

IMPACT OF DISTRIBUTED GENERATION ON THE FUNCTIONING OF LINE CURRENT PROTECTION

Enhancing the operational reliability of distribution electrical networks (DENs) necessitates the implementation of intelligent systems that enable the real-time optimization of network operating modes, improve the reliability of power supply, and effectively integrate renewable energy sources.

Distributed generation (DG) plays an increasingly crucial role in modern power systems. However, its integration into distribution networks can significantly affect the operation of existing protection systems. To evaluate this impact, it is essential to conduct calculations, justifications, and simulations of relay protection (RP) operation in networks with DG. Low- and medium-voltage DENs are critically important for ensuring the reliable and high-quality power supply to end consumers. Their effective functioning directly influences the overall reliability and quality of electricity in the integrated power system of Ukraine.

This article investigates the impact of distributed generation on the functioning of the line relay protection of DENs. For the research, a typical fragment of an electrical network with distributed generation is utilized, based on which short-circuit current calculations were performed, and the minimum value of the short-circuit infeed current from the power system was substantiated. It was established that the additional generation source affects the proportion of the power system current in the total short-circuit current, and there is an interrelation between the location of DG in the electrical network and the sensitivity of the line current protection.

Keywords: current relay protection, distribution networks, distributed generation.

Introduction

The current state of the energy sector poses significant risks to the country's energy security, as the majority of thermal and nuclear power units are nearing the end of their operational lifespan, and dependence on fossil fuels remains critically high. Thermal power plants, used for system balancing, are operating at the limit of their reserves, leading to equipment wear and increased accident rates. According to international obligations, a significant portion of thermal power capacity needs to be modernized or decommissioned by 2033, which complicates the situation.

Furthermore, Ukraine's power grids require updating and modernization [1]. As of 2021, over 837.1 thousand km of power transmission lines were in operation, a significant portion of which requires modernization. In particular, 64.45% of overhead power lines with a voltage of 220-330 kV have been in operation for 40 years or more, and 4.95% of lines with a voltage of 220-750 kV require complete replacement or reconstruction due to their emergency condition. DENs also require major repairs. Moreover, 61% of the main equipment of electrical substations has exceeded its service life.

In the context of the aforementioned challenges, the development of distributed generation based on renewable energy sources (RES) is an important factor for ensuring the energy security and sustainable development of the country. Distributed generation not only increases the resilience of the power system, making it less vulnerable to centralized attacks, especially in wartime conditions, but also reduces dependence on fossil fuels, lowering the need for imports and protecting against price fluctuations in global markets. In addition, it enhances the reliability of power supply, providing local consumers even in the event of accidents on main power transmission lines, facilitates the integration of RES into the power system, and modernizes DENs, increasing their operational efficiency and reliability [1].

At the same time, for the successful development of distributed generation, it is necessary to create favorable conditions for investment in RES, ensure the development of maneuvering capacities and energy storage systems, modernize distribution networks, and implement intelligent control systems, promoting the transition to "green" technologies. The development of distributed generation is crucial for Ukraine as it allows for ensuring energy security, reducing import dependence, and increasing the reliability of power supply.

However, the integration of distributed generation into DENs leads to changes in the parameters of the power system, the magnitude and direction of the fault current may change when RES are connected to the electrical network [2]. This, in turn, affects the operating algorithm of relay protection and requires new approaches to its implementation.

Changes in the composition of generating capacities and their operating mode necessitate a continuous update of short-circuit current calculations and the corresponding adjustment of relay protection tripping parameters based on the determination of the current contribution of each generation source during fault conditions. Modern systems utilize databases or event logs to identify the current state and apply pre-developed

response measures [3]. However, considering the current trend of continuous commissioning (decommissioning) of new RES capacities and loads in distribution networks, this approach becomes less effective. Furthermore, power plants based on RES have non-linear characteristics and variable parameters. To guarantee the reliable operation of the power system, it is necessary to continuously monitor all elements of the protection system and promptly make changes to their settings adaptively to the operating conditions.

Aim and objectives of the study

The aim of this study is to investigate the impact of distributed generation on the functioning of relay protection. In accordance with this aim, the study examines the influence on the sensitivity of relay protection depending on the connection point of DG to the electrical network.

Materials and research results

Changes in short-circuit currents caused by the connection of additional power plants are a key factor that must be considered in the design and operation of relay protection systems [4, 5]. Traditionally, stepped current protection schemes are used as primary and backup protection in distribution electrical networks. To investigate the impact of connecting an additional generation source on the magnitude of short-circuit currents at various points in the network, which is necessary to consider when setting the parameters of backup relay protection, a fragment of an electrical network shown in Fig. 1 was selected.

