]	X [p.u]	P_{pt} [p.u]	Q_{pt} [p.u]
1	0	1	0.0068	0.01298	0.000	0.000	29	28	29	0.0225	0.02595	0.000	0.000
2	1	2	0.0068	0.01298	0.000	0.000	30	29	30	0.0225	0.02595	0.000	0.000
3	2	3	0.0068	0.01298	0.000	0.000	31	30	31	0.0225	0.02595	0.000	0.000
4	3	4	0.0143	0.02527	0.1653	0.0802	32	31	32	0.0225	0.02595	0.000	0.000
5	4	5	0.0143	0.02527	0.000	0.000	33	32	33	0.0225	0.02595	0.000	0.000
6	5	6	0.0143	0.02527	0.3702	0.1793	34	33	34	0.0225	0.02595	0.0661	0.0322
7	6	7	0.0143	0.02527	0.000	0.000	35	25	35	0.0157	0.01366	0.8264	0.4000
8	7	8	0.0143	0.02527	0.2116	0.1025	36	26	36	0.0157	0.01366	1.2397	0.6000
9	8	9	0.0068	0.01298	0.000	0.000	37	27	37	0.0157	0.01366	1.2397	0.6000
10	1	10	0.0157	0.01366	0.0496	0.024	38	28	38	0.0157	0.01366	0.119	0.0579
11	5	11	0.0157	0.01366	0.6612	0.3198	39	38	39	0.0157	0.01366	0.3702	0.1793
12	7	12	0.0451	0.05259	0.000	0.000	40	29	40	0.0157	0.01366	0.9091	0.4405
13	12	13	0.0116	0.01298	0.119	0.0579	41	31	41	0.0157	0.01366	0.6198	0.3000
14	13	14	0.0225	0.02595	0.000	0.000	42	32	42	0.0157	0.01366	0.9091	0.4405
15	14	15	0.0225	0.02595	0.2116	0.1025	43	33	43	0.0157	0.01366	0.6612	0.3198
16	15	16	0.0225	0.02595	0.1653	0.0802	44	9	44	0.0451	0.05259	0.0331	0.0157
17	16	17	0.0225	0.02595	0.2116	0.1025	45	44	45	0.0225	0.02595	0.119	0.0579
18	17	18	0.0225	0.02595	0.0661	0.0322	46	45	46	0.0225	0.02595	0.7603	0.3686
19	14	19	0.0157	0.01366	0.2645	0.1281	47	46	47	0.0225	0.02595	0.000	0.000
20	9	20	0.0225	0.02595	0.000	0.000	48	47	48	0.0628	0.05396	0.1653	0.0802
21	20	21	0.0225	0.02595	0.000	0.000	49	48	49	0.0314	0.02732	0.119	0.0579
22	21	22	0.0157	0.01366	0.1653	0.0802	50	49	50	0.0314	0.02732	0.1653	0.0802
23	21	23	0.0157	0.01366	0.000	0.000	51	50	51	0.0314	0.02732	0.119	0.0579
24	23	24	0.0314	0.02732	0.0496	0.024	52	51	52	0.0314	0.02732	0.119	0.0579
25	20	25	0.0225	0.02595	0.3702	0.1793	53	47	53	0.0314	0.02732	0.1653	0.0802
26	25	26	0.0225	0.02595	0.000	0.000	54	53	54	0.0471	0.04030	0.000	0.000
27	26	27	0.0225	0.02595	0.000	0.000	55	54	55	0.0471	0.04030	0.119	0.0579
28	27	28	0.0225	0.02595	0.1653	0.0802	56	54	56	0.0314	0.02732	0.1653	0.0802