

Voltage quality improvement of distribution networks connected distributed generations

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Abstract: Generator technology from distributed sources (DG) are powerful development on a global scale due to the many advantages they bring. Set for a power generator unit and the size of the grid-connected DG is increasing. However, when the DG connected to the distribution grid, they can cause voltage fluctuations at the connection node and adjacent nodes due to the specific characteristics of this type of generator. Paper introduces a content distribution network design solutions and requirements equipped with reactive power from DG to improve voltage quality in the grid

Keywords: Distributed generation technology, distribution networks, voltage quality improvement

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I. INTRODUCTION

Many distributed generators currently in use are induction generators (such as wind turbines) or sources that only supply active power (such as photovoltaic systems) [1]. Therefore, during operation, they often consume a certain amount of reactive power from the power system. This increases the risk of voltage drops at buses along the feeders to which the distributed generators are connected. In addition, due to their limited generation capacity and the use of induction generators, short-circuit faults occurring near the point of connection can cause a severe voltage dip at the connection node. This may lead to voltage collapse, resulting in generator instability and reduced reliability of power supply [2, 3]. To enhance the stable operation capability of distributed generation (DG) and improve voltage quality in distribution networks, it is necessary to install reactive power compensation devices and increase the system's short-circuit capacity. However, the short-circuit capacity at the point of connection varies depending on the connection location, and the required reactive power support from DG also differs across various distribution networks. Within the scope of this paper, the authors present a design solution for distribution networks and distributed generators. The proposed method establishes a relationship between voltage deviation in the network and system parameters, and determines the required reactive power contribution from DG to ensure that the voltage deviation between the DG connection point and the system voltage remains within permissible limits. The research results serve as an important reference for the design of distribution networks with integrated distributed generation.

II. RESEARCH METHODOLOGY

Figure 1 illustrates a distribution network with integrated distributed generation (DG). U_L is the voltage at the system-side busbar, and U_N is the voltage at the busbar at the point of common coupling (PCC) between the DG units and the network. $Z=R+jX$ represents the equivalent impedance of the network.

From Figure 1, we have:

$$U_N^* = U_L^* + (R + jX) \cdot I^* \quad (1)$$

$$\text{because : } S = U_N^* \cdot \hat{I} \Rightarrow I = \frac{\hat{S}}{\hat{U}_N} = \frac{P - jQ}{\hat{U}_N} \quad (2)$$

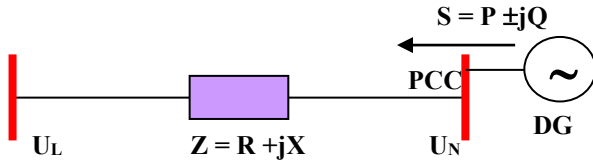


Figure 1: Distribution power system with integrated distributed generation (DG)

From Equations (1) and (2), it can be seen that:

$$\hat{U}_N^* \cdot \hat{U}_N = \hat{U}_L^* \cdot \hat{U}_N + (R + jX)(P - jQ) \quad (3)$$

It is known that: $\dot{U}_N = |U_N| \cdot e^{j\delta} = |U_N|(\cos \delta + j \sin \delta) \quad (4)$

From Equations (3) and (4), we obtain: $|U_N|^2 = U_L \cdot |U_N| \cdot \cos \delta + P \cdot R + Q \cdot X + j(P \cdot X - P \cdot R - U_L \cdot |U_N| \cdot \sin \delta) \quad (5)$

In practice, the term

$$(P \cdot X - P \cdot R - U_L \cdot |U_N| \cdot \sin \delta)$$

is small. Therefore, the magnitude of $|U_N|$ can be determined from Equations (4) and (5):

$$P \cdot X - Q \cdot R - U_L \cdot |U_N| \cdot \sin \delta \approx 0$$

$$\Rightarrow \cos \delta = \frac{\sqrt{(U_L \cdot |U_N|)^2 - (P \cdot X - Q \cdot R)^2}}{U_L \cdot |U_N|} \quad (6)$$

From Equations (4) to (6), we obtain:

$$|U_N|^2 = \sqrt{(U_L \cdot |U_N|)^2 - (P \cdot X - Q \cdot R)^2} + P \cdot R + Q \cdot X$$

(8) or The

$$|U_N|^4 - |U_N|^2 \cdot (2 \cdot (P \cdot R + Q \cdot X) + U_L^2) + (P \cdot R + Q \cdot X)^2 + (P \cdot X - Q \cdot R)^2 = 0$$

solution of the above equation is:

$$(7) \quad |U_N| = \sqrt{\frac{U_L^2 + 2(P \cdot R + Q \cdot X)}{2} + \frac{\sqrt{U_L^4 + 4(P \cdot R + Q \cdot X)U_L^2 - 4(P \cdot X - Q \cdot R)^2}}{2}}$$

Equation (8) describes the relationship between the voltage at the connection node and the system-side voltage, as well as the network parameters. It can be observed that the voltage U_N varies significantly depending on the power flow distribution along the line, the grid impedance, and the ratio of the DG cluster capacity to the system short-circuit capacity.