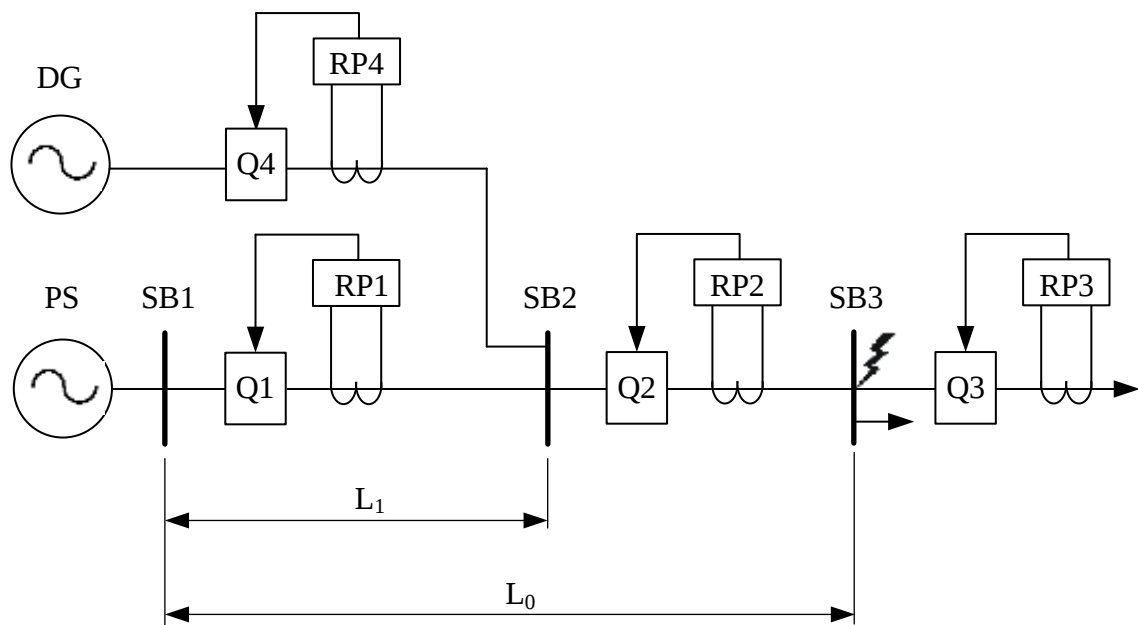


Figure 1 – Investigated fragment of DEN

To analyze the influence of the DG connection point on the magnitude of the short-circuit current, the connection from the supplying substation SB1 to the final substation SB3 (base line) was chosen, where DG is connected at a distance L_1 , and a three-phase short circuit, as the most severe type of fault, is simulated at the buses of substation SB3.

We assume:

$$L = \frac{L_1}{L_0}, \quad (1)$$

where L is the relative parameter of the DG distance from the supplying substation SB1; L_0 is the length of the base line from substation SB1 to SB3; L_1 is the distance from substation SB1 to the DG connection point.

The equivalent single-phase substitution circuit for short-circuit current calculations is shown in Fig. 2.

In the circuit (Fig. 2), the following are denoted: U_{PS} and U_{DG} – the EMF of the power system source and the distributed generation, respectively; Z_{PS} and Z_{DG} – the internal impedances of the power system and DG, respectively; Z_L – the total impedance of the supply line.

Assuming that $U_{EQ} = U_{DG} = U_{PS}$, the substitution circuit can be transformed to the form shown in Fig. 3.

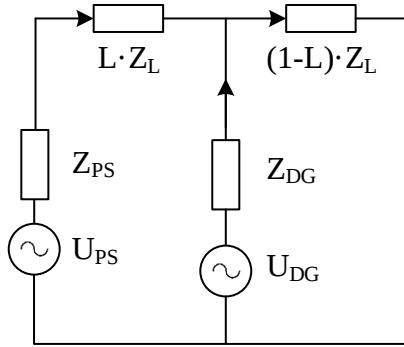


Figure 2 – Calculated single-phase equivalent circuit of DEN fragment

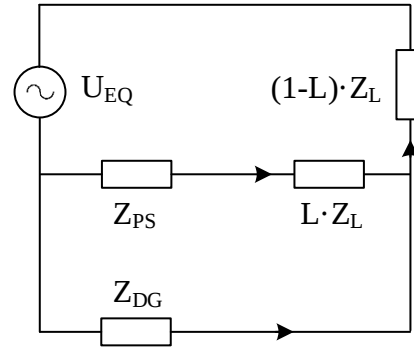


Figure 3 – Simplified single-phase equivalent circuit of DEN fragment

According to the circuit (Fig. 3), the equivalent impedance of the DEN can be determined as:

$$Z_{EQ} = \frac{(Z_{PS} + L \cdot Z_L) \cdot Z_{DG}}{Z_{PS} + L \cdot Z_L + Z_{DG}} + (1-L) \cdot Z_L, \quad (2)$$

The obtained total equivalent impedance is used to calculate the three-phase short-circuit current:

$$I_K = \frac{U_{EQ} \cdot (Z_{PS} + L \cdot Z_L + Z_{DG})}{\sqrt{3} \cdot ((Z_L \cdot Z_{DG} + Z_{PS} \cdot Z_{DG} + Z_{PS} \cdot Z_L) + L \cdot Z_L (Z_L - Z_{PS}) - L^2 \cdot Z_L^2)} \quad (3)$$

The magnitude of the current from substation SB1 to substation SB2 will be determined as:

$$I_{K1} = \frac{Z_{DG}}{Z_{PS} + L \cdot Z_L + Z_{DG}} \cdot I_K \quad (4)$$

or

$$I_{K1} = \frac{U_{EQ} \cdot Z_{DG}}{\sqrt{3} \cdot ((Z_L \cdot Z_{DG} + Z_{PS} \cdot Z_{DG} + Z_{PS} \cdot Z_L) + L \cdot Z_L (Z_L - Z_{PS}) - L^2 \cdot Z_L^2)} \quad (5)$$

The second stage of the two-stage current protection (maximum current protection) of substation SB1, which backs up the possible failure of the protection of substation SB2 in the event of a short circuit on the buses of substation SB3, must respond to the current I_{K1} . The maximum current protection of substation SB1 does not operate if its tripping setting exceeds the magnitude of the power system's current contribution to the short-circuit current. That is, when the sensitivity coefficient of the current protection critically decreases.

Distributed generation has the maximum impact on the three-phase short-circuit current when the power system's current contribution is minimal. Therefore, to find the minimum value of the function given by equation (6), it is necessary to calculate its derivative with respect to the relative parameter L :

$$\frac{dI_{K1}}{dL} = -U_{EQ} \cdot Z_{DG} \frac{3 \cdot (Z_L (Z_L - Z_{PS}) - 2 \cdot L \cdot Z_L^2)}{2 \cdot (3 \cdot (L \cdot Z_L \cdot (Z_L - Z_{PS}) - L^2 \cdot Z_L^2 + Z_L \cdot Z_{DG} + Z_{PS} \cdot Z_{DG} + Z_{PS} \cdot Z_L))^{3/2}} \quad (6)$$

The short-circuit current from the power system will be minimal if the derivative (7) is equal to zero:

$$-U_{EQ} \cdot Z_{DG} \frac{3 \cdot (Z_L (Z_L - Z_{PS}) - 2 \cdot L \cdot Z_L^2)}{2 \cdot (3 \cdot (L \cdot Z_L \cdot (Z_L - Z_{PS}) - L^2 \cdot Z_L^2 + Z_L \cdot Z_{DG} + Z_{PS} \cdot Z_{DG} + Z_{PS} \cdot Z_L))^{3/2}} = 0 \quad (7)$$

Since U_{EQ} and Z_{DG} are not equal to zero, the equality will be satisfied if the numerator of the fraction is equal to zero:

$$3 \cdot (Z_L (Z_L - Z_{PS}) - 2 \cdot L \cdot Z_L^2) = 0 \quad (8)$$

Solving the obtained equation (8) with respect to L :

$$L = \frac{Z_L - Z_{PS}}{2 \cdot Z_L} \quad (9)$$

In practice, usually, the impedance of the power system Z_{PS} is significantly lower than the impedance of the base line Z_L . If we neglect the power system impedance and assume $Z_{PS} \approx 0$, then the relative parameter L will be equal to 0.5. That is, the greatest impact of DG on the power system's current contribution will occur if the DG connection point is located in the middle of the supply line. In this case, in the event of a fault at the end of the base line, the short-circuit current infeed from the power system will be minimal.

As an example, calculations are provided for a 10 kV base line, type AS-50, with a length of $L_0 = 10$ km ($Z_L = 7.2$ Ohm), $Z_{DG} = 1.5$ Ohm, $Z_{PS} = 0.211$ Ohm. The results of the short-circuit current calculations from the power system depending on the DG connection point are presented in Table 1.