The voltage deviation at the DG connection node relative to the system-side voltage is expressed by Equation (9).

$$\Delta U = \frac{|U_N| - |U_L|}{|U_L|} \cdot 100 \quad (9)$$

Equation (9) allows the evaluation of the voltage deviation at the connection node relative to the system busbar voltage. This equation also shows that the voltage deviation between the two nodes depends not only on the variation of the DG output power, but also on the characteristics of the network - specifically, the X/R ratio. To reduce this voltage deviation, reactive power compensation at the DG units (or at the point of common coupling - PCC) is essential. Based on Equation (8), the reactive power demand at the DG connection point can be determined.

$$Q = \frac{1}{R^2 + X^2} \left(\begin{array}{l} |U_L|^2 \cdot X - \\ \sqrt{|U_L|^2 (2 \cdot P \cdot R + U_L^2) (R^2 + X^2)} \\ - \sqrt{-|U_L|^4 \cdot R^2 - P^2 (R^2 + X^2)^2} \end{array} \right) \quad \text{Here,} \quad (10)$$

R and X are the equivalent Thevenin resistance

and reactance of the power network.

III. ANALYSIS RESULTS OF VOLTAGE DEVIATION IN POWER NETWORKS WITH INTEGRATED DG

The distribution network is characterized by its Thevenin equivalent impedance and the impedance angle ψ , ($\psi = \arctan(X/R)$) [4]. In practice, since the short-circuit power at the connection point of the DG cluster varies depending on the location, the simulation is carried out for different short-circuit power ratios at the point of connection. This is represented by the ratio S_k/P_n , where S_k is the system short-circuit power and P_n is the total capacity of the DG units at the connection node.

“Weak” grids typically have a ratio $S_k/P_n < 25$, while “strong” grids have $S_k/P_n > 25$ [5]. The impedance angle ψ of transmission networks usually ranges from 55° to 85° . For lower-capacity distributed generation connected to distribution networks, ψ typically lies within the range of 25° to 55° . In most modern power systems, distributed generation is required to either produce or absorb a certain amount of reactive power, along with the installation of automatic reactive power control devices to improve voltage quality [6]. Accordingly, DG units can be voltage-controlled similarly to conventional power sources, enabling their integration into the grid.

The analysis method is based on an equivalent network model, in which the DG source is considered as a constant power source at the point of study, connected to the network through a Thevenin equivalent impedance, as shown in Figure 1. Here:

$$\tan \psi = \frac{X}{R}; \quad S_k = \frac{U_L^2}{\sqrt{R^2 + X^2}}; \quad (11)$$

$$\bar{Z} = R + jX = Z \cdot e^{j\psi}$$

The short-circuit power ratio and the grid impedance angle are varied. The voltage deviation in the network is then determined corresponding to different short-circuit power ratios, grid impedance angles, and power factor levels (leading, lagging, and unity power factor).

The results are presented in Figures 2, 3, and 4.

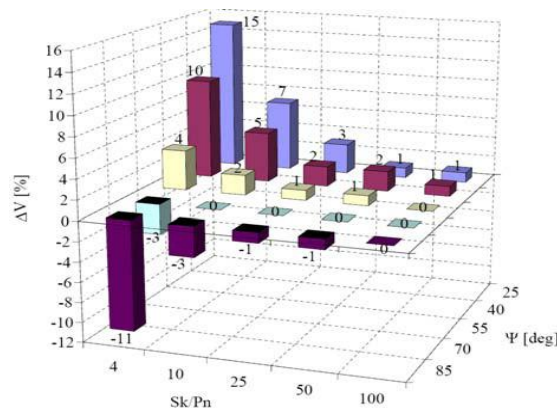


Figure 2: Voltage deviation when the power factor at the connection point is 0.95 lagging (inductive)

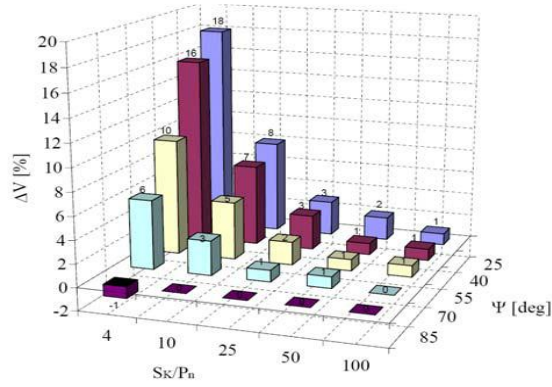


Figure 3: Voltage deviation when the power factor at the connection point is 1 (unity)