Table 1 – Short-circuit current calculation

L, p.u.	I_{K1} , A
0	686
0,1	506
0,3	376
0,5	349
0,8	440
1	780

The graphical interpretation of the current calculation is shown in Fig. 4.

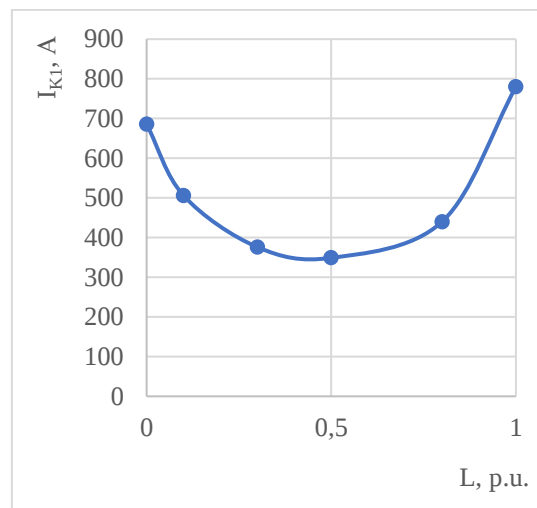


Figure 4 – Graph of the dependence of short-circuit current on the DG connection point

The conducted analysis shows that the greatest reduction in the sensitivity of the backup current protection occurs in cases where the DG connection point is located in the middle of the main power supply line to the load, regardless of the total capacity of the distributed generation source.

The total short-circuit current, calculated using equation (3), has a non-linear characteristic, consequently, the current from the power system is also non-linear. If the total impedance of the section between substations SB1 and SB2 is greater than Z_{DG} , then the magnitude of the short-circuit current in this branch will decrease due to changes in current distribution in the branches. Equation (5) determines the power system's current contribution to the fault current at substation SB2, to which the distributed generation source is connected.

Furthermore, the preliminary analysis showed that the power system's current contribution to the total short-circuit current depends on the total impedance of the line from substation SB1 to substation SB3, the local short-circuit capacity, the relative capacity of the DG, its location and connection method, which may be the subject of further research.

Conclusions

The results of the conducted research indicate the possibility of the backup protection of SB1 failing to operate due to a critical reduction in its sensitivity, which is caused by a decrease in the power system's current contribution to the total short-circuit current under the influence of DG. The tripping settings of the relay protection may be incorrect according to the new network structure.

For further analysis of the impact of distributed electricity generation on the functioning of current protection, it is advisable to investigate the impact under different DEN topologies and various parameters of the power system and DG (type, capacity, connection method, etc.), which will allow for increasing the efficiency of the relay protection of DENs with DG.

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ВПЛИВ РОЗОСЕРЕДЖЕНОЇ ГЕНЕРАЦІЇ НА ФУНКЦІОНУВАННЯ СТРУМОВОГО ЗАХИСТУ ЛІНІЇ

Підвищення надійності роботи розподільних електричних мереж (РЕМ) передбачає впровадження інтелектуальних систем, які дозволяють оптимізувати режими роботи мережі в реальному часі, підвищити надійність електропостачання та ефективно інтегрувати відновлювані джерела енергії.

Розосереджена генерація (РГ) відіграє все більш важливу роль у сучасних електроенергетичних системах. Проте, її інтеграція в розподільні мережі може суттєво вплинути на роботу існуючих систем захисту. Для оцінки цього впливу, необхідно провести розрахунки, обґрунтування та моделювання роботи релейного захисту в мережах з РГ. РЕМ низької та середньої напруги є критично важливими для забезпечення надійного та якісного електропостачання кінцевих споживачів. Їх ефективне функціонування безпосередньо впливає на загальну надійність та якість електроенергії в об'єднаній енергосистемі України.

У статті досліджується вплив розосередженої генерації на функціонування релейного захисту лінії РЕМ. Для досліджень використовується типовий фрагмент електромережі з розподіленою генерацією, на основі якого було проведено розрахунки струмів короткого замикання та обґрунтовано мінімальне значення струму підживлення короткого замикання від енергосистеми. Встановлено, що додаткове джерело генерації впливає на частку струму енергосистеми в загальному струмі короткого замикання та існує взаємозв'язок між місцем розташування РГ в електромережі та чутливістю струмового захисту лінії.

Ключові слова: струмовий релейний захист, розподільні мережі, розосереджена генерація.

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