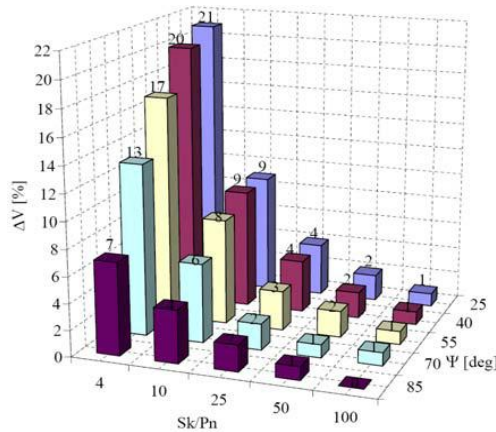


Figure 4: Voltage variation when the power factor at the connection point is 0.95 leading (capacitive)

The voltage deviation at the connection node relative to the system-side busbar voltage can be approximately calculated by the following equation:

$$\Delta U = \frac{R.R + Q.X}{U_L} \quad (12)$$

The reactive power demand from the DG source required to ensure $\Delta U \approx 0$ khi $S_k/P_n > 25$, is calculated by the ratio

$$\frac{Q}{P_n} = -\frac{R}{X} = -\frac{1}{tg\psi} \quad (13)$$

Based on Equations (8) to (13), the required level of reactive power support from the DG source is determined for different voltage deviation levels (0%, ±5%, ±10%), in combination with variations in the short-circuit power ratio and the grid impedance angle.

The results are presented in Figures 6a, 6b, and 6c.

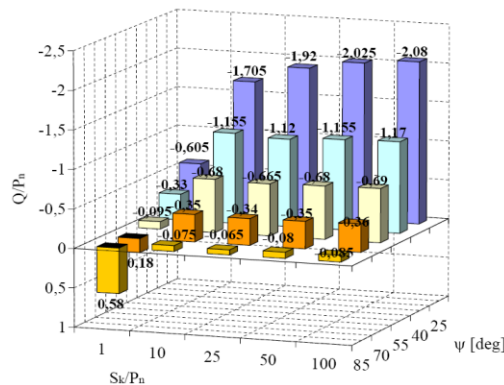
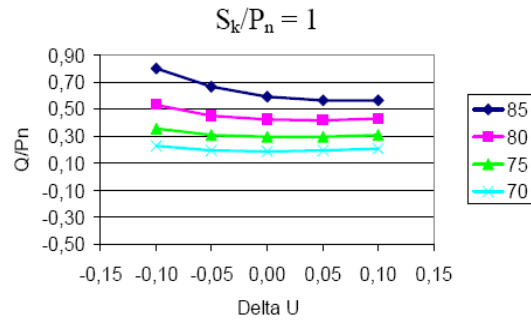
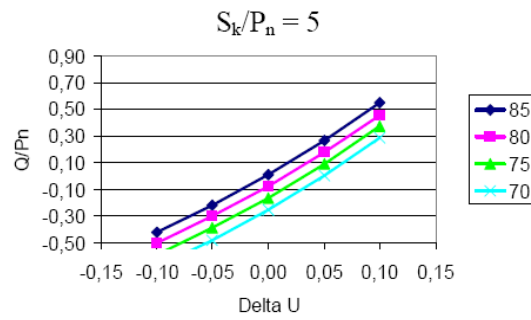


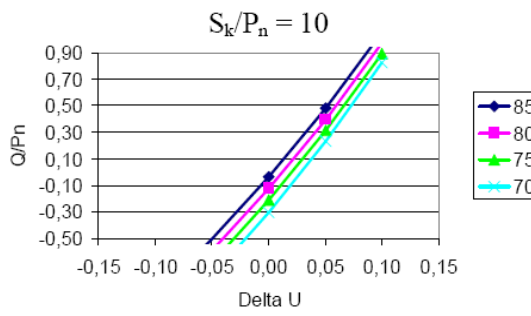
Figure 5: Reactive power demand (Q/P_n) required to maintain zero voltage deviation for different short-circuit power ratios



(6a)

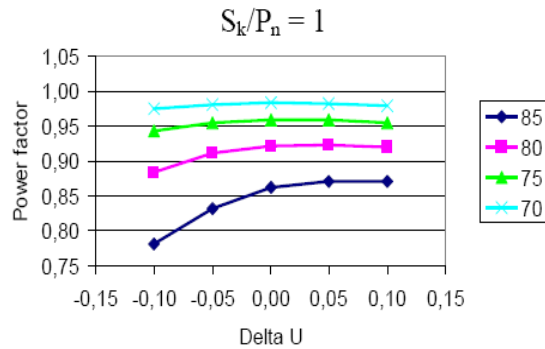


(6b)



(6c)

Figure 6 (a, b, c): Voltage deviation corresponding to the reactive power output level of the generator, depending on the short-circuit power ratio and the grid impedance angle, for short-circuit power ratios of 1, 5, and 10.



(7a)

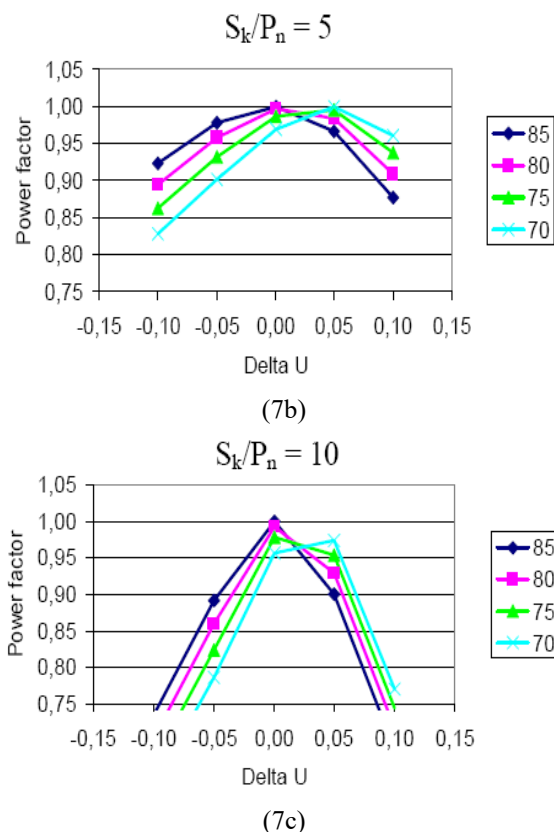


Figure 7 (a, b, c): Voltage deviation corresponding to different generator power factors, depending on the short-circuit power ratio and the grid impedance angle, for short-circuit power ratios of 1, 5, and 10

Remarks:

Based on the calculated results shown in the above figures, it can be observed that:

- In the case where the power factor at the connection node is inductive, the maximum voltage deviation can reach up to 15% (higher than the system busbar voltage) when the short-circuit power ratio is 4 and the impedance angle is small ($\approx 25^\circ$). With the same short-circuit ratio, when the impedance angle increases to 85° , the voltage at the connection node decreases by 11% compared to the system busbar voltage. Therefore, when the power factor at the connection node is 0.95 (inductive), to ensure zero voltage deviation, the required short-circuit power ratio should not be less than 4, and the impedance angle must be within the range of 40° to 85° .
- When the power factor is unity, the voltage difference between the connection node and the system busbar reaches a maximum value of 18% when the impedance angle is 25° and the short-circuit power ratio is small. In this case, to ensure zero voltage deviation, the short-circuit power ratio must not be less than 10, and the impedance angle must be greater than 40° . If the short-circuit power ratio is less than 10, then the impedance angle must exceed 70° .
- When the power factor at the connection node is 0.95 leading (capacitive), the maximum voltage deviation can reach up to 21% when the impedance angle is 25° and the short-circuit power ratio is 4. The voltage deviation remains within the permissible range of $\pm 5\%$ only when the short-circuit power ratio is greater than 10. With this ratio, the voltage deviation always stays within acceptable limits and is nearly independent of the X/R ratio.

Figures 7a, 7b, and 7c also show that as the short-circuit power ratio increases, the required reactive power compensation capacity at the PCC also increases. In most cases, selecting a power factor $\cos\phi$ at the connection node within the range of 0.85 to 0.95 (both inductive and capacitive) is sufficient to maintain voltage balance when the impedance angle is within 70° to 85° . For example, when $S_k/P_n = 1$ and the impedance angle is 75° , a required power factor of 0.96 at the connection point results in zero voltage deviation. This serves as an important reference for deciding the connection of distributed generation sources to distribution or transmission networks appropriately.

IV. CONCLUSION

The paper presents a method for evaluating voltage deviation in power networks with integrated distributed generation (DG). A design solution for the network, along with the requirements for reactive power installation from these sources to ensure that voltage deviation remains within permissible limits, has also been introduced.

The calculation and analysis results show that the level of voltage deviation strongly depends on network parameters, particularly the X/R ratio, the system short-circuit power ratio S_k/P_n , and the power factor of the DG. The illustrated results can be applied to determine optimal parameters during the design process and to evaluate voltage deviation in networks with DG under various operating conditions, thereby enabling the proposal of appropriate solutions. In addition, to improve the stable operation capability of distributed generation, it is necessary to install devices capable of supplying reactive power with minimal dependence on voltage (such as SVC, STATCOM, etc.) to support voltage recovery during fault restoration or in cases of significant voltage fluctuations in the network. Design parameters for the network and reactive power compensation for DG should be determined based on simulation results, as there are currently no common standards applicable to this type of network and generation system.

